Australian Government
Australian Renewable Energy Agency

ARENA

Hybrid power generation for Australian off-grid mines

Handbook – June 2018

Prepared by Ekistica for the
Australian Renewable Energy Agency

Ekistica

Cover Photo Source: Neoen's DeGrussa Solar Project

Acknowledgements

Over 100 industry professionals have kindly provided their time and energy to share insights, technical direction and invaluable perspectives to this handbook, drawn from their wealth of individual and collective experience. This handbook benefits from the diversity, strength and willingness of their participation – for which we are appreciative. Of significant note are those acknowledged below.

Contents

List of Equations

List of Figures

List of Tables

1.0 Introduction

Australia has more than 400 operating mines, of which approximately 65 per cent meet their electricity needs from the primary electricity markets: the National Electricity Market (NEM) and the South West Interconnected System (SWIS). The NEM supplies electricity to the majority of mines in the eastern states as well as around half the mines in South Australia, while the SWIS powers around a third of Western Australian mines. It is estimated that approximately half the mines not powered by the primary electricity markets have their power supplied by Independent Power Producers (IPPs).

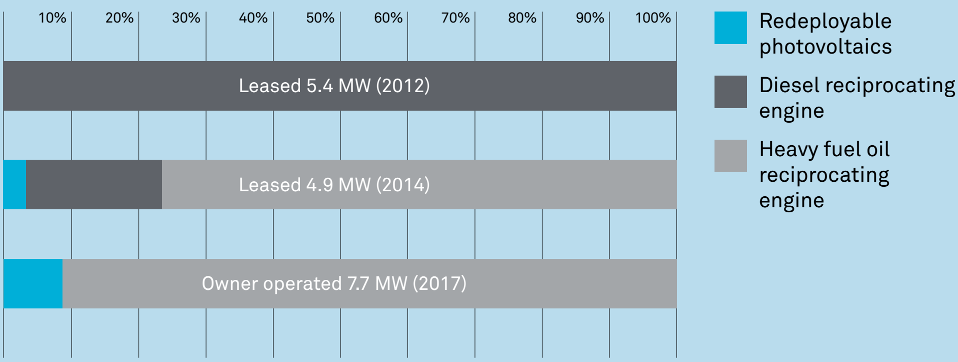
The development of this handbook was driven by an observed lack of easily accessible information about the initial considerations required to develop business cases for hybrid power generation, as well as an equal lack of literature demonstrating its potential to produce economical, reliable power for Australian mines. The handbook forms part of a broader effort by the Australian Renewable Energy Agency (ARENA) to build the mining sector's capacity to more readily work with renewable energy and capture savings from lower operating costs.

ARENA promotes the uptake of small-scale renewable power generation as a low-risk gateway to longer term, more extensive renewable integration – an approach not unlike the progressive integration steps taken by New Luika gold mine in Tanzania over the past decade. Two low impact strategies that may be implemented either sequentially or concurrently are to allocate 100 per cent renewable power to small applications such as bore pumps or camp infrastructure, or adopt hybrid

New Luika gold mine, Tanzania

The mine has implemented a progressive adoption of hybrid power generation, transitioning from a leased model in 2012 to owner operated in 2017 financed by a $10M bank loan.

Fig 1.1 Progressive increase of renewable power fraction



power generation at a low renewable power fraction (refer Chapter 2.4), which pursues long-term cost savings and is the focus of this handbook.

The forms of hybrid power generation addressed in this handbook are diesel or gas fuelled power generation hybridised with photovoltaics (PV), wind turbines or concentrated solar power (CSP). While enabling technologies such as battery storage lie in the near future, and electric vehicles at mines are emerging, the next immediate milestone lies in the reliable, financeable integration of renewable sources alone. Accordingly, the focus of this handbook is hybrid power generation that does not incorporate enabling technologies.

Acknowledging the variety of project circumstances in the off-grid Australian mining sector, this handbook intends to find utility and value in specific cases. It aims to plug key gaps in awareness, clarify principles, solidify understanding and improve confidence. Ultimately the handbook aims to build the capability of potential proponents seeking to develop projects involving hybrid power generation in mining contexts, thus laying a broad foundation from which bankable, site-specific execution can be initiated.

1.1 Legislated Renewable Requirements

When considering the use of hybrid power generation, a company must take into account the legal requirements concerning renewable energy. A non-registered entity that sells power from a grid with greater than 100 MW capacity to a legally different entity can be liable under the *Renewable Energy (Electricity) Act 2000* (Cth) to generate a percentage of its electricity from renewable sources or purchase the equivalent in Renewable Energy Certificates (RECs). This percentage is defined by the Clean Energy Regulator each year as the sum of two forms of RECs, as shown in Figure 1.2. For example, 2017 regulations require the equivalent of 21 per cent of the liable entity's electricity acquisitions to be surrendered as RECs or a fine of $65 (2017) per unit of shortfall (MWh).[1]

1.2 Role of Power in Mining

The supply of power is crucial to the success of a mining project. Yet while reliable power is pivotal to the mine's revenue, the capital expenditure (CAPEX) and operating expenditure (OPEX) attributed to power production are often comparatively low. No more than 15 per cent of initial direct CAPEX is generally attributed to electrical infrastructure and equipment [2], while electricity costs on average represent 15-40 per cent of a mine's OPEX. The higher end of this range typically reflects projects with mineral processing requirements (refer to Table 1.1). These figures are not only low in absolute terms but low in comparison to the commodity revenue, hence the reliability of the power is far more important than any marginal cost savings in its supply. Having an appreciation of this context as well as the power requirements for different mining methods and processing, is vital for proponents of hybrid power generation.

Table 1.1 Example ores of operational Australian mines

Processing typically undertaken at mine site	Metallic minerals: Gold, copper, zinc, nickel, lead, silver, uranium, tin
Limited or no on-site processing	Metallic minerals (refined off-site): Iron ore, bauxite Industrial minerals and fuel: Diamond and other precious stones, mineral sands, rare earths, gypsum, talc, coal

Half of the Australian mines that undertake metallic minerals processing on-site are not connected to the primary electricity markets (NEM or SWIS). For these mines, the major electricity consuming process tends to be comminution. The consumption of up to three per cent of the world's generated electric power is attributed to comminution[3], and in Australia's copper and gold mines comminution processes alone account for 1.3 per cent of national electricity consumption.[4]

Minerals that require more intense or extensive processing to achieve liberation have higher electricity demands. But while electricity dependencies tend to be characteristic of a certain commodity, they are also specific to individual projects as outlined in Figure 1.3, reflecting characteristics such as the type of mine, processing or product delivery.

Fig 1.2 Legislated renewable requirements (adapted from [1])

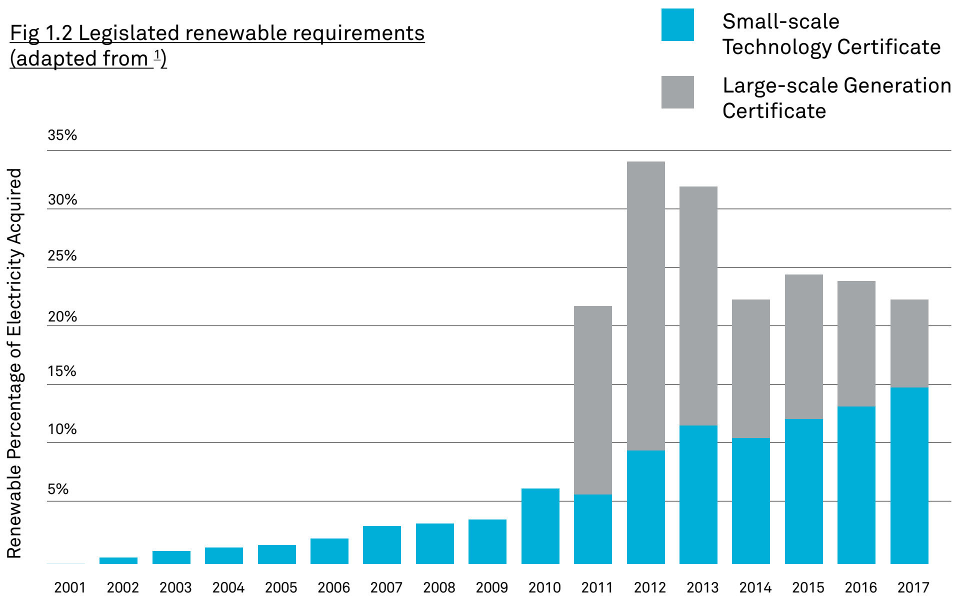


Fig 1.3 High electricity consumption activities for mining projects

Project Area	High Electrical Consumption Activities
Mining	Underground mining: • Underground mine ventilation • Continuous miners In-situ mining: • Pumping Open cut mining: *Limited 'high' electricity consumption activities*
Processing	Communition Crushing: • May include primary, secondary and tertiary • Installed power capacity can range from 0.2 to 1.2 MW per crusher Milling: • Can consume up to 75% of processing electrical demand • May assume start-up power up to 1.5 times the installed power • Installed power capacity can range from 0.2 to 25 MW per mill • 24/7 operation Benefaction • Electrowinning • Smelting (furnace)
Tailing Storage *Typically only processed Ore*	• Conveying or pumping
Product Delivery *Typically only non-processed Ore*	Transport of product off-site for refinement: • Rail • Port facilities
Administrative Areas and Camp	*Limited 'high' electricity consumption activities*

1.3 Timing and Decision-Making

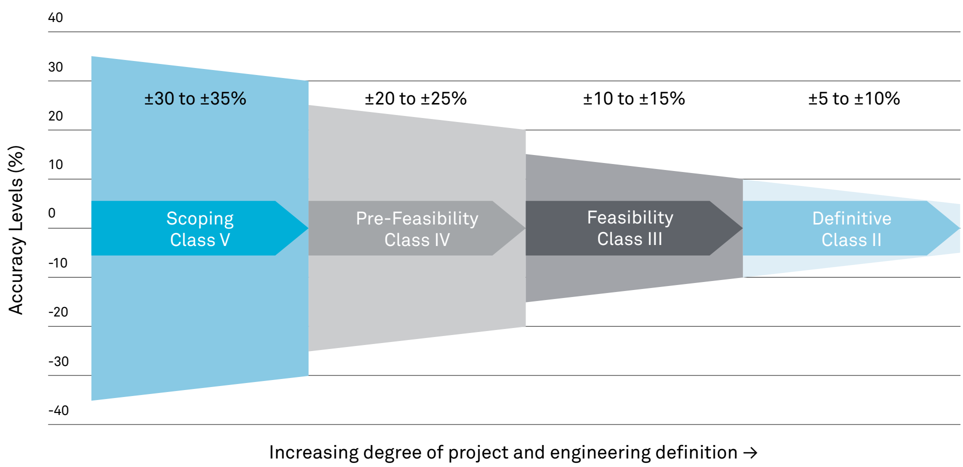
The timing of contract decisions and options studies for a mine's power supply have a significant bearing on the technical and economic viability of employing hybrid power generation. This applies to decisions about the power supply directly – such as the generation technology to be adopted – and indirectly – such as the selection of consultants and or contractors whose capabilities may further impose constraints on the power supply options.

While the required development period allowances for hybrid power generation will vary significantly from project to project, it can be assumed that trucked gas and diesel generation will require the shortest development time. The development period allowance for PV may be anywhere from six months to two years, whereas wind or gas pipelines are in the range of three to seven years and CSP typically takes two to five years.

1.3.1 Greenfield Projects

Mines may or may not undertake studies for each estimate class and may undertake multiple studies within a given phase. For projects following typical mine development phases, as shown in Figure 1.4, a power options study that considers hybrid power generation should be conducted during the mine's Pre-Feasibility Study phase, or commenced in the scoping study phase. Attempts to integrate hybrid power generation at a later phase may encounter obstacles such as early contractor engagement restricting the ability to change scope, a lack of sufficient weather data to conduct a proper study of the site's renewable resource potential, and a constrained timeframe for approvals or environmental studies that may result in project delays.

Fig 1.4 Typical mine development phases and degrees of engineering definition[2]



Typically, outputs from an earlier study phase form an input to a future study phase. It is therefore critical to understand how hybrid power generation criteria vary from single-source power generation at the outset, as the early identification of inputs required for a given phase determine the electrical, instrumentation and control design as well as the cost estimation.

1.3.2 Brownfield Projects

Typically for brownfield sites, an investigation of hybrid power generation options one to three years prior to intended implementation will significantly reduce risks and increase confidence in viability assessments.

As well as considering the stage at which power supply decisions are to be made, the timing of construction and commissioning itself requires consideration, as was learnt during the construction of the DeGrussa copper-gold mine's 19 MW diesel power station retrofit with PV. Key considerations that will determine the optimal timing for renewable energy integration are the Life of Mine, mine production schedule, mineral processing schedule, maintenance regime, service life of existing power generation infrastructure, IPP contract terms or contract end dates, availability of site weather data, and availability of existing hourly load data covering all seasons.

1. 4 Load Profile and Power Demand

Many mines operate 24/7 with limited fluctuations in the daily load profile. The effective design of a mine's power system therefore requires sound understanding of the consumer load profiles and power demand, both forecast and actual/historical. The variable nature of solar and wind sources makes it especially critical that the design configuration of hybrid power generation accommodates the load's characteristics.

System design requires understanding of demand requirements, magnitude of load, time and duration. In the case of processing, loads can be more sensitive, with major equipment such as mills for some operations consuming more than half the total mine site load, which can have significant ramifications in the event of a fault in either generation or demand. More specifically, the nature of equipment at a mine should be understood for its electricity draw characteristics and potential effects on peer equipment. Examples may include:

- significant motor fault current contributions
- significant harmonic current injection by motors
- regeneration capacity of equipment
- cyclic fluctuations (flickers) due to load cycle of draglines, shovels or winders
- power oscillations between synchronous generators and motors
- motor starting transients
- over-voltages due to partial load rejection
- voltage collapse due to large motors stalling[5]

Photo source: Sandfire Resources

DeGrussa copper-gold mine,
Western Australia

Lessons learnt by Neoen, owner of the facility and juwi Renewable Energy Pty Ltd, the Engineering Procurement Construction Management (EPCM) and Operation and Maintenance (O&M) contractor of the PV and storage plant to the DeGrussa copper-gold mine, highlighted that the risk profile of the existing mine operations must be fully understood and considered throughout the process to effectively deliver hybrid power generation on a brownfield site. The core processes of the mine must be considered to ensure the construction or retrofitting of a new or existing power station minimises disruption to the mine's production schedule and site procedures. The construction methods should be flexible and complementary to current processes, for example, by commissioning during scheduled maintenance downtime.

In juwi's experience, energisation of the system and implementation of the hybrid control system requires a significant amount of design and planning to minimise impact on existing mine systems and processes.

The 10.6 MW_{DC} / 10 MW_{AC} PV installation, covers 20 ha comprising 34,080 polycrystalline modules with single-axis tracking and a 6 MW_{DC} / 1.8 MWh lithium battery for solar smoothing/ramp rate control. The PV provides an estimated 15-20 per cent of the mine's energy needs by generating approximately 21 GWh per annum, reducing diesel consumption by around 5 ML per annum. The PV and storage plant was commissioned mid-2016 and its $41M CAPEX was part funded by ARENA ($20.9M recoupable).

For brownfield sites, annual hourly demand data (kW and kvar) should be assessed in conjunction with the planned Life of Mine production schedule and forecast energy and power demand. Note that better results are achieved using higher resolution data, for example at five minute resolution. Less data results in a more conservative design, which subsequently will create increased costs and increased complexity within control systems.

Assessments should consider:

- start-up power requirements
- critical versus non-critical loads
- operating hours and flexibility for peak-shifting in operation
- major equipment reactive and active power requirements
- existing control philosophy
- existing maintenance strategy.

An electrical equipment, instrumentation and control audit should be undertaken to identify the characteristics and constraints of legacy infrastructure at a brownfield site, as well as the opportunities presented by it. At a minimum, this audit should include existing generator model, controller, fleet controller and minimum load factors. For detailed design, one second data is necessary to understand potential integration scenarios, as well as ramp rates and diesel or gas loading.

These requirements equally apply to greenfield design in regard to planned infrastructure. Greenfield projects provide the additional opportunity to schedule operations or size equipment (pumps, pipelines, tanks/dams) to take advantage of energy output, rather than applying a one-way design process. This is further discussed in Chapters 3.2 and 3.4.

2.0 Hybrid Power Generation

Characteristics of a specific mine must be assessed to determine the applicable design criteria and scope of a power system. However, before committing funds to analyse options or prepare a business case, the potential economic viability of hybrid power generation may be anticipated, based on some simple, high-level checks. These include characteristics such as location, available land area, land tenure and access status, brownfield constraints and Life of Mine. These factors can have an immediate bearing on technology selection. The pointers may be conclusive or inconclusive, with traits suggesting various degrees of amenity to hybrid power generation or in some cases, a preferable technology may become apparent. These basic considerations can indicate the appropriateness of hybrid power generation at a mine, prima facie. Armed with such high-level gateway indications, mining proponents can avoid wasting time and proceed with greater clarity, surety and context towards the business case assessment of hybrid power generation.

2.1 Generation Options

2.1.1 Generation Technologies

The forms of hybrid power generation that sit within the scope of this handbook have two defining generation elements: a synchronous generation source that provides inherent mechanical inertia and a variable generation source as shown in Figure 2.1.

2.1.2 System Architecture Design

The system topology (system architecture) defines the way these generation sources can be interconnected in a complementary manner to enable smooth, seamless power transmission by means of a network and the appropriate interfacing technology as shown in Figure 2.2.

Fig 2.1 Power generating technologies

Synchronous Generation

Reciprocating Engines

Engines powered by typically diesel fuel or gas coupled with an electrical generator to produce electricity

- Typically plants <75 MW
- Diesel produces greater CO_2e emissions than gas
- Fast to respond to fluctuations in demand or variable generation
- Start-up time from cold start 1-5 minutes
- Minimum load factor ~30%

Combustion Turbines

For open cycle gas turbines (OCGTs), ambient air is continuously combusted in a thermodynamic cycle fuelled by gas, then passed through a turbine to drive a generator for electricity. Combined cycle gas turbines (CCGTs) are OCGTs with exhaust gases utilised to power an additional steam turbine (Rankine cycle).

- Typically plants >50 MW (economic viability achieved at scale)
- Slower to respond to fluctuations in demand or variable generation
- CCGT higher CAPEX than OCGT
- CCGT potential to generate up to 50% more electricity than OCGT from same gas fuel volume
- CCGT part load efficiency higher than OCGT
- Minimum load factor ~40% for OCGT and ~50% for CCGT

CSP Steam Turbines

Mirrors focus sunlight and typically store energy as heat in a molten salt solution to generate steam and drive a turbine to produce electricity. Two common configurations are: tracking parabolic trough reflectors with receiver tube, OR heliostat (flat tilted) reflectors with receiver tower.

- Plants >50 MW (economic viability achieved at scale)
- Emerging technology in Australia
- Typically gas used to power turbine where shortfall in storage occurs
- Minimum load factor ~40%

Variable Generation

Wind Turbines

Convert wind into a torque, driving an electric generator to produce electricity

- Standard manufacture for <600 kW or 1.5-4.5 MW per turbine
- Inverter to control voltage AC/DC-DC/AC
- Able to ramp up/down quickly in response to fluctuations in demand
- Minimum generation defined by design cut-in wind speed

Photovoltaics

Convert sunlight to DC power via a flat collecting surface with a silicon or a thin-film coating and an inverter that converts DC to AC power

- Crystalline modules most common (90%)
- Fixed or tracking; tracking arrays are optimally oriented true north and tilted to match latitude
- Responds to fluctuations in demand instantaneously
- Minimum load factor considerations not relevant

Fig 2.2 Hybrid power generation architecture considerations

Synchronous Generation	The macro design of synchronous generation includes: • options for unit commitment strategies: – balanced load strategy – all generators produce same output – cascading typology – merit order applied: high order generators run at optimum loading efficiency and lower orders operate within a broader range • size of reciprocating turbines, if multiple, are all the same or different in capacity • spinning reserve or separate backup generator • fuel transport (truck, pipeline), handling and storage • location of generation proximate to consumption.
Control System	Instrumentation and control software are key to successful hybrid power generation integration. A Supervisory Control and Data Acquisition (SCADA) system or Distributed Control System (DCS) using Programmable Logic Controllers (PLC) is designed to coordinate all elements for overall demand and supply management, control and monitoring. Option to control as small discrete distributed systems or one large centralised system.
Variable Generation	Considerations for the macro design of variable generation may include: • geographical dispersion of wind turbines or PV arrays • numbers of inverters and string configurations (including sizing or oversizing of inverters) • cable layout across site • location of generation proximate to consumption • functional design • single line diagrams.
Transmission and Distribution	Private network infrastructure delivers hybrid generated electricity and transformers ensure voltage from generators meet mine grid requirements. Optimal design incorporates bidirectional communication to enable both demand and supply control.

2.2 Selecting a Generation Technology

2.2.1 Life of Mine

A longer Life of Mine enables more hybrid power generation options to be economically viable. As technology and prices stand at the end of 2017, hybrid power generation at scale is not economically viable for Life of Mine shorter than three years. For Life of Mine exceeding three years, Table 2.1 presents potential hybrid power generation options. Note that Table 2.1 refers to greenfield sites; where considering hybrid power generation for brownfield sites, savings due to the utilisation of existing infrastructure may allow for lesser Life of Mine values, or potentially increase them by placing constraints on the integration of the renewable power source.

Table 2.1 Potentially economically viable generation technologies for Life of Mine

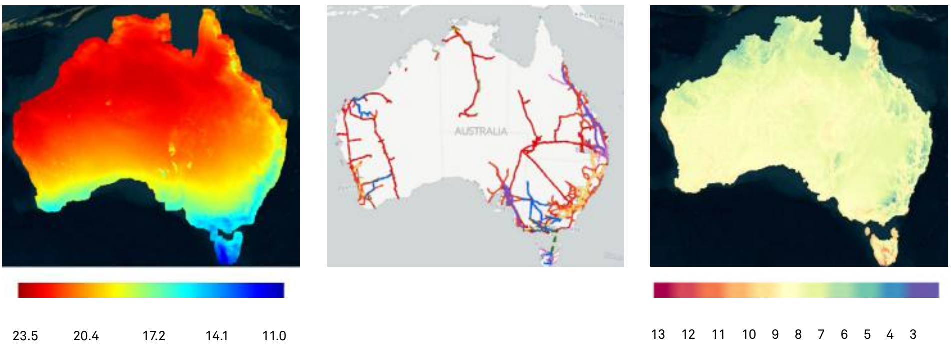
Technology	Life of Mine 3-7 years	Life of Mine 7-15 years	Life of Mine 15+ years	Influencing factors
Reciprocating Engines	✓	✓	✓	Gas price volatility has opened up medium-term market and diesel prices at decade low.
Gas Combustion Turbines	✓	✓	✓	Gas price volatility has opened up medium-term market.
Photovoltaics (PV)	✓	✓	✓	Redeployable PV and reduced CAPEX of technology.
Wind Turbines	Unlikely	✓	✓	Limited salvage value or redeployment options.
Concentrated Solar Power (CSP) Steam Turbines	Unlikely	Unlikely	✓	Less mature technology for power generation.

The discussion above may not be applicable if an IPP is willing to supply power (assuming that power is hybrid power generation) for the anticipated Life of Mine at a competitive rate, which could be a realistic possibility when the IPP is already established with customers.

2.2.2 Location

An initial consideration is the mine's proximity to existing grids, gas supply pipelines and ports with road access for diesel or gas supply, as well as the site's solar irradiance potential and/or wind patterns. As shown in Figure 2.3, there are free tools available that enable such high-level evaluation of a location. An example is the Australian Renewable Energy Mapping Infrastructure (AREMI), an online platform that allows the overlay of meteorological, topographical, statistical, energy infrastructure and other data on a map of Australia. This free service draws data from a range of sources, allowing selected parameters to be added, managed and viewed via an interactive user interface. AREMI has a focus on data pertinent to the planning of renewable projects and is available at: nationalmap.gov.au/renewables/

Fig. 2.3 High-level location considerations



Australian average daily global horizontal irradiation (GHI) (MJ/m^2)[6]

Map of Australia's gas and electricity grid networks (2017)[6]

Australian average 150 m wind speed (m/s)[7]

2.2.3 Siting Power Plants and Their Land Requirements

Hybrid power generation can cover significant land areas, so sterilisation drilling should be undertaken to confirm that power plants are not sited on potential mineral resources. As for any development, the land under consideration will also require adequate geotechnical and hydrological studies to confirm structural suitability as well as activities to ensure compliance with all legislation.

Land area requirements are determined by the power capacity of the system, which is often but not always in a linearly proportional manner, bearing in mind that PV and CSP tend to occupy land in a uniform manner while wind farms may accommodate alternative uses such as grazing, pastoral cultivation and access roads in the areas between wind turbines.

The following advice is intended for class IV-V estimates of the land demands for a given technology.

Photovoltaic arrays

The ground area to be covered by a PV array may be taken as 1 ha for 1 MW_{DC} of fixed, ground-mounted PV (linearly scalable). Additional area should be provided where module efficiency is less than 16.5 per cent, terrain is sloped, site latitude is greater than 39°S, orientation is not true north, tilt is greater than 25° or less than 20°, or where other structures or geographical features induce shadow. Single- and dual- axis tracking systems also require special consideration to avoid shading between adjacent rows or arrays, by allowing for adequate spaces between them. When planning the array layout, access for maintenance vehicles and lifting should be considered. Accordingly, the land required for PV arrays is often described using the ground coverage ratio (GCR) defined in Equation 2.1 and, depending on all these variables, typically occupies a range between 30 per cent and 60 per cent.

To house ancillary equipment, modularised options such as 20 foot containers comprising DC board, solar inverters and controls may be allocated for central inverter stations.

Equation 2.1 Ground coverage ratio

$$GCR = \frac{Ground\ area\ covered\ by\ PV\ modules}{Total\ area\ of\ PV\ site}$$

Wind farms

While a wind farm may be sited across a large area, individual wind turbines have a comparatively small footprint with foundations typically 8-20 m in diameter for turbines 40-120 m high accompanied by a crane pad occupying approximately 0.2-0.3 ha. A general rule for larger turbines (1.5-4.5 MW) is an inter-turbine spacing equalling 2.5 times the rotor diameter to avoid wake effects.

Concentrated solar power

Typically, CSP is uneconomical on a small scale (<10-50 MW). A blanket allowance of 600 ha for 50-200 MW can be assumed for each heliostat field and collecting tower. Further land allowances for storage tanks (assume 100 MWh capacity tank as 8 m diameter and 3 m height) and turbines are trivial compared to the heliostat field footprint. For solar trough collectors, 1 km of trough piping per MW may be required. CSP systems require a large, flat, contiguous piece of land that has undergone confirmed sterilisation drilling.

Diesel or gas fuelled power

Reciprocating engines below 30 MW are, for mining operations, typically self-contained, fully enclosed in noise-attenuating enclosures and mounted on a rigid base (skid) and suitable for outdoor operation.[2] The land required for reciprocating engine generators can be approximated as 0.3 ha for every 10 MW of generation, while for open cycle gas turbines and combined cycle gas turbines the applicable ratios are 0.4 and 0.6 ha respectively. Additionally, fuel storage areas should be accounted for, and where a new gas pipeline is to be installed, logistical needs such as area for access must be considered accordingly.

2.2.4 Land Tenure and Access

Road inclines and bends should be examined for wind turbines to ensure that their blade lengths do not require greater turning circles than the existing layout can accommodate. The quality of the road material will generally influence the speed of trucking rather than the ability for road transportation to be used, but it should also be ensured that the road construction is adequate to sustain heavy tonnage. Large megavolt transformers, cranes and wind turbines are likely to be the most challenging with respect to power supply equipment. It is likely that general access for mining equipment will have resulted in access that would be suitable for transporting all other power generation equipment, including PV modules, reciprocating engines, combustion turbines and concentrated solar power infrastructure.

The construction of any new gas pipelines may impose additional access requirements such as rights of way. Land tenure may result in constraints and opportunities so the implications of locating a power station outside the mining lease should be investigated. For example, the DeGrussa PV installation, due to being a brownfield site, found that installing PV outside the mining lease had lowered compliance requirements, resulting in lower costs and faster delivery.

2.3 Climate Data for Effective Decision-Making

Where high-level desktop studies tend towards the pursuit of further studies, the type of data collection that may be required to assess wind and solar irradiance at a given site is as denoted in Table 2.2.

Table 2.2 Data collection methods

Technology	Estimate Class V-IV (refer Figure 1.4)	Estimate Class III-I (refer Figure 1.4)
PV	Satellite data via free services (e.g. NASA, Bureau of Meteorology) or synthetic data (e.g. Meteonorm) may provide sufficient accuracy.	• For PV <20 MW_{AC} single pyranometer to measure irradiance for one year, if >20 MW_{AC} two pyranometers; OR • Purchase one year and ten year data sets of high quality satellite solar insolation data (e.g. SolarGIS, 3TIER, METEONORM) The advantage of pyranometer over satellite data is that it can continue to be used during operation, increasing prediction accuracy through having a larger data set from site. Either may be viable in terms of financing, however this should be verified with the funder. Baseline site weather data is also required. IEC61724-1:2017 gives guidance on equipment, methods and terminology for monitoring and analysis of PV systems.
CSP		• Measure a minimum of one year direct normal rather than global horizontal irradiance using single pyrheliometer; OR • Purchase one year and ten year data sets of high quality satellite solar insolation data (e.g. SolarGIS, 3TIER, METEONORM) The advantage of pyrheliometer over satellite data is it can continue to be used during operation, increasing prediction accuracy through having a larger data set from site. Either may be viable in terms of financing, however this should be verified by the funder. Baseline site weather data is also required. Few standards for CSP are available, IECTS62862-1-2:2017 may provide guidance.
Wind	• Metmast(s) topped with wind sensors such as an anemometer and wind vane should be installed according to IEC 61400-12-1:2017 for at least six months to two years depending on wind speeds and directions at the site. Metmasts can be 60-100 m high pending location and desired data quality/resolution (typical meteorological stations are at maximum 30 m high, which is insufficient for adequate modelling given a hub height that may be two to four times higher). • If terrain is simple (as defined in IEC61400-12-1:2017), wind speeds at the metmast may be assumed equal to those at the turbine. Instead of using metmasts, a shorter mast and ground-based measurement device (SODAR or LIDAR) with accuracy certified in the standard may be used. Such devices must be calibrated against a tall mast but this can be undertaken offsite. • While IEC61400-12-1:2017 considers data collection upstream of turbines, IEC61400-12-2:2013 considers data collection at the nacelle. Due to blade influences, such data is more liable to error so a transfer function is applied for correction although uncertainty can remain high. • Drones can be used to map out land topography and features to improve the accuracy of wind modelling.	
Gas	Price forecasting	Pending on stage of project, contracts for supply should be secured.
Diesel	Price forecasting and short term contracts pending the stage of the project	

For the purposes of forecasting energy yields of renewable generation, the quality of local weather station data may be assessed as 'high quality' for stations less than 20 km away with simple terrain, and 'medium quality' for stations up to 50 km away with more complex terrain.

The cost of data collection can vary considerably depending on whether data is collected and interpreted in-house or externally. In terms of raw equipment costs (excluding freight, installation and maintenance), the following values are typical:

- pyranometers: ~$2-7K
- pyrheliometers: ~$20-50K
- metmasts (tower, anemometers, data loggers): ~$100-150K
- high quality satellite data (solar irradiance): ~$3-15K

Alternatively, these equipment can be leased with the option to include data analysis as part of the lease agreement.

Variability – Wind and Sun

In the context of hybrid power generation, the issue of variability and intermittency is often raised. These two terms are commonly, but incorrectly, used interchangeably. They are two distinct terms, which can be broadly defined as follows:

- Intermittency: The extent to which solar irradiance or wind starts and stops at uncontrollable intervals.
- Variability: The extent to which solar irradiance or wind exhibits changes in magnitude of its output.

The extent to which the variability and intermittency of solar irradiance or wind translates into variability and intermittency of generated output depends on a wide range of factors as described in Table 2.3.

Table 2.3 Variability and intermittency in different renewable generation sources

Nature of renewable source	Impact of variability and intermittency on renewable technology
Solar irradiance **Variability:** *Seasonal:* Solstice-equinox cycle leads to predictable seasonal changes in irradiance intensity. *Daily:* Cloud cover causes short term changes in irradiance intensity, typically a reduction but in certain circumstances, an increase due to sunlight being reflected by the clouds. Clear sky days provide highly predictable irradiance levels. **Intermittency:** *Daily:* Solar irradiance falls to zero every night.	**Variability impact on PV output:** PV generation responds linearly to seasonal solar irradiance levels. Highly variable PV output will occur where daily irradiance is highly variable. This variability is easily managed by existing generation where RE power fraction is low. Where RE power fraction is higher, additional mitigation and control measures are required. **Intermittency impact on PV output:** At night no PV contribution to generation is available.

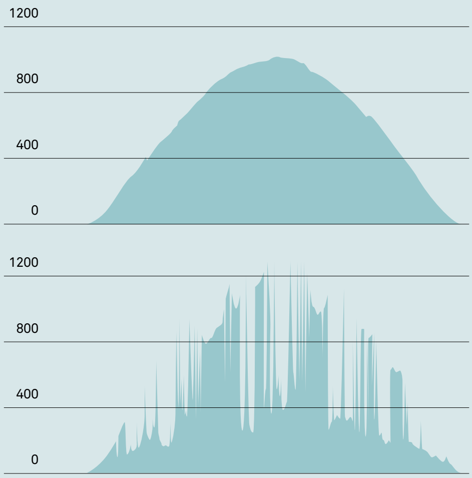
table cont'd overleaf

Table 2.3 Variability and intermittency in different renewable generation sources (cont'd)

Nature of renewable source	Impact of variability and intermittency on renewable technology

Solar irradiance (cont'd)

Fig 2.4 Demonstration of variability: Solar irradiance recorded by a pyranometer during a clear sky day (top) and cloudy day (bottom) (W/m^2)



Variability impact on CSP output:

CSP technologies have significant in-built thermal inertia and therefore daily irradiance variability has limited impact on CSP power generation. The exception to this is where the net irradiance is significantly below the average for the design storage, so CSP is unable to achieve its critical thermal levels for generation. Seasonal cycles affect the amount of energy available, up to 30 per cent between the best and worst months of the year.

Intermittency impact on CSP output:

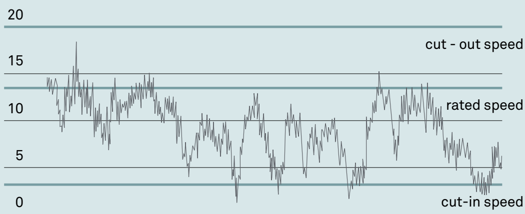
As CSP has a storage component of molten salt, intermittency in output is not experienced.

Wind

Variability:
Seasonal: Site specific. Historical data provide guidance.

Intermittency:
Daily: Site specific. Historical data provide guidance.

Fig 2.5 Demonstration of variability: Wind speeds during a 10-day period (m/s)



Variability impact on wind turbine output:

Wind turbines have built-in mechanical inertia that allows the turbine to continue operation through short term variability in wind speed (over seconds and minutes) without adversely impacting the stability and magnitude of power generation. However, variability in wind speed over longer periods will lead to variability of plant output.

Intermittency impact on wind turbine output:

Wind speeds outside the turbine cut-in/cut-out speeds will cause generation from the turbine to drop to zero.

2.4 Penetration and Contribution

Penetration is a descriptor ascribed to the ratio of renewable output to total output of hybrid power generation, with output encompassing definitions such as power or energy used. More recently, a distinction has been made wherein the word 'contribution' has been introduced to the industry vernacular to describe the energy ratio and 'penetration', the power ratio. Academia has recognised there is a need for clearer descriptors and thus is increasingly replacing penetration and contribution terminology with fractions:

- Renewable power fraction (RPF): The amount of renewable power delivered to the loads compared to the total amount of power required by the load as defined in Equation 2.2.
- Renewable energy fraction (REF): The portion of the total energy serviced by the renewable technology being discussed over a defined amount of time as defined in Equation 2.3.

Equation 2.2 Renewable power fraction

$$RPF = \frac{P_{REN}}{P_{tot}}$$

RPF	Renewable power fraction (kW_{AC}/kW_{AC})
P_{REN}	Renewable power delivered to load (kW_{AC})
P_{tot}	Total power delivered to load (kW_{AC})

Equation 2.3 Renewable energy fraction

$$REF_t = \frac{E_{REN,t}}{E_{tot,t}}$$

REF_t	Renewable energy fraction (kWh/kWh)
$E_{REN,t}$	Renewable energy consumed over period, t (kWh)
$E_{tot,t}$	Total energy consumed over period, t (kWh)

RPF and REF levels can be constrained by legacy infrastructure such as the minimum loading factors of the synchronous generators. Alternatively, hybrid power generation can be designed to a specified RPF to achieve a given economic case, resulting in for example designed curtailment of the renewable output. With respect to the former, design considerations include preventing cylinder glazing, increased blow-by, wet stacking through the assessment of integration risk due to age of infrastructure, manufacture, RPM and electrical and mechanical governor.

RPF and REF are site specific, requiring modelling to estimate the impact on the system. Note that impact on the system is not only the ratio but also the rate of change between the maximum and minimum ratios (fractions) experienced by the system and subsequent impact on satisfying the supply demand.

This handbook applies only to systems with a small RPF and REF, that is, those that are less likely to require enabling technologies and, in the case of brownfield sites, have limited need for control system change for integration. However, some of the projects referred to in this handbook for illustrative purposes are also examples of systems with enabling technologies.

3.0 Integration Considerations

3.1 Fundamentals

The selection of power sources and design of the hybrid power generation system must be compatible with all design criteria and operating philosophies of the mine, processing plant, tailings storage and material delivery methods as well as broader plant infrastructure, including incumbent power equipment and other hardware in the case of brownfield sites. Proper integration is critical as it determines whether the mine receives a reliable and secure power supply, economic benchmarks are met, and the total plant operates as an efficient whole. Integration also sets the tempo for future operations and maintenance, finding its importance not only at the implementation stage but throughout the Life of Mine. Knowing the nature of hybrid power generation and understanding the direct and indirect implications of different sources on power demand or supply is the crux of successful planning, implementation and operation.

The key technical integration areas to consider relate to the mine's demand requirements (refer to Chapter 1), the inherent nature of the generation technologies (Chapter 2), and the operating control philosophy applied (Chapter 3). Unfortunately, especially in the case of brownfield sites, commercial agreements (Chapter 4) can place restrictions on achieving optimal technological outcomes, and thus also need to be considered when designing hybrid power generation.

Over the past fifty years, there has been limited change to fundamental electrical power systems design principles as they are technology agnostic. Hybrid power generation, if designed with these principles at the forefront, has no greater risk of blackout or brownout than a standalone diesel generator or gas turbine – in fact the added diversity can lower the risk. Take, for example, the scenario of rapid demand fluctuations in reactive power due to a drag line operation in an underground mine: where a reciprocating engine may take minutes to respond, causing voltage flutter and frequency collapse, the ability of PV inverters to respond instantaneously to supply the reactive power needed, can decrease the risk of system fault. To facilitate application of these fundamental principles, this chapter provides a summary of issues to be considered, focussing on those with a unique perspective in the case of hybrid power generation.

3.2 Control Philosophy and Control System

The development of a control philosophy for hybrid power generation and the control system that implements it can be complex if a holistic approach to design is not taken to ensure stability and reliability. While a system with a low RPF can simplify integration, challenges may remain if the control philosophy is poorly designed, the design does not adequately consider risks associated with hybrid power generation design, the control system does not effectively implement the control philosophy, or it is not properly commissioned. Various elements compose the control philosophy and will vary depending on the plant architecture. In this respect the control philosophy of hybrid power generation has little distinction from that of a single-fuel power plant.

Manual elements of a control system are possible for hybrid power generation, but their use can make it more complex to achieve reliable output than with a fully automated system using SCADA or DCS and PLC. The two key nodes for control in hybrid power generation are the load (demand) and generation (supply) ends, with software and hardware at each end that facilitates their communication as well as the switching of equipment at these ends and intermediate to them.

To maximise the economic benefits of hybrid power generation, control systems can be optimised through bi-directional communication between the load and generation. The mine production schedule, processing schedule and other operations need to be clearly articulated within the control system to achieve this benefit. As an example, because the decision to switch loads on or off can have far-reaching and significant effects on the site, distinguishing the priorities of different loads is important; separate feeders for critical and non-critical loads are required at minimum.

If well designed and implemented, control systems can unlock flexibility from a brownfield system, often more economically than by changing the physical power system.

3.2.1 Load Management

Load management is premised on the ability to anticipate power supply fluctuations with a recognition of their timescales and relevant characteristics, anticipated demand such as scheduled needs and critical loads, and the ability for the load to respond in a timely manner. There are two primary demand modification strategies, namely load shedding and load shifting.

Load shedding is the automatic disconnection of loads or transmission/ distribution feeders to reduce the overall demand, typically in response to a fault or strain in generation. Also known as 'load dump', this practice can prevent a fault from cascading to the rest of the network or causing a blackout, and it requires considered definition and identification of critical and non-critical loads within the control system and the ability to isolate feeders and loads. The added diversity of hybrid power generation may reduce the need to implement load shedding.

A potential advantage of load management with regard to hybrid power generation is the application of load shifting. Load shifting is a technique in which the time of day at which electricity is consumed for a particular purpose is postponed (or brought forward) to coincide with a time better suited to the available generation. Load shifting is termed 'peak shaving' when the magnitude of the peak demand is reduced. In the case of a shifted load being large enough to constitute a change of the day's overall maximum demand time, the term 'peak shifting' may be used. When loads have been shifted to the most amenable time, the renewable source is optimally utilised – either as a natural result or, in the case of CSP, when stored energy is intentionally discharged for use.

An example of this load shifting technique is to schedule electricity-intensive activities at the time of day with high solar irradiance to capitalise on PV system output. Load shifting control can be done manually by equipment or load operators. An alternative method is the use of ripple-control, which uses a superimposed higher-frequency signal on to the standard 50 Hz power supply. When the signal is received by control devices connected to the controllable load, they switch off the load until the signal is disabled.

3.2.2 Unit Commitment

Unit commitment is the schedule or dispatch of generating units' operation levels and times within a power system, subject to equipment and operating constraints. The decision process undertaken by the control system involves selecting the units to be on or off, the power generation operating level for each unit, the fuel mixture economy when applicable, and the spinning reserve margins. Multiple approaches such as balanced load strategy and cascading topologies may be implemented (refer Section 2.1.2).

A unit commitment strategy identifies which generators will be load following, that is, which generators adjust their power output to satisfy moment-to-moment load fluctuations. This generator capability is used for frequency regulation, which is a fundamental function for a reliable power system. Frequency regulation is implemented using generator governors, as well as a control system that controls the output of the spinning reserves made available under unit commitment schedules. However it is not necessary for all generators in a system to contribute to regulation. The amount of regulating generation required depends on system conditions including anticipated load changes, ramp rates, and availability of other generators. Determining the amount of required regulating capacity is one function of unit commitment scheduling.

A fine-tuned control system can maximise the benefit of unit commitment strategies. For example, making changes closer to real time such as day-ahead generation scheduling makes it possible to take into consideration more recent, accurate forecasts of renewable resource availability and demand, which can in turn lower the cost of reserves.

3.2.3 Generation Management

The alternative to load management is generation management, which most simply can be applied through curtailment, reflective of load dumping, or more eloquently through load following. The use of spinning reserve and standby generators is another form of generation management, such as in the case of diesel fire pumps as contingency and back up.

Power curtailment is the process of reducing the power generated or transmitted onto a local grid by wind or PV for reasons such as enhancing network stability. Synchronous generators have a minimum loading limitation if they are to function efficiently, although they can also be taken offline completely. The ramp up/down rates of these generators are also lower than inverters, for example. This can lead to overproduction in a hybrid power generation system when PV or wind generation increasingly comes online. Since the 'must-run' generation takes precedence over renewable generation for meeting demand, renewable sources tend to be curtailed. This can undermine the benefit of introducing renewable generation, if intended to offset fossil fuel consumption, unless the load profile and relative generator sizing is appropriate, that is, the economics of the added renewables is justified by the savings achieved in practice. Power curtailment of variable generation can, however, be used to provide frequency and voltage control services to improve the quality of power supplied. Curtailment is often done by controllers situated directly at the generation end, for example, through the inverters of a PV system.

There is an option to approach the design of standby arrangements and back-up generation for hybrid power generation differently to single-source power generation, where the configuration and control system can use the synchronous generation sources as the standby arrangement.

Spinning reserve is the extra on-line generation capacity of reciprocating engines or combustion turbines created to cover contingency events such as the failure of a generator, sudden increase in generation demand due to a reduction in the variable energy source, or sudden unscheduled increase in demand. In the mining context, spinning reserve to support the start-up of large mining equipment (e.g. mills, draglines) as well as address intermittent loads (e.g. conveyor belts) must be considered. Synthetic or virtual spinning reserve such as additional molten storage in the context of CSP may be considered as an alternative to traditional spinning reserve, although virtual or synthetic lacks rotating inertia. In the case of hybrid power generation with PV or wind, a general rule is to size the spinning reserve at 70 per cent of the renewable generators' design AC power output for critical loading.

3.3 Geographical Dispersion of Generators

A smoothing effect (to limit high frequency and voltage flicker) can be achieved by geographical dispersion of wind turbines or PV arrays.

3.3.1 Wind Farms Smoothing

Aggregation of the power output of wind farms geographically dispersed across a region, that is, greater than 100 km apart, results in a smoothing effect on the network as the variation in output from individual wind farms is, in general, partially offset by nearby wind farms.

Similarly, widely spaced wind turbines in a single wind farm experience different winds due to fluctuating wind conditions. This difference results in varying power output from each wind turbine, and if control systems permit these fluctuations in output from each turbine, a smoothing effect (reduction in power fluctuation from the wind farm) is expected compared to if individual turbine output was curtailed to have the same output. For wind turbines experiencing the same mean wind speed and uncorrelated turbulence with the same statistical description, the mean power output of the wind farm and standard deviation of the resulting aggregated power are as per Equation 3.1.

Equation 3.1 Smoothing effect of wind turbine geographic dispersion[8]

$$P_N = NP_1 \quad \text{where} \quad \sigma_{P,N} = \frac{N\sigma_{P,1}}{\sqrt{N}}$$

$\sigma_{P,N}$	Mean standard deviation of wind farm power output
$\sigma_{P,1}$	Standard deviation of one wind turbine output
N	Number of wind turbines
P_1	Average power produced by one turbine
P_N	Power produced by wind farm

Thus, the relative increase in fluctuation of total power from the wind farm is less than the fluctuation of power from individual wind turbines, hence achieving power smoothing.

3.3.2 Photovoltaic Arrays Smoothing

Spatial distribution of PV arrays is a method of reducing variability in PV generation. By breaking up a single large PV plant into multiple smaller systems and dispersing them geographically across a relatively small area, clouds shadow the dispersed PV arrays at different intervals resulting in a lower PV generation variability than would otherwise be individually experienced.

This significant reduction in variability occurs with relatively small geographic dispersion of the PV arrays (i.e. arrays greater than 1 km apart). In effect, spatial distribution is tantamount to a temporal distribution, with reduction of variability influenced by cloud speed, cloud length (1-10 km) and the geographic dispersive arrangement of the arrays. The reduction in output variability may be quantified using Equation 3.2.

Equation 3.2 Smoothing effect of PV geographic dispersion[9]

$$VR = \frac{\sigma_{\Delta t}^{1}}{\sigma_{\Delta t}^{Fleet}}$$

VR	Variability reduction (%)
$\sigma_{\Delta t}^{1}$	Nominal variability of the irradiance at a single array location
$\sigma_{\Delta t}^{Fleet}$	Nominal variability of the irradiance for the fleet of arrays
	where $\sigma_{\Delta t}^{Fleet} = \frac{\sigma_{\Delta t}^{1}}{\sqrt{N}}$ (N = number of locations composing the fleet)

Similarly, large-scale PV systems (>3 MW_{DC}) intrinsically experience smoothing (low pass filter response). Due to the extensive footprint of the system, cloud-cover effects occur at different times across the system. Put simply, solar output variability is inversely proportional to PV system size.[10]

3.4 Flexibility

Flexibility can be defined as the ability to change the level of electricity output (or consumption) in response to an instruction or another signal. All forms of electricity production or consumption are flexible over certain timeframes.[11]

Effective hybrid power generation requires architecture and control systems designed to account for the differing extents of component flexibility. The power system must be able to compensate for, or impose, such constraints and other variations to establish a stable and flexible power system, with examples detailed in Table 3.1.

Although generally referred to as thermal generators in Table 3.1, there are inherent differences in the flexibility timescales or different technologies. These differences are often manufacturer-specific, but in some cases are inherent to the technology and affect their loading capacity or ramp rates at different operating conditions.

For example, OCGT has a faster ramp rate (~10 % rating/min) than CCGT (~5 % rating/min) to avoid any thermal fatigue on the steam turbine. Generally, CSP steam turbines behave similarly to CCGT and wind turbines are similar to OCGT, whereas reciprocating engines have a shorter start up time and higher ramp rates (~20 % rating/min). PV is however capable of an almost instantaneous ramp rate and start up time, thus restriction of output should be considered so as not to cause grid instability (frequency or voltage).

Table 3.1 Integration considerations for flexibility

Timescale	Integration consideration	Issues	Response or implementation measure
Seconds	Other generation sources in network must compensate for drastic changes in solar PV generation	• Cloud cover can cause sharp losses in generation supply. • Variation can cause frequency and voltage instability of the network.	✓ Use the capability of thermal generators to load follow while allowing sufficient reserve (Chapter 3.2). ✓ Use geographical dispersion of PV arrays to reduce the proportion of output variability (Chapter 3.3). ✓ Use weather monitoring devices to forecast PV generation.
	The dynamic power factor correction capability of PV inverters	• Losses in active power generation are possible. • Excess reactive power generation.	✓ Set limitations on inverter output using this capability.
	Fast frequency response of thermal generators (due to variable generation or demand spikes or loss)	• Inertial response of system is not controllable. • Automatic generation control (back-up) can take minutes to respond. • Declining frequency poses risk of cascading outages. • Governors in generators can over- or under-shoot in response to sudden changes in variable generation supply.	✓ Curtail output using PV inverters (Chapter 3.2). ✓ Undertake load shedding (Chapter 3.2). ✓ Use stricter governor settings in thermal generators. ✓ Use weather monitoring devices to inform generator unit commitment and dispatch decisions.
Minutes	Changes in weather conditions, such as wind speeds, causing change in generation from wind turbine	• System imbalance can occur due to variations in generation output.	✓ Use geographical dispersion of wind farms to provide grid smoothing (Chapter 3.3). ✓ Use the capability of thermal generators to do load following while allowing sufficient reserve (Chapter 3.2). ✓ Use weather monitoring devices and forecasting.
	Ramp rate of wind turbines, CSP and thermal generators	• Demand that is greater/ lesser than can be satisfied by generation due to ramp rate limitations, causes system instability (frequency instability).	✓ Balance active power generation (Section 6.1.2). ✓ Undertake load management (Chapter 3.2). ✓ Utilise spinning reserve as appropriate.

Table 3.1 Integration considerations for flexibility (cont'd)

Timescale	Integration consideration	Issues	Response or implementation measure
Minutes	Thermal generator start-up times	• There may be insufficient supply to cover the load, leading to system imbalance and unwanted load dump.	✓ Spinning reserve to cover contingency events. ✓ Undertake load management (Chapter 3.2).
Hours	PV output at night time reduces to zero	• Grid may be susceptible to fault due to loss of generation at night.	✓ Ensure appropriate protection settings and design (Section 6.1.1). ✓ Ensure adequate baseload generation with sufficient spinning reserve (including virtual or synthetic).
	Thermal generator minimum run-times	• Excess generation in system can cause over-frequency.	✓ Manage the unit commitment of thermal generators (Chapter 3.2). ✓ Run generator offline.
	Fault in network causing loss of feeder and drastic loss of load	• Demand may be less than minimum load factor for thermal generators while retaining grid forming capability.	✓ Unit commitment strategy to take into account RPF during peak PV generation period. ✓ Curtail renewable generation, if applicable. ✓ Ensure energised grid to synchronise (no dead bus livening ability from PV).
Months	Solar seasonality over the year impact on PV output	• PV generation will reduce or increase at specific parts of the year.	✓ Appropriately size PV system to suit seasonal variation of solar resource and demand. ✓ Undertake load management / load shifting (Chapter 3.2). ✓ Use historical irradiance data sets to predict seasonal variation.
	Seasonal variation of wind (speed and direction) impact on wind turbine(s) output	• Wind turbine(s) generation may reduce or increase during specific times of the year.	✓ Undertake load management / load shifting (Chapter 3.2). ✓ Manage the unit commitment (Chapter 3.2).
	Repairs and maintenance	• There may be insufficient supply while generation units are down.	✓ In the maintenance schedule, ensure sufficient supply to cover the committed load, for example, during off-peak times using other generation units to cover load. ✓ System design to consider smaller distributed systems that can be individually disconnected.

4.0 Commercial Structure Options

4.1 Commercial Arrangements

The economic viability of hybrid power generation can be limited by an individual mine's characteristics such as Life of Mine, source of project finance, legacy infrastructure or legacy contracts. These limitations may be overcome with appropriate commercial arrangements, such as differing commercial structures that allow for the cost of risk to be distributed, putting alternative hedging strategies in place, realising additional streams of financing, or shifting expenditure between CAPEX and OPEX.

Capitalising on this potential requires clarity with respect to commercial terms and comprehensive understanding of the technical and financial risks reflected in a financial model for a given commercial arrangement.

As a starting point, commercial models are outlined in Table 4.1 that could be appropriate to the Australian off-grid mine context. This should not be taken as an exhaustive list – other models such as energy conversion agreements (pseudo tolling agreement) and commodity swap agreements are used in other continents such as Africa.

Commercial agreements can place restrictions on achieving optimal technological outcomes, and so wherever possible agreements should aim to not restrict technical design, and allow for modification of hybrid power generation over time with the role and responsibilities of each stakeholder clearly defined.

Table 4.1 Commercial agreement models

Agreement type	Description	Features
Owner (or Subsidiary) Built and Operated	Owner constructed power plant that is operated by the owner upon commissioning. Construction and commissioning may be completed in-house or contracted depending on internal capabilities. For commercial liability purposes a subsidiary may be created to build and operate the power plant.	• Higher electrical CAPEX but lower electrical OPEX. • Exposed to higher ramp up period risk and yield risk. • Lowest lifetime costs, however exposed to the most risk of commercial arrangement options. • Operations can be more efficient as there are less parties involved with no competing motives. • Higher resource requirement, that is, resources redeployed from operations personnel to projects personnel. • Project financials may not meet the mine Net Present Value (NPV) or other financial requirements.
Build Operate Transfer (BOT); Build Own Operate (BOO); Build Own Operate Transfer (BOOT)	A third party constructs the power plant and operates the plant upon commissioning for an agreed period, such as 24 months, whereupon it is transferred to the mine for ownership and operation. Different models are possible with ownership by the contractor until transferral or with the owner throughout.	• Ramp up period risk mitigated (refer Section 5.1.1) however profit margin applied by operator increases marginal cost. • Higher electrical CAPEX but lower electrical OPEX. • Experienced contractor can implement an efficient and low cost solution (particularly for complex projects, can reduce implementation and integration risk) – removes risk associated with construction period, however problems may arise with the transferral period.
Lease Agreement	A third party constructs and owns the power plant and the infrastructure is leased by the mine to be operated by them. The lease agreement in some circumstances may include operational spares and maintenance. Redeployable power generation such as PV and diesel generators are more common, however this can apply to all forms of hybrid power generation, that is both permanent or temporary structures.	• Third parties have access to spares due to other operations within Australia. • Contracts may allow for shorter Life of Mine to be accommodated. • Redeployable lease modular and fast construction. • If owner operated – training may be required as there is potential for delays for manufacturer onsite troubleshooting.

Table 4.1 Commercial agreement models (cont'd)

Agreement type	Description	Features
Joint Venture	In the context of this handbook, the joint venture model is considered where parties (the mine being one of the parties) form a joint venture and then sell the power to the mine as an IPP with a PPA between the joint venture and mine.	• Electrical CAPEX partially deferred to OPEX. • Enable access to expertise of specialist companies and thus training/capacity building of mine staff for a given technology. • Diversifies shared risks across both parties.
Power Purchase Agreement (PPA)	Refers to a contract between two separate entities regarding the supply and purchase of electricity.	• Owner pays no CAPEX attributed to power generation but rather only an OPEX cost. • Lowest risk exposure to the mine however due to IPP profit margins highest overall lifetime costs. • If the IPP charges unit electrical costs based on life of power station rather than mine, then for a mine with a Life of Mine shorter than the power station asset life, a lower total Life of Mine electrical cost (CAPEX and OPEX) may be achieved – potentially a unique benefit of PPAs compared to other commercial arrangements. For mines whose OPEX is attributed in high proportion to power supply, a reduced cost could in theory impact extent of Ore Reserve. • IPP may have access to low cost finance; this may not be passed on to the mine however that financing may make a viable case for the IPP to take on the long-term risk and thus sell on to the mine. • IPP may be willing to accept lower Internal Rate of Return (IRR) than mine. • Termination payment if company does not see out the terms of the PPA. • Bank guarantees to underwrite CAPEX and obligations to pay. • Consumer should ensure PPA commercial terms do not impact technical integration and thus consumer benefits. As an example, an existing PPA with an IPP would be preferable when entering into an agreement with a third-party variable source generator than the mine entering into two separate contracts, to avoid conflicting commercial interests, which result in higher cost to the consumer (mine) through less efficient design.

Levelised Cost of Energy

The Levelised Cost of Energy (LCOE) is an indicator often used in the energy industry to compare the long-run marginal costs of different power generation technologies. Expressed in terms of cost per energy unit ($/kWh) it is not to be confused with electrical OPEX. The solar industry often uses Equation 4.2, whereas the Federal Government's Office of the Chief Economist and many in the broader energy industry use Equation 4.1. The two formulas represent similar concepts however inclusions may vary and the denominator is not amortised in both.

Equation 4.1 Levelised Cost of Energy

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

$LCOE$	Average lifetime levelised electricity generation cost
I_t	Investment expenditure in the year *t*
M_t	Operations and maintenance expenditure in the year *t*
F_t	Fuel expenditure in the year *t*
E_t	Electricity generation in the year *t*
r	Discount rate
n	Amortisation period

Equation 4.2 Levelised Cost of Energy – alternate

$$LCOE = \frac{NPV\left(Costs_{lifetime}\right)}{Yield_{lifetime}}$$

$NPV(Costs_{lifetime})$	Net Present Value, $NPV(\sum CAPEX + \sum OPEX)$ over asset life
$Yield_{lifetime}$	Energy generated over asset service life

The use of LCOE as a cost indicator can be highly misleading and a poor indicator of the real unit price of generation, as underlying assumptions in the formula – if unknown – may give rise to invalid interpretations and applications of the LCOE. Additionally, research indicates multiple alternative formulas are used to calculate LCOE, resulting in its potential to be misrepresentative. Key points to consider when appraising a cited LCOE value or assessing the LCOE of a project are:

- **Assumptions underlying 'lifetime'**
  LCOE is calculated based on the asset life rather than the Life of Mine. Where the asset life is longer than the Life of Mine, the LCOE will be lower than the Life of Mine marginal cost of electricity.

- **Influence of energy yield**
  By definition, LCOE is not a measure of power infrastructure and supply cost but a ratio of that cost to the energy generated. This means a high LCOE does not necessarily imply a high power infrastructure cost. It may in fact be due to the system's energy yield being poor, for example, due to low solar or wind potential, yet be a low cost system to install and/or maintain. Similarly, an increase in energy yield can reduce the LCOE.

- **Exposure to the vagaries of scope of included costs and Net Present Value**
  The applied discount rate may skew the LCOE value as can the choice to include or exclude various parameters in the scope of costs. Costs that are known to be sometimes excluded include sustaining capital, distribution and transmission, and other costs such as financial and environmental costs. Additional choices to apply escalation, deflation or tax or use weighted capital costs can influence the resultant LCOE.

- **Common conflation of general LCOE values with project-specific LCOE values**
  Project-specific considerations of hybrid power generation can render the standard LCOE benchmarks for PV, wind and CSP invalid, being blind to site conditions such as legacy infrastructure and site energy yield potential. This gap between theoretical and actual values is particularly pronounced where hybrid rather than single-source plants are concerned.

4.2 Financing and Incentives

Australian investment in grid-connected renewable power generation is well established. Typically, financiers seek projects that have certainty, creditworthiness and a profitable term with limited potential for stranded assets. For off-grid generation projects that have a Life of Mine less than 10 years, enlisting Australian mainstream investment for hybrid power generation may be challenging. However, owner operators with foreign investors may face less challenges.

Federally, the two major institutions driving innovation in Australia's energy mix are ARENA and the Clean Energy Finance Corporation (CEFC). ARENA provides funding, knowledge and networks to accelerate Australia's shift to an affordable and reliable renewable energy future. The CEFC is a clean energy financier, investing in renewable energy, energy efficiency, low emissions technologies and activities such as mineral extraction that contribute to renewable energy generation. The CEFC has also allocated $100 million annually to a clean energy innovation fund with a target rate of return of one per cent over the government bond rate.[12] Either ARENA or the CEFC may be an option to source additional funding for hybrid power generation.

Agencies such as National Energy Resources Australia, which is a national industry-led initiative supported by the Department of Industry, Innovation and Science, also run specific funding programs to facilitate the uptake of clean technology projects in the resource sectors, which are available to eligible proponents by expressions of interest or other application processes. At a state and territory level, government grants, subsidies and other incentives may also be available.

Weipa bauxite mine,
Queensland

First Solar, which constructed the Weipa bauxite mine's 1.2 MW_{AC} (1.7 MW_{DC}) PV plant in Queensland, received $3.5M funding from ARENA to install the 18,000 thin-film ground-mounted PV modules as part of a 15 year PPA with Rio Tinto. The hybrid power generation facility includes four medium speed diesel reciprocating engines. The PV plant reduces diesel use by 600,000 litres each year by generating 2,800 MWh annually.

Photo source: First Solar

Government Incentives

Emissions Reduction Fund

Introducing hybrid power generation to a brownfield site and thereby lowering greenhouse gas emissions may garner eligibility for a government financial incentive under the Emissions Reduction Fund (ERF). The ERF is an incentive scheme administered by the Clean Energy Regulator since 2015 under the *Carbon Credits (Carbon Farming Initiative) Act 2011* (Cth). Credits take the form of Australian Carbon Credit Units (ACCUs). Previously companies participated in government auctions each year to receive credits for initiatives that achieve significant greenhouse gas abatement. Projects may be registered independently or aggregated with other companies to on-sell project credits and achieve a more competitive proposal for the auctions. The continuation of the auctions is not guaranteed in future years.

As an alternative to auction participation, projects may be registered under the ERF to generate and trade ACCUs with other entities. The market for ACCUs enables companies who are mandated to purchase ACCUs under the Australian Government's safeguard mechanism rules.

For ERF project eligibility, hybrid power generation would need to demonstrate compliance with an eligible method, each method having its own specific rules of compliance for executing the projects. Further information is available on the ERF website: environment.gov.au/climate-change/emissions-reduction-fund/methods

Renewable Energy Certificates

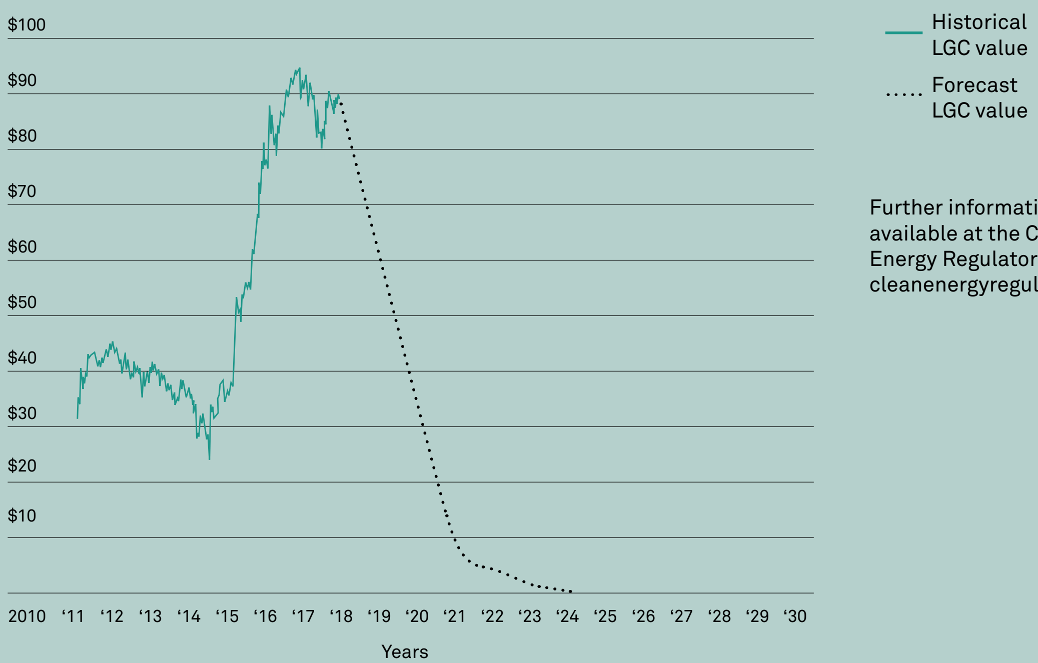
In 2000, the Australian Government set a renewable energy target for 2020 implemented under the *Renewable Energy (Electricity) Act 2000* (Cth). Current legislation provides financial incentives under two schemes valid to 2030, with eligibility criteria described in Table 4.2.

The currency of the two schemes is known collectively as Renewable Energy Certificates (RECs), which are administered by the Clean Energy Regulator. REC revenue is subject to both corporation tax and a processing fee per REC. Australia's current progress to fulfil its legislated renewable energy target indicates that cessation of REC value will occur earlier than the designated 2030 end of scheme. The monetary equivalent of RECs is market-based, with historical and forecast LGC market spot prices shown in Figure 4.1. STC values are $40 or less per STC as restricted by legislation and have historically ranged from $20-$40 per STC prior to 2017. All forward values for both STCs and LGCs are subject to the sustained demand for RECs which, influenced by current installation trends of renewable power relative to legislation, results in the predicted decline shown in Figure 4.1.

Table 4.2 Summary of Renewable Energy Certificates [1]

	Small-scale Technology Certificates (STC scheme)	Large-scale Generation Certificates (LGC scheme)
Renewable installed rated power	PV ⩽100 kW & <250 MWh per annum Wind ⩽10 kW & <25 MWh per annum	PV >100 kW & ⩾250 MWh per annum Wind >10 kW & ⩾25 MWh per annum
Basis	1 STC = 1 MWh predicted energy generated within the deeming period = installed power system capacity [kW] x deeming period [years] x regional rating [between 1 & 2] Note: the deeming period declines by one year per annum from 15 years in 2016.	1 LGC = 1 MWh actual energy generated = energy production measured by approved meters, calculated using a specified formula to discount losses
Timing	Claimed when the system is commissioned	Claimed retrospectively, either monthly or annually, and managed via the REC Registry online user portal

Fig 4.1 Historical and forecast LGC spot prices in AUD (adapted from [1,13])



Further information is available at the Clean Energy Regulator website: cleanenergyregulator.gov.au

5.0 Financial Modelling Considerations

5.1 Risk-Weighted Economic Comparisons

Perceptions can be limiting, and misconceptions can continue to prevail if not updated to reflect today's economic and technical realities. In a field that is rapidly moving, this handbook aims to present a snapshot of where economic realities are at and technical challenges lie. Clarity of interpretation and identification of actual risk are crucial, and typical examples of pitfalls due to a lack of these may be:

- taking generic LCOE of a technology as being representative of economic viability for a site, whereas parameters need to be clarified and inputs specific to the site for its representativeness to be sound
- assuming that hybrid power generation has greater risk than a single-source power supply of blackout or brownout, where in fact the added diversity can lower that risk.

Economic modelling of power generation options for a given site can be undertaken separately from the overall mine project financial model. While this approach can be informative for high level studies, alone it cannot be decisive on the implementation of hybrid power generation to supply a mine. A technology or value proposition may be assessed on its own to have an attractive economic viability but may still carry a risk that could render the project unbankable or inappropriate to proceed. Thus, any economic assessment must be tempered by due consideration of the associated risks, whether by being built into the economic model itself, or applied in the interpretation of modelling results and their sensitivities. Essentially, an attractive cost saving should be interpreted with caution as potentially a reduction in power supply costs can increase the exposure to risk. The key driver to be applied is that the loss of power supply can result in a loss of revenue – in such a situation the cost of power is typically insignificant compared to the value of lost revenue in the event of a loss of power supply loss. As such, a more reliable power supply with a higher CAPEX and OPEX can be the more attractive solution. Liquidated damages within a power supply contract that extend to revenue loss could be a potential remedy, however such contracts are unlikely to have uncapped liability, which ultimately results in loss.

Thus, the identification of risk and the sound assessment of its likelihood and consequence are critical steps to be taken. The assessment should include indirect (secondary, tertiary, etc.) outcomes of risk eventuating, that is, the flow-on effects such as business interruption costs and opportunity costs due to loss of production. These may be greater than the immediate outcomes, reinforcing the critical need for subsequent appropriate quantification of risk to allow risk-weighted economic modelling.

Some identified financial modelling inputs that require sensitivity analyses are discussed in this chapter. Scenario modelling should be incorporated as studies progress towards project implementation, preparing multiple scenarios based on various combinations of high risk parameters. Understanding the technical risks associated with each financial input and ensuring this is suitably modelled improves the quality of financial modelling results.

This dynamic environment opens up rich opportunities and pitfalls alike, emphasising the importance of sound business case modelling to ensure that a mine's investment in hybrid power generation is leveraged for greatest return.

5.1.1 Integration

Hybrid power generation at scale is emerging in off-grid mining applications and as such financial forecasts should include a ramp up period to account for integration such as operator knowledge development and unforeseen integration issues. Experiences to date suggest that implementation of technology solutions must be owned and led by site personnel.[14] In an attempt to reduce ramp up periods, this is considered especially critical in the case of brownfield sites.

The higher the RPF or the less mature the technology, the longer the ramp up period should extend. For example:

- Weipa bauxite mine, Queensland: The PV-diesel hybrid power generation facility (6.5 % RPF) experienced a six month ramp up period.
- DeGrussa copper-gold mine, Western Australia: The PV-diesel hybrid power generation plant with storage (35.8 % RPF) experienced an 18 month ramp up period.
- Ivanpah CSP power plant: The 392 MW USA grid-connected generator (solar trough type) experienced a four year integration ramp up period.[15]

A standard learning curve that can be considered applicable for OPEX and output estimates is as expressed in Equation 5.1.

<u>Equation 5.1 Learning curve</u>

$$y = ax^{I} \quad \text{or} \quad log\, y = log\, a + I\, log\, x$$

y Cumulative average hours per unit (h)

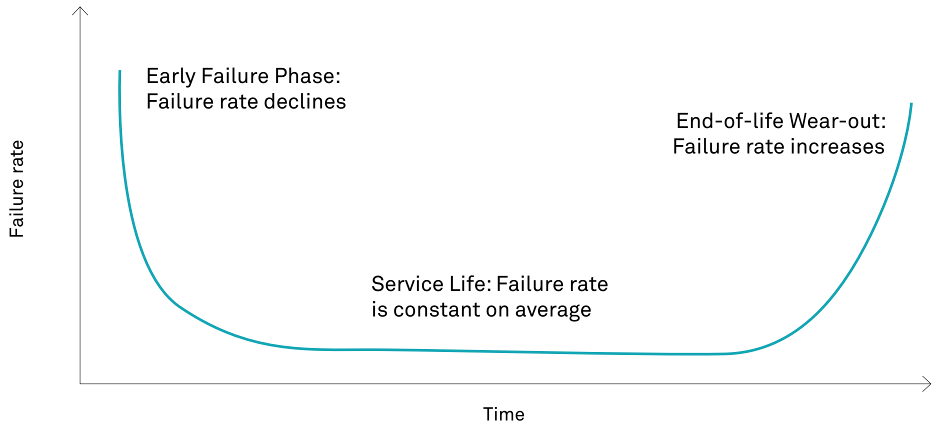
a Hours for the first unit (h)

x Cumulative number of units

I Index of learning equal to the log of the learning rate divided by log (2)

From the technical perspective, a bath tub curve as shown in Figure 5.1 is applicable to reliability forecasting of hybrid power generation installations.

Fig 5.1 Potential reliability curve of hybrid power generation components



5.1.2 Insurance

Costs of insurance are based on the perception of risk by underwriters. The cost of insuring PV has halved since 2010, a trend likely to continue across other hybrid power generation technologies. As well as insuring equipment, hybrid power generation performance can be insured, which is sometimes known as 'shortfall coverage'. Depending on the insurance policy, this may apply where the actual energy generated is less than forecast due to:

- solar radiation or wind speeds being lower than expected
- unintentional errors being made in the performance forecasts/models
- the power generation system being defective or otherwise underperforming
- specific parts breaking down or underperforming
- direct/indirect implications of any of the above, such as business interruption costs.

Insurance can rely on the warranty of components and in turn, the warranty of components can rely on structural (or electrical) design loads. This should be considered when calculating structural design loads such as service life and importance level to determine the return period or designing control philosophy. For example, a consideration for PV systems with trackers is that component warranties are valid only under defined conditions of service, which if not reflected in actual circumstances of use, may void the warranty.

5.2 Financial Model Sensitivities

Bias in a financial model may be introduced due to the industry of the model author. Typical examples with respect to financial parameters may include:

Discount Rate: 3-5 % (regardless of study phase) – renewable power industry
10-15 % (pending study phase) – mining industry

Contingency: 2-5 % (regardless of study phase) – renewable power industry
5-30 % (pending study phase) – mining industry

Amortisation Period: Hybrid asset life or PPA term – renewable power industry
Life of Mine or 10 years – mining industry

Similarly, an acceptable financial model result for a power station for an IPP could be an IRR of 5-10 per cent with a 10-20 year payback period, whereas a mining company modelling a mine that includes power infrastructure and supply may expect a much shorter payback period of two to seven years and greater IRR.

These differences can be advantages if applied within a commercial arrangement. The benefit to the mine is the significant de-risking of the power supply and the potential lower cost power of the IPP. Pending terms of the commercial arrangements, extension of Life of Mine may see further reduction in electrical OPEX as discussed in Section 5.2.1.

5.2.1 Contract Considerations

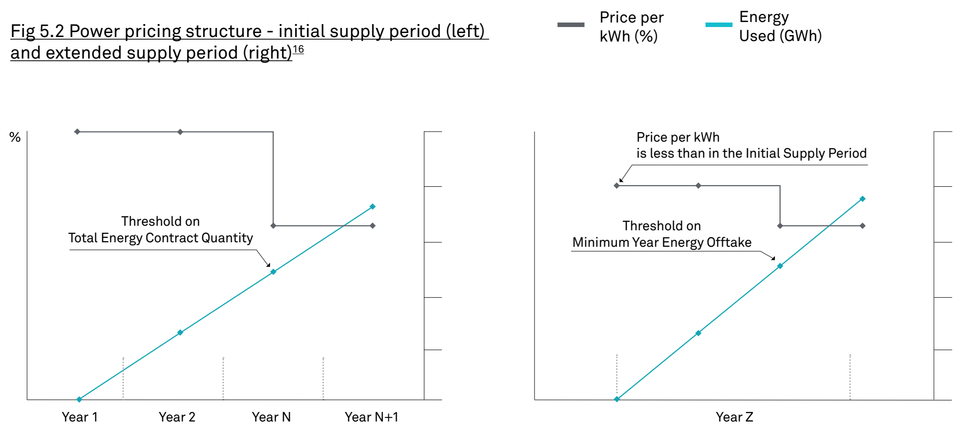
Contract terms and conditions can present both constraints and opportunities that should be reflected in the financial model. Such considerations include the implication of an early termination payment schedule (typical of a take or pay supply agreement), government incentives retained by the IPP, existing infrastructure or operating cost commitments, and the cost of contracted fuel supply.

It is also worth considering the relationship between loan tenure and amortisation profile. The expected frequency of received revenue (or calculated savings) from the system should be considered when defining a suitable amortisation profile, and the loan tenure must correspond accordingly. Conversely, the loan tenure may dictate the amortisation profile; in either case, the financial model should aim to optimise both these parameters.

Of significant potential opportunity in the case of hybrid power generation where an IPP is contracted, pending phase of project and contract negotiations, is that financial modelling sensitivities may include allowance for a variable electricity unit price that changes over the Life of Mine. During the initial supply period, the price could be sensitive to the total contract quantity offtake and change when the total offtake goes above this level. During the extended supply period, the price is sensitive to the minimum energy offtake and changes when the yearly energy uptake goes above this level. For example, the PPA between Sandfire Resources (miner) and Neoen (IPP) for the DeGrussa copper-gold mine is based on such a power pricing mechanism sensitive to the offtaker's energy consumption.

Within the initial supply period, a nominal energy price ($/kWh) applies to all energy consumed up to an agreed threshold called the total energy contract quantity (GWh). When this threshold is reached, which may be after any number of years within the initial supply period (denoted as N years in Figure 5.2), the price is modified to a lower rate ($/kWh), which continues for the remainder of the initial supply period. This consumption-sensitive model incentivises higher energy offtake and results in dual benefits to both parties.

Fig 5.2 Power pricing structure - initial supply period (left) and extended supply period (right)[16]



For the extended supply period, an energy price ($/kWh) that is lower than the nominal price in the initial supply period is offered. It applies to all energy consumed in any given year of the extended supply period up to an agreed threshold, the minimum year energy threshold (GWh). If this threshold is reached during that year, the price is modified to a lower rate ($/kWh), which continues for the remainder of that year. In the next year, the price reverts to the previous price until (and if) the minimum year energy threshold is reached in that year, in which case the rate is reduced as before, as illustrated in Figure 5.2. This applies to any given year of the extended supply period. As well as providing an incentive for higher energy offtake (similar to the initial supply period), it also encourages extension of the PPA contract by setting a nominal price lower than the initial PPA price.

5.3 Power System Modelling

5.3.1 Modelling Mining Operations and Unit Commitment

There are innumerable methods and parameters to consider when modelling hybrid power generation that in turn need to be accounted for in a financial model. Rather than provide guidance, which may be limiting as considerations are project specific, an example and brief discussion has been provided to give an idea of the type of modelling that may be applicable.

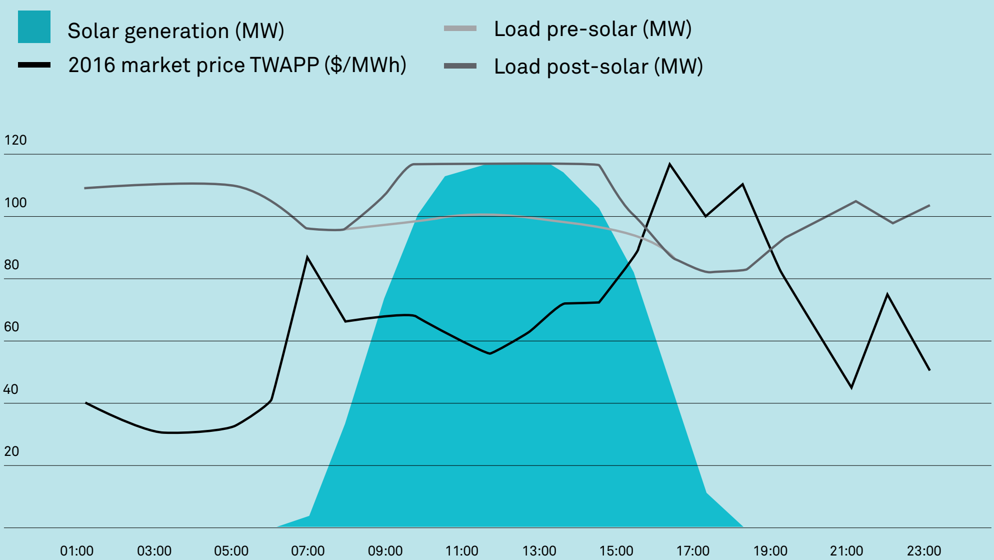
When completing an options study to assess the technical and economic viability of hybrid power generation, a simple but valuable exercise is to compare the hybrid system to a fossil fuel only system for supplying power to the proposed mine. Modelling the hybrid power generation operating strategy enables an optimal combination of generators to meet site demand and maximise financial returns. Based on the site's load profile and probable renewable sources, modelling determines the number and size of generators and their merit order, as well as predicting diesel or gas fuel savings, tonnes of greenhouse gas avoidance and financial model outputs (IRR, NPV).

Models must be premised on key principles in consideration of the mine – a common one is the necessity of diesel generation to supply a reference voltage and power, while another may be the retention of full diesel capacity to enable the supply of total load requirements as backup. Theoretical modelling must also be backed by a realistic ability to achieve the proposed operating strategies. The levels of flexibility and responsiveness required of the configurations mean that any chosen generators must be capable of being ramped up and down as needed. The control system, which includes power management and load control, will be the aspect with greatest custom design requirements in the majority of projects.

Scheduling demand to take advantage of peak generation

Sun Metals zinc refinery in Queensland owns and operates a 124 MW_{AC} (151 MW_{DC}) PV array installed in 2017. NEM electricity costs prior to installation were 48 % of total OPEX due to the 900,000 MWh consumed each year. The site's demand stems largely from the electrolysis process (100 MW). Installation of the PV array allows for the increase of production up to 5 %, and reduction of OPEX by 15 %. This is demonstrated for example in Figure 5.3 of how the PV generation (blue area) allows the plant to operate at greater capacity (increasing its load from the light grey line to the dark grey line) during peak PV hours (roughly 9am to 4pm) by timing electrolysis to coincide with PV generation output as much as possible. The new PV plant affords greater operational freedom to the refinery as well as the chance for overall higher throughput. While the primary objective of the PV array is to meet one third of the refinery's power needs, it can reduce grid pricing risks and grid reliance.

Fig 5.3 Daily load profile before/after the solar PV farm (adapted from[17])

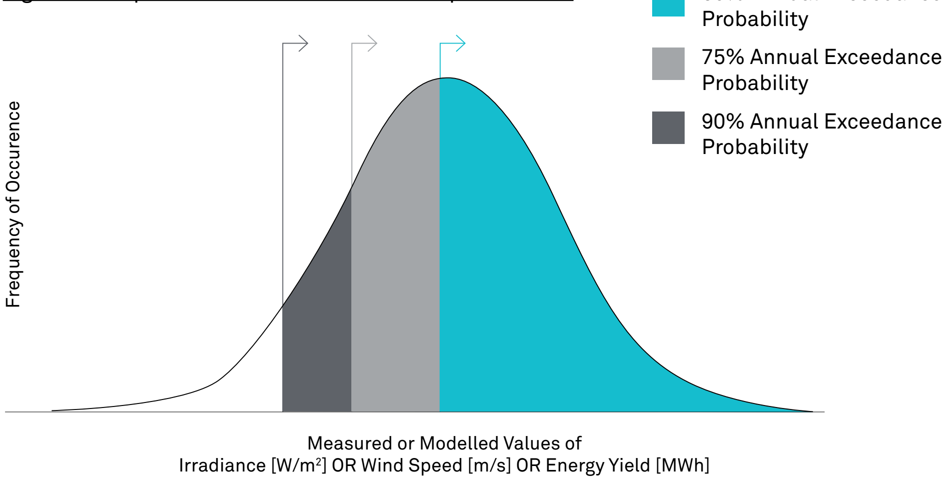


This principle can be applied to off-grid mining operations, the primary method being load shifting, where the process schedule and staff shifts are designed with the peak renewable generation times. This approach could also be applied to bore pumps, packaging plants, administrative offices or processing stockpiles.

5.3.2 Energy Yield Forecasting

To calculate the energy output for financial modelling, the solar or wind potential must be forecast. Renewable potential and the corresponding system energy yield are expressed as a curve of probabilities based on the selected risk benchmark, which is the exceedance probability: P50, P90 and so on. Solar and wind potential is typically modelled as a normal distribution as shown in Figure 5.4; however, increased accuracy is attained by plotting site-specific irradiation or wind data as a scatter plot. To reduce uncertainty, long-term datasets should be used as, for example, the average wind speed tends to vary by 6-8 per cent between years[18] and annual solar irradiation by 2-6 per cent.[18]

Fig 5.4 Conceptual illustration of exceedance probabilities



Solar or wind potential may be undervalued if an overly conservative exceedance probability is adopted. Typically, P90 is used by banks/creditors, with P95 used for interest calculations. On the other hand, P75 or P50 is typical for equity investors, while P50 may be used by engineers or analysts to determine technical feasibility. For unconstrained operation, variations in the exceedance probability values for renewable input resource have an almost linear flow-through to the exceedance probability yield values. For systems constrained by control philosophy, such as those subject to renewable generation curtailment, the link between the renewable source exceedance probability value (input) and system yield exceedance probability value (output) is less direct and is subject to more analysis/modelling – the relationship is not necessarily proportional due to system inefficiencies and non-linearity. Specifically, a curtailed system will behave very similar in a P50 or a P90 year.

Another metric to consider is the ratio between the P50/P90. For example, a high P50/P90 ratio (say 120 per cent) suggests that the P90 scenario in this dataset is significantly more conservative than P50, but a low ratio (say 105 per cent) suggests the use of P90 in the model rather than P50 carries little additional risk mitigation. These ratios in turn influence the debt service recovery ratio.

Additional factors that affect the overall energy yield and which should be considered in the financial model are:

- yield loss due to shading (affects PV and CSP systems)
- yield loss due to soiling (affects PV and CSP systems)
- deviation from standard test conditions
- inefficiencies from DC wiring losses
- inefficiencies from AC distribution and transmission losses
- curtailment due to control philosophy
- non-operation (or grid availability).

5.3.3 Fossil Fuel Price Forecasting

In the case of brownfield sites especially, estimation of offset fossil fuel costs is part of the business case. Volatility of fossil fuel price is a function of global oil prices and gas prices, and can be linked to both global oil prices and Asian gas benchmarks, especially Japanese pricing. Given the cost range displayed over the past decade (as shown in Figure 5.5) caution should be taken when interpreting forecast cost savings for fossil fuels. More certainty is given to gas offset costs compared to diesel where an existing contract is in place. However, the key metric to be agreed as part of cost basis prior to any diesel offset calculations is the diesel dollar per litre to be applied, as it could vary with interpretation from say $0.65 per litre for the mine company calculation whereas a renewable energy company may adopt $1 per litre. Offset calculations must also account for the fact that the fuel consumption of fossil fuel generators is not linear to engine/turbine operation per kWh as efficiency varies with loading. Hedging and fixed pricing are available to minimise the impact of future fuel price changes but these introduce additional costs and there is no consensus on future fuel price movements.

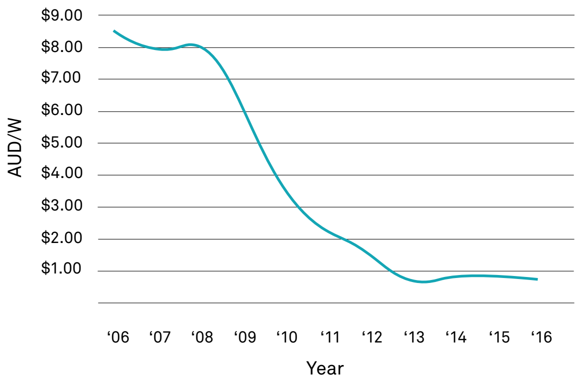
5.4 Cost Estimation

5.4.1 Capital Expenditure Estimation

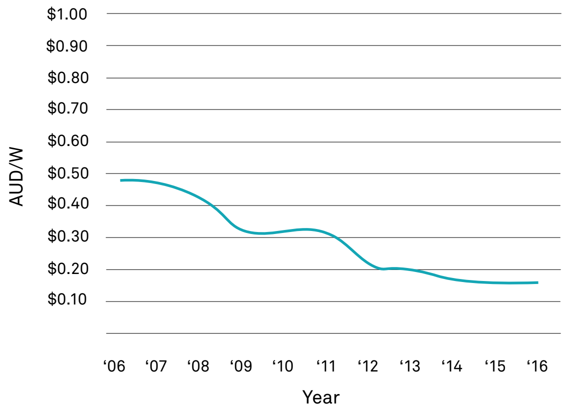
Hybrid power generation CAPEX estimation is heavily influenced by the development of technology, most notably the changing scales of production and the improvements on cost efficiencies in the renewables sector as demonstrated in Figure 5.5. This evolving environment presents difficulties for benchmarking costs reliably in a time- and context-agnostic manner, so for the purposes of project cost estimation, current quotations should always be sought, regardless of the estimate class.

Fig 5.5 Major component price fluctuations in recent decade (ex. GST and excise)

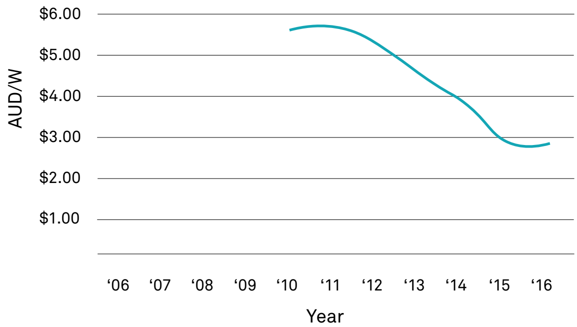
Solar PV modules cost trend[19]



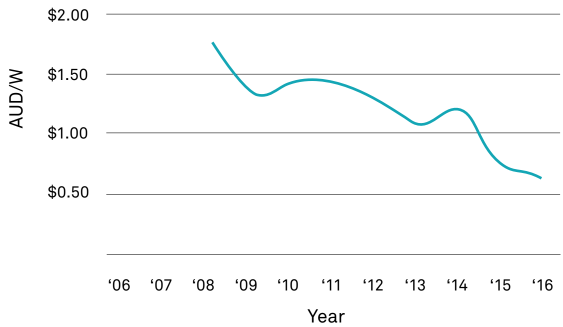
Solar PV inverters cost trend[20]



CSP hardware cost trend[20]



Wind turbines cost trend[21]



Diesel cost trend[22]

Natural gas cost trend (WA wholesale)[23]

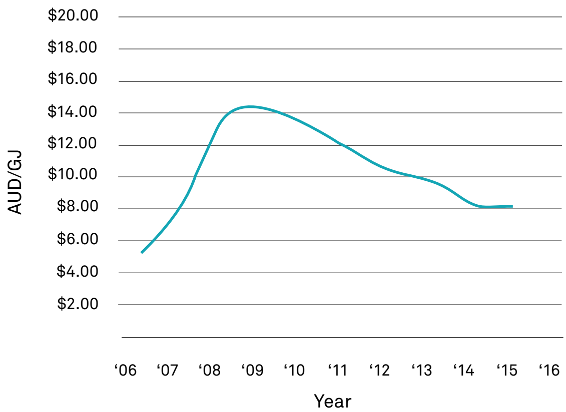


Table 5.1 Approximating CAPEX for class IV-V estimates

	Plants >1 MW ($/W)[24]	Spares	Scalability
Reciprocating engines	0.65 - 1.05	3-5 % initial CAPEX	Linear per generator else six-tenths rule
Gas turbines	0.85 - 1.45 (OCGT) 0.90 - 1.70 (CCGT)	3-5 % initial CAPEX	Six-tenths rule
Wind turbine	1.55 - 2.20	3-8 % initial CAPEX	Linear per turbine
Photovoltaics	1.45 - 2.50	0.5 % initial CAPEX	Linear
CSP	4.95 - 13.05	3-8 % initial CAPEX	Linear per tower, tank or turbine else six-tenths rule

It is predicted that the greatest cost reduction areas for PV will be efficiency improvements, balance of system costs due to market expansion, and inverter costs owing to the emergence of Asian manufacturers. For wind farms, the diversification of manufacturing locations are foreshadowed as significant sources of cost reduction. For CSP in power generating applications, ample scope for price reduction is forecast due to supply chain improvements, increased competition, financing costs as systems become more widely deployed, greater technical efficiencies such as different ways to build heliostats, and other lessons learnt. Diesel prices are at near decade lows, and there is uncertainty as to whether gas prices will continue to decline.

In the absence of quotations, the installed CAPEX costs shown in Table 5.1 can be applied for class IV or V estimates with caution. For sustaining capital costs refer to Table 5.2.

5.4.2 Operating Expenditure Estimation

An advantage of hybrid power generation can be lower OPEX as was the case for Diavik Diamond Mine in Canada that reduced its total OPEX by 25 per cent by transitioning to hybrid power generation.

Hybrid power generation OPEX includes both fixed costs ($/kW) such as those for insurance, labour, monitoring, on-costs and contracts, and variable costs ($/kWh) such as fuel consumption, overhauls and maintenance, lubricants and spares. For estimation at a high level (such as estimate classes IV-V) the general rules of thumb shown in Table 5.2 may be applied.

Table 5.2 Approximating OPEX for class IV-V estimates – valid 2017

	Fixed costs per annum	Variable costs per annum
Reciprocating engines	\$3/kW	\$0.33/kWh plus fuel cost
Gas turbines	\$4-\$17/kW	\$7-\$12/MWh plus fuel cost
Wind turbine	\$49-\$101/kW[20]	\$0.02-\$0.04/kWh[20]
Photovoltaics	1-2 % of initial CAPEX Assume self-cleaning where mean rainfall >150 mm/month and module tilt is >5°	
CSP	\$65-\$75/kW	\$0.03-\$0.04/kWh (parabolic trough) \$0.04-\$0.05/kWh (heliostat & tower)[20]

During warranty periods, OPEX is largely determined by the labour costs of ongoing system operation and maintenance; for example this could be taken as five days per month for PV arrays. The lengths of these warranty periods typically reflect the equipment's service life, which are indicatively listed in Table 5.3.

Table 5.3 Service life of hybrid power generation major components

Asset	Typical service life
Photovoltaic modules	25 years Risk of failure may be modelled as 2-10 % applied as a bathtub curve
Solar inverters	10 to 20 years
Wind turbine	20-25 years or 120,000 hours
CSP	30 years
Reciprocating engines	100,000-150,000 hours (heavy continuous use) to 20 years (low or standby use)
Combustion turbines	12-20 years or 100,000-160,000 hours

Photo source: (c) 2017 Rio Tinto

Diavik Diamond Mine,
Canada

The underground mine commenced operation in 2003 powered by diesel supplied to the mine via an ice road (50 million litres per annum), with electricity costs representing more than 25 per cent of the total OPEX. In 2012 an AUD $32M four-turbine wind plant (9.2 MW) was commissioned to provide 10 per cent of power demand, but also supplying up to 50 per cent of the mine's electricity requirements at times. Since installation, Diavik's annual OPEX has been reduced by 25 per cent (AUD $6M) per annum, and resulted in six per cent greenhouse gas emissions reduction.

6.0 Detailed Considerations for Final Studies and Design

There are many further areas to consider as the project development phase reaches detailed design. As a taster, some considerations that are lesser known as more specific to the hybrid power generation case are presented below.

6.1 Transmission And Distribution

6.1.1 Protection Philosophy

Electrical faults in a system cause voltage or flow of current in the system to be outside the standard design ratings. Table 6.1 presents characteristic faults by generation source that should inform system design.

Table 6.1 Power generation fault characteristics

Characteristics	Wind turbines	Photovoltaics	Concentrated solar power	Reciprocating engines	Gas turbines
Max. fault current contribution	1.1-2 x rated load current (inverter) or 5-8 x rated load current (direct)	1.1-2 x rated load current	5-8 x rated load current	5-8 x rated load current	5-8 x rated load current
	Inverters lack inductive characteristics which causes a faster decaying envelope for fault currents thus reducing the fault current contributions of PV and wind turbines				
Differential fault	Yes	Design dependent	Design dependent	Yes	Yes
Source unit fault	Yes	No	Yes	Yes	Yes
Considerations	Variable speed generation turbines independent regulation of active and reactive power	Rate of change of frequency	Power supply philosophy – time and magnitude of supply in to local grid	Generator synchronisation – operating philosophy	

Table 6.1 Power generation fault characteristics (cont'd)

Characteristics	Wind turbines	Photovoltaics	Concentrated solar power	Reciprocating engines	Gas turbines
Black start capability	Require grid (or battery backup) to synchronise	Requires energised grid to synchronise (no dead bus livening ability)	Yes	Yes	Yes
Energisation	Large transformer energising the entire network can lead to excess inrush current causing nuisance tripping or maloperation of the protection equipment and loss of supply				

AS/NZS2081:2011 lays out protection requirements specific to mining sites that assist in the planning, design and commissioning of the protection philosophy.

Fault-level studies and network contingency analyses are required to identify potential system fault characteristics, which inform protection levels and protection philosophies. This, in turn, determines the protection equipment to be installed, such as numerical protective relays. Although off-grid hybrid power generation at scale is in its infancy, standard software modelling packages can be utilised to determine system fault levels. The accuracy of fault level studies depends on the quality of inputs and thus the following should be determined:

- Rating of legacy infrastructure such as switchboards and cables
- Fault characteristics of different generation sources, for example:
  - A brownfield gas combustion turbine network retrofitted with wind turbines would require transmission equipment to be updated for increased fault levels.
  - A brownfield reciprocating engine with PV would need its protection system to detect when irradiance is low (such as at dusk) and reduce fault levels in response. Thus the protection system would need two fault protection settings, day time and night time.
- Smart current grading, smart time grading, and invoking different protection setting groups are crucial in determining these different fault settings within a protection system.

6.1.2 Quality of Supplied Power

Delivered power must be of high quality so as not to damage equipment or cause local grid instability. The impact of this instability and possible mitigation measures are listed in Table 6.2.

Table 6.2 Grid power quality

Instability	Impact	Mitigation measures
Frequency	• Motors require constant frequency to maintain constant speed for operation • Frequency of supply not matching that of the load could cause strain on the equipment • Damage to coils in transformers and motors	Balance active power generation and demand by: • Dumping loads (load management by load shedding) • Controlling output of variable speed wind turbine • Increasing or reducing generation from thermal generators (stay within restricted range of generator requirements) • Setting frequency operating bandwidth to 50 Hz ± 2.5 Hz • Implementing control hierarchy
Voltage	• Over-voltage can cause insulation damage • Under-voltage leads to overheating within equipment • High potential induced current could damage equipment	Control voltage by generating or absorbing reactive power using: • Voltage regulator of thermal generator • PV inverters
Power factor	• Speed of motors affected • Inefficient power generation leads to higher production costs	• PV inverters used to dynamically and instantaneously vary active or reactive power output to ensure power factor meets equipment specification, grid requirements and AS/NZS3000:2007 • Use spinning reserve of thermal generators as reactive capacitance
Harmonics	• Voltage distortion • Overheating in equipment • Strain on equipment reducing their lifespan	• Harmonics standards set limits of total harmonic distortion and individual harmonics • Power electronic converters used in variable speed wind turbines can shift harmonics to higher frequencies where they can be removed with small filters • PV inverters are capable of filtering harmonics

6.2 Commercial Terms

A typical contractual approach is to agree to a given unit price for the purchase of energy ($/kWh) and the availability of the power supply, whether in the mode of a warranty (if the asset is purchased) or a guarantee (if a PPA or leases are adopted). Being covered by a warranty or guarantee may decrease risk and increase cost.

Where greater risk cannot be accepted in order to reduce the cost, the following commercial terms can be considered in the context of a PPA. Responsibility for and methods of monitoring should be detailed in contractual clauses.

6.2.1 Wind Turbines – Noise Guarantee

Wind turbines produce airborne pressure waves, more commonly known as noise. Legislation prohibits the subjection of receptors to noise levels exceeding the Environmental Protection Agency (EPA) guidelines in the applicable state. Accordingly, a third-party specialist noise consultant should confirm noise limits are not exceeded during operation, and pre-installation noise studies should establish a baseline that can address potential litigation. Remote mines have the advantage of limited receptors and are already producing noise from operations such as haulage and comminution. As a general rule, turbines should be sited a minimum radius of 1-2 km from receptors to significantly reduce the risk of noise curtailment.

If noise limits are exceeded, then curtailment is required. If this exceedance and the ensuing curtailment occur within the defect liability period and is remedied, then liability is limited to the period of curtailment. However, if noise curtailment extends past the defect liability period, then liability applies for the life of the project. Liability is typically calculated for the difference between the projected output (without noise curtailment) and the actual output as described by Equation 6.1. Liability for noise liquidated damages is often capped as a percentage of the contract sum.

Equation 6.1 Noise liquidated damages

$$Liability = (NAEP - CAEP) \times PE \times EP \times \left\{\frac{1}{r}\left(1 - \frac{1}{(1+r)^n}\right)\right\}$$

$Liability$	Noise liquidated damages ($)
$NAEP$	Nominal energy production (kWh/a)
$CAEP$	Curtailed energy production (kWh/a)
PE	Project efficiency (%)
EP	Average electricity price ($/kWh) (pre-estimate)
n	Period (years)
r	Weighted Average Cost of Capital (%) (mutually agreed at time of calculation)

6.2.2 Wind Turbines – Power Curve Guarantee

It is customary for wind turbine manufacturers to guarantee energy outputs in the form of a power curve guarantee. At both the completion of reliability testing and the commencement of commercial operation, mines should ensure that onsite power curve verification tests are completed.

Power curves should be obtained by adjusting the measured wind speed data points to the average air density and then multiplying this distribution with the power output of the wind turbine in accordance with IEC 61400-12-1:2017. The resulting power curve is then calculated; this calculation is performed for both actual and guaranteed scenarios to verify real performance. The criterion for passing a power curve test is commonly defined as the energy production based on the measured power curve being greater than or equal to energy production based on the guaranteed power curve minus measurement uncertainty. However, wind farm owners may omit testing a wind turbine's power performance where terrain is very flat and power curve modelling reliable, unless they have cause to suspect an issue.

If the power curve guarantee is not satisfied in the testing period, liability for power curve liquidated damages often applies, as calculated in Equation 6.2 or a permutation thereof. Often there will be an agreed liability cap for performance liquidated damages as a percentage of the contract sum between the two parties involved.

Equation 6.2 Lifetime power curve liquidated damages

$$Liability = \left\{\left(1 - \frac{AAEP}{CEP \times GP}\right) \times EPE\right\} \times BEP \times LDF$$

$Liability$	Power curve liquidated damages ($)
$AAEP$	Average energy production of all turbines (MWh/a)
EPE	Energy production estimate, long-term, at P50 (MWh/a)
CEP	Calculated energy production (MWh)
GP	Guaranteed power level (%)
BEP	Agreed price of energy generated ($/MWh)
LDF	Lifetime damages factor applied to liquidated damages in one year, to represent the NPV of damages over the expected life

6.2.3 Photovoltaics – Performance Ratio

Performance ratio is a term often employed in performance guarantees to quantify system performance. It is calculated using Equation 6.3. The actual energy EN_{AC} and irradiance G_{POA} are measured over a user-specified interval *i*, typically both daily and annually, with some contracts including weekly or monthly performance reviews.

Equation 6.3 Performance ratio

$$PR = \frac{Electricity\ generated}{Electricity\ that\ could\ have\ been\ generated}$$

typically expressed in contracts as a variation of the IEC61724-1:2017 definition:

$$PR = \frac{EN_{AC}/P_{STC}}{G_{POA}/G_{STC}}$$

PR	Perfomance ratio (%)
EN_{AC}	Measured PV generated energy (kWh)
P_{STC}	Peak installed PV capacity (kW_p)
G_{POA}	Energy measured by a plane-of-array pyranometer per square metre (kWh/m^2)
G_{STC}	Global irradiance under standard test conditions 1,000 W_p/m^2

Various parameters influence the performance ratio value and so are typically incorporated within the contracted minimum performance ratio. These include system component degradation (typically 0.5-0.7 per cent per annum), transmission losses and inverter losses. Other influencing parameters such as weather, availability, apparent power and curtailment are optional and contractually agreed, as described in Table 6.3. Altitude may be a further consideration at elevations greater than 2,000 m, especially with reference to inverter manufacturer warranty conditions.

Subject to other contractual considerations, it may also be worthwhile for larger PV installations to maintain at least two site pyranometers, one mounted in line with the array to measure plane-of-array irradiance and another mounted elsewhere to measure global horizontal irradiance. Preferably, a third pyranometer would be installed as a plane-of-array data backup and all instruments should be mounted free from any shading or other interference; shaded pyranometers may lower the irradiance reference values, leading to an overstated performance ratio.

A possible compensation for the failure to meet performance ratio guarantees is liability equal to the potential unrealised savings, relative to the alternative use of gas or diesel.

Table 6.3 Potential modifiers of performance ratio

Consideration	Comments
Weather	The following international standard formula (Equation 6.4) may be applied to account for weather effects, giving rise to a 'weather-corrected' variant of Equation 6.3. Equation 6.4 Performance ratio corrected for weather [25] $$PR_{corr} = \frac{\sum_i EN_{AC\_i}}{\sum_i \left\{ P_{STC} \left(\frac{G_{POA\_i}}{G_{STC}} \right) \left(1 - \frac{\delta}{100} \left(T_{cell\_typ\_avg} - T_{cell\_i} \right) \right) \right\}}$$ $T_{cell\_typ\_avg}$ Annual average temperature used in model (°C) T_{cell_i} Average ambient temperature during time period *i* (°C) δ Temperature coefficient (module manufacturer specified) (%/°C)
Availability	Time periods excluded from the performance ratio calculation may include maintenance downtime and periods of downtime not inherent to the power plant.
Apparent power	Dynamic inverters can produce both reactive (kvar) and active (kW_{AC}) power to maintain a specified grid power factor. If the meter used to calculate performance ratio is installed on the AC side of the inverter, both quantities kvar and kW_{AC} should be measured. Contracts may specify that the conversion of measured kvar to kW_{AC} for calculating the performance ratio can only be completed for time intervals *i* when the power factor was above the specified grid power factor.
Curtailment	Curtailment events that arise from mutually agreed causes can be excluded from the performance ratio calculation. However, curtailment is not measurable but rather calculated under certain conditions, which can create contention if the contract is not explicit. For example, curtailment due to start or synchronisation of thermal generators, minimum load factors or spinning reserve should be clearly stated.

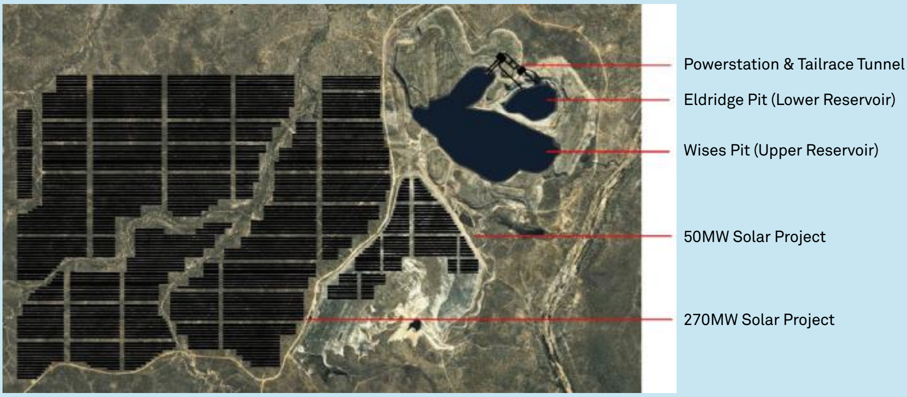
Kidston gold mine, Queensland

The Kidston gold mine ceased operations in 2001 and in 2017 Genex Power commenced construction of a 50 MW_{AC} (63 MW_{DC}) PV single-axis tracking system on the former mine's tailings storage facility (TSF). The power station received $8.9M for construction under ARENA's Large-Scale Solar (LSS) Program. Additionally, the project is supported by a 20-year Queensland Government revenue support deed through its Solar 150 Program.

The site benefits from being located in one of the highest solar irradiance areas in Australia (>24 MJ/m^2 per day). Locating the power station at a former mine has resulted in a lower power station CAPEX being achieved through the use of legacy mine infrastructure such as camp accommodation, water supply and infrastructure (Copperfield Dam), a substation, access roads and 185 km of power lines (132 kV) that connect the site to the grid. Licencing and permit requirements also benefited from approval processes previously undertaken for the mine.

The development of the second stage of the power station is being supported by ARENA in the form of up to $9M in funding. The second stage of the project comprises an additional PV system of up to 270 MW_{AC} expected to generate up to 783 GWh per annum and a 250 MW pumped hydropower system (PHES). The latter will utilise the former mine's 'Wises' (52 ha) and 'Eldridge' (54 ha) pits, taking advantage of their height difference to create a gross maximum water head of 230 m. The proposed PHES includes two reversible Francis pump-turbines with a total nameplate capacity of 250 MW. In PHES pumping mode, such as when wholesale prices are at their lowest (overnight or off-peak), water will be pumped from the lower to upper reservoirs, creating an energy storage system of up to approximately 2,000 MWh. During PHES generating mode, when wholesale prices are at their highest, water will be released and the system will export electricity to the grid with the ability to provide continuous generation over eight hours.

Photo source: Genex Power



Redeployable renewables, Australia

Acknowledging that their ease, convenience and portability make reciprocating engines popular on off-grid mines, a number of companies have developed a similar approach for PV and wind systems. Modular, scalable systems enable renewable energy to be integrated at mines with greater efficiency and familiarity. For example, 1 MW_{DC} PV module arrays are prefabricated offsite, delivered in 20 foot containers and deployed at a mine.

The scalability of the product addresses risk by allowing low-penetration integration of PV or wind energy to be followed with scaling to higher capacities if suited to the mine's operations. Reducing onsite labour requirements and invoking rental options if appropriate can make for a commercially viable approach to integration. While securing warranties on relocated modules or other equipment may present a risk, various options to allow the redeployment of PV or wind infrastructure several times within the asset life and/or combining the manufacturer and vendor warranties may be available.

Dedicated redeployable players are emerging in Australia such as SunSHIFT, 5B, ECLIPS and Onetide while Redavia has installed such systems overseas.

Photo source: SunSHIFT

Newman power station, Western Australia

The 178 MW gas-fired power station, built in 1996 and owned by Alinta Energy, is located 1,200 km north of Perth and provides energy to the Roy Hill Mine. In 2017 a 30 MW lithium-ion battery storage facility was installed to improve the security and quality of supply through network support functions and additional spinning reserve.

Photo source: Alinta Energy

Coober Pedy power station, South Australia

Energy Developments Ltd's (EDL) Coober Pedy power station was hybridised in 2017 and now consists of two 2.05 MW turbines, 1 MW_{AC} PV and 3.9 MW diesel (eight reciprocating engines) as well as enabling technologies such as a 1 MW / 495 kWh lithium ion smoothing battery and dynamic resistors. It is an example of hybrid power generation using multiple generation sources and enabling technologies to achieve an REF of 70 per cent over the duration of the 20 year PPA. Less than three months after commissioning, the power station achieved a 35 hour period where power was generated solely by renewables with no need for diesel generation. From 1 July 2017 to 31 December 2017 the plant delivered reliable electricity while saving one million litres of diesel by running without diesel generation for over 1,300 hours.

Photo source: Les Pullen Photography for Senvion Australia

8.0 Glossary

$	Refers to Australian Dollars (AUD) in all cases
AC	Alternating Current
ARENA	Australian Renewable Energy Agency
AS/NZS2081:2011	AS/NZS 2081 Electrical protection devices for mines and quarries
AS/NZS3000:2007	AS/NZS 3000 Electrical installations (Wiring Rules)
AUD	Australian Dollars
Balance of System	The solar industry equivalent of balance of plant encompassing all supporting and auxiliary components other than the PV modules (delineated at the inverters and frame supports) that are required to make the power plant operate such as the wiring, mounting structure, inverters and substation.
Balance of Plant	The wind industry equivalent of balance of system, encompassing all supporting and auxiliary components other than the wind turbine and tower (delineated at the holding down bolts and junction boxes at the base of the turbine) that are required to make the power plant operate such as the tower foundations, cabling and substation.
BOO	Build Own Operate
BOOT	Build Own Operate Transfer
Brownfield	Development undertaken at or near the site of an operating mine that takes advantage of established infrastructure and is often intended to extend the current Life of Mine.
Bureau of Meteorology	Australia’s national weather, climate and water agency.
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine

Clean Energy Regulator (CER)	Government body responsible for accelerating greenhouse gas abatement for Australia through the administration of the National Greenhouse and Energy Reporting Scheme.
Commodity swap agreement	Commercial arrangement in which two parties exchange a cash flow, the value of which is partially tied to the market price of a particular commodity.
Concentrated Solar Power (CSP)	A technology that uses mirrors to concentrate sunlight and store energy as heat, typically in a molten salt solution, to generate steam and drive a turbine to produce electricity. Configurations include a central collecting tower surrounded by a field of reflective heliostats or a trough type which comprises linear rows of reflectors and tube collectors. Heat is a potential product of such systems but this handbook deals solely with the power generation application of CSP.
Continuous miner	A machine designed to scrape ore from a seam using a rotating steel drum with tungsten carbide teeth, feeding a conveyor belt that carries the ore away continuously. The predominant form of underground mining for coal, gypsum, potash and salt mining, it may be used for any underground mine. These electrically powered machines have high capacity motors and require power for their traction, pump, control and dust suppression systems. These machines are increasingly driverless and remotely controlled.
DC	Direct Current
Dispatchability	The ability of a power system or generation source to meet electricity demand upon instruction. A dispatchable source needs to both be available at the time of requirement and be able to switch on/off or ramp up/down its output to meet the demand. Dispatchability implies the ability to respond quickly (seconds to minutes) although in some cases, a longer time frame (minutes to hours) may be permitted if adequate to meet the demand. A dispatchable source may be invoked uniquely or as part of a broader unit commitment strategy.
Enabling technologies	Any technology that, through its characteristics allows/enables higher levels of penetration than if it were not integrated. Examples include synchronous condenser, low load diesel generators, cloud prediction cameras, battery storage, pumped hydro storage and flywheels.

Energy conversion agreement	Commercial arrangement in which a raw commodity is traded for power, for example excess gas from a process plant is converted by an IPP to power.
Estimate class	Refers to the five classes defined by AACE International, namely I-V, that reflect project maturity level, estimate end usage, methodology and expected accuracy range as shown in Figure 1.4.
ERF	Emissions Reduction Fund
Greenfield	Development undertaken at a site on which there is no incumbent operating mine and power generating infrastructure.
Hybrid power generation	System for generating power that uses the combination of a fossil fuel source complemented by a renewable source. In this handbook, renewable technologies include PV, wind turbines and concentrated solar power and fossil fuels include diesel and gas.
IEC	International Electrotechnical Commission
IEC61400-12-1:2017	IEC 61400 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines
IEC61400-12-2:2013	IEC 61400-12-2 Wind turbines - Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry
IEC61724-1:2017	IEC 61724 Photovoltaic system performance - Part 1: Monitoring
IECTS62862-1-2:2017	IEC TS 62862 Solar thermal electric plants - Part 1-2: General - Creation of annual solar radiation data set for solar thermal electric (STE) plant simulation
In situ mining	A method characterised by vertical injection and recovery wells drilled alternately to the depth of the mineral deposit. Two horizontal branches are drilled at the bottom of each well, and barren leach solution is pumped under pressure into the injection wells to leach the minerals in the stratum. The pregnant leach solution is then pumped out through the recovery wells.

IPP	Independent Power Producer
IRR	Internal Rate of Return
LCOE	Levelised Cost of Energy – refer to Chapter 4
LGC	Large-scale Generation Certificate – refer to Chapter 4.2
Life of Mine	Time over which an operation plans to extract Ore Reserves
Mineral resource	*The term 'Mineral Resource' covers mineralisation, including dumps and tailings, which has been identified and estimated through exploration and sampling and within which ore reserves may be defined by the consideration and application of the Modifying Factors.*[26]
Minimum load factor	Minimum allowable load on a generator as a percentage of its rated capacity. It is usually set by the generator manufacturer. (Further discussion with respect to impact on PV-diesel hybrid power generation is provided in the Solar Diesel Mini Grid Handbook.[10])
National Greenhouse and Energy Reporting Scheme	National framework defined in the *National Greenhouse and Energy Reporting Act 2007* that requires and specifies the terms of company disclosure on greenhouse gas emissions, energy consumption, energy production and related parameters.
NEM	National Energy Market, the regulated Australian energy market covering five state-based networks and six cross-border interconnectors across New South Wales, Queensland, South Australia, Victoria and Australian Capital Territory. It is regulated by the Australian Energy Regulator.
NPV	Net Present Value
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine

Off-grid	Off-grid indicates a context under which electricity is generated, distributed and consumed without being connected to or constrained by the regulations of a primary power network in Australia such as the NEM or SWIS, or other regional utility networks such as Power Water Corporation (PWC), North West Interconnected System (NWIS), etc. In the case of off-grid mines, the mine forms majority of the load on the local power network.
Open-cut mining	Open-cut mining involves blasting and removing surface layers of soil and rock to reach a deposit. When the mineral seam becomes exposed, it is drilled, fractured and ore reserve recovered.
OPEX	Operating Expenditure
Ore reserve	*Ore Reserves are those portions of mineral resources that, after the application of all modifying factors, result in an estimated tonnage and grade which, in the opinion of the competent person making the estimates, can be the basis of a technically and economically viable project, after taking account of material relevant Modifying Factors.*[26]
Overburden	Any material, loose or consolidated, lying over an Ore Reserve. Overburden is relevant as it represents the material to be removed to access the Ore Reserve.
PLC	Programmable Logic Controllers are control units designed for industrial process applications such as mineral processing. They are typically characterised by their robust unit construction, ease of programming, ease of use for troubleshooting, modularity, scalability, general purpose use, and tens to thousands of inputs/outputs that enable compatibility with other PLC or SCADA units or systems.
PPA	Power Purchase Agreement

Pre-feasibility study	*A preliminary feasibility study, which is a comprehensive study of a range of options for the technical and economic viability of a mineral project that has advanced to a stage where a preferred mining method, in the case of underground mining, or the pit configuration, in the case of an open pit, is established and an effective method of mineral processing is determined. It includes a financial analysis based on reasonable assumptions on the Modifying Factors and the evaluation of any other relevant factors which are sufficient for a competent person, acting reasonably, to determine if all or part of the mineral resources may be converted to an Ore Reserve at the time of reporting. A pre-feasibility study is at a lower confidence level than a feasibility study.*[26]
(Mineral) Processing	*Physical and/or chemical separation of constituents of interest from a larger mass of material. Methods employed to prepare a final marketable product from material as mined. Examples include screening, flotation, magnetic separation, leaching, washing, roasting, etc. Processing is generally regarded as broader than metallurgy and may apply to non-metallic materials where the term metallurgy would be inappropriate.*[26]
PV	Photovoltaic(s)
Ramp rate	The rate of change in power that a generator can experience, typically expressed in MW/min or % (of rated capacity)/min.
REF	Renewable energy fraction, also often termed ‘contribution’ – refer to Chapter 2.4
RPF	Renewable power fraction, also often termed ‘penetration’ – refer to Chapter 2.4
SCADA	Supervisory Control and Data Acquisition
SI	International System of Units (used throughout this handbook)
Six-tenths rule[27]	A method of cost estimation based on known costs of a comparable project.
STC	Small-scale Technology Certificate

SWIS	South West Interconnected System is one of the primary regulated electricity networks in Western Australia. It is regulated by the Australian Energy Regulator.
'Take or pay' contract	*A gas supply take-or-pay contract is a supply agreement between a customer and a supplier in which the pricing terms are set for a specified minimum quantity of gas and conditions with varying degrees of complexity (e.g. simple fixed pricing, stepped pricing or variable pricing). For payments made in relation to volumes not taken (i.e. where the customer does not take the minimum quantities of gas specified) the terms may vary. For example, some take-or-pay arrangements may include a clause that allows the customer to 'make-up' the volumes not taken at a later date. The ability to make-up the unused volumes means that consideration has been received in advance by the producer for product that has not yet been delivered to the customer. Alternatively, the arrangement may contain a 'use it or lose it' clause, where the customer cannot make-up the unused volumes in the future.*[28]
Underground mining	Underground mining methods are divided into selective mining methods (room and pillar, retreat, stoping, cut and fill) and bulk mining methods (block caving). Primarily, mining is completed by diesel powered equipment, an exception being ventilation with fan sizes varying pending mine design and philosophy, with an individual fan being anywhere up to 10 MW in size.
Waste rock	Waste rock is material that contains minerals in concentrations considered too low to be extracted at a profit.

9.0 References

1. Clean Energy Regulator (CER). [Online] May 2015. cleanenergyregulator.gov.au.
2. AusIMM. Cost Estimation Handbook. s.l. : The Australasian Institute of Mining and Metallurgy, 2012.
3. Coalition for Energy Efficient Comminution. Smart Facts and Smart Focus - Comminution. CEEC The Future. [Online] 2012. ceecthefuture.org/why-smart-companies-are-focusing-on-comminution.
4. Ballantyne, G R and Powell, M S. Benchmarking comminution energy consumption for the processing of copper and gold ores. Minerals Engineering. 2014.
5. Bozic, Zoran. Mining Power Systems - characteristics and issues. Perth : MEMMES Western Power, Engineers Australia, 2012.
6. Australian Bureau of Meteorology. Australian Gridded Solar Climatology Data Services. [Web Map Service (WMS)] s.l. : Australian Renewable Energy Mapping Infrastructure (AREMI).
7. Garrad Hassan Pacific Pty Ltd. Average Wind Speed at 150 metres. [Web Map Service (WMS)] s.l. : Australian Renewable Energy Mapping Infrastructure (AREMI), 2015.
8. Manwell, J.F., McGowan, J.G., Rogers, A.L. Wind Energy Explained: Theory, Design and Application.
9. International Energy Agency. Characterisation of the spatio-temporal variations and ramp rates of solar radiation and PV. 2015.
10. PWC. Solar/Diesel Mini Grid Handbook. 2013.
11. Wärtsilä. Flexible Energy for Efficient and Cost Effective Integration of Renewables in Power Systems. 2013.
12. Clean Energy Finance Corporation (CEFC). Enabling Legislation: CEFC Act and Associated Key Governance Events. CEFC. [Online] 2017. annualreport2016.cleanenergyfinancecorp.com.au/governance/law-and-policy/enabling-legislation/.
13. Jacobs. Retail Electricity Price History and Projected Trends. 2017.
14. Kirke, Anthony. Fortescue Metals Group. s.l. : IMARC, 2016.
15. BrightSource Energy. Ivanpah Plant Gets More Time to Generate Required Power. BrightSource. [Online] March 2016. brightsourceenergy.com/ivanpah-plant-gets-more-time-to-generate-required-power#.WS-Df02wdzk.
16. Neoen Australia. DeGrussa Solar Hybrid Project Lessons Learnt - ARENA Knowledge Sharing Workshop. 2017.
17. Sun Metals Corporation. Sun Metals Solar Project: Stabilising Electricity Costs with Large-scale Solar. 2017.

18. Bollinger, Mark. Using Probability of Exceedance to Compare the Resource Risk of Renewable and Gas-Fired Generation (presentation). s.l. : Lawrence Berkeley National Laboratory, 2017.

19. Australian PV Institute (APVI). National Survey Report of PV Power Applications in Australia 2016. s.l. : International Energy Agency, July 2017.

20. International Renewable Energy Agency (IRENA). The Power to Change: Solar and Wind Cost Reduction Potential to 2025. s.l. : IRENA, 2016.

21. Wiser, Ryan and Bolinger, Mark. 2015 Wind Technologies Market Report. s.l.: Berkeley Lab, 2016. LBNL-1005951.

22. Australian Institute of Petroleum (AIP). Terminal Gate Prices (Wholesale). Australian Institute of Petroleum. [Online] AIP, 2017. aip.com.au/pricing/tgp.htm.

23. Oakley Greenwood. Gas Price Trends Review. s.l. : Commonwealth of Australia, 2016.

24. Lazard. Lazard's Levelised Cost of Energy Analysis, Version 11.0. 2017.

25. Direauf, T., et al. Weather-Corrected Performance Ratio. s.l. : National Renewable Energy Laboratory, 2013.

26. Joint Ore Reserves Committee. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves ("JORC Code") Appendix 5A. 2012.

27. Mular, A. The Estimation of Preliminary Capital Costs. Mineral Processing Plant Design. 1978.

28. Ernst and Young. The new revenue recognition standard - mining and metals. s.l. : EY, 2015.

Australian Government
Australian Renewable Energy Agency

ARENA

Prepared by Ekistica for the Australian Renewable Energy Agency

Ekistica