ENG70 Engineering Thesis Honours:
Cost-effective solution for electric micro-grid in Rottnest Island

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Abstract

Microgrids are a relatively recent technology, but the concept has been around for a long time. Since the first power system built in 1881, power systems have experienced substantial changes leading to the current networks where all the electrical energy is produced in large plants that are heavily dependent on fossil fuels, hydro and sometimes nuclear power (Ernst 2014). Micro grids have always been in existence but the technology to implement them on a large scale has limited micro grids from flourishing.

Rottnest Island is a notable example of a place currently implementing the use of a hybrid micro-grid (HMG) on a large scale. Up until recently, the island was solely dependent on diesel generators for electricity, in 2004 a 600kW wind turbine was added to supplement the electricity energy produced by generators and offset some diesel fuel consumption. Due to the high costs of shipping diesel into the island, The Rottnest Island Authority (RIA) decided to upgrade the island’s electrical network by incorporating a 600-kW photovoltaic system into the network and upgrading the existing water treatment plant as the RIA had recorded increasing levels of salt levels in the island’s underground water.

This research evaluates multiple aspects of running the upgraded hybrid solar-wind-diesel micro-grid and how the levelised cost of electrical energy production can be reduced by using Homer software to analyse the island’s electrical load profile and using the data to assess every possible system combination. The current setup of the network is quite inefficient as there is excess power being produced which is then being sent to a dump load. The results have been conclusive in terms of finding better combinations that will not only increase the reliability of the HMG but also reduce the overall LCOE. Storage capabilities in the network would be
advantageous not only in reducing the LCOE but also producing a high quality of power while also increasing the overall stability of the network.

Further simulations were conducted to include a theoretical load into the existing system. This was viewed as a theoretical thermal load that simulates the idea of hot water storage for the island. The thermal load was designed in a way that it would consume any excess energy being generated in the system to heat up water for later usage.

The conclusion has been that while the current HMG setup is functional and environmentally friendly, the LOCE of the overall network is high and impractical. For the current design of the microgrid, a lot of energy is wasted, which is energy that can be utilised by incorporating components such as storage devices or maybe utilising the already existing desalination plant to heat and store hot water. These components could help reduce the number of diesel generators used and utilise most of the electricity generated by the renewable energy sources.
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Dedications

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Thank you for believing in me.
Abbreviations

Pf – Power Factor
RIA- Rottnest Island Authority
MG - Micro-grid
HMG - Hybrid Micro-grid
DG - Distributed Generation
RDG, renewable distributed generator
PCC - Point of common coupling
WT/WTs - wind turbine /Wind Turbines
PV – Photovoltaic
AMI – Advanced metering infrastructure
ADI – Advanced Dynamic Islanding
Batt – Battery
Leon - Leon 680 converter
LCOE - Levelised cost of energy
Ren Fraction – renewable fraction in the system (Renewable penetration)
O&M – Operations & maintenance
NPC – Net present cost
LF – Load Following
CC – Cycle Charging
Gen: 200kW diesel generators
TLC – Thermal Load Controller
Batt – Battery storage
Ren Frac – Renewable Fraction
OP - Output
1 Introduction

Electricity generation and transmission is increasingly moving away from the traditional centralised generation due to the economic and environmental changes. Self-sustainability and local generation has begun growing as centralised generation declines, giving rise to cleaner energy and lower emissions compared to traditional generation methods (Lasseter, R. H. 2011). Renewable energy technologies that are emerging and gaining wide spread acceptance as primary sources such as photovoltaic systems, wind turbines, biomass and hydro bring new definition to power generation. These modern technologies promise reduced emissions and lower cost of energy production compared to centralised generation and self-sustainability.

The majority of the studies conducted have only been focused on the self-sustainability of micro-grids with very limited studies on their reliability (Yokoyama, R., T. Niimura, and N. Saito. 2008.) One of the major issues that arise when modelling hybrid micro-grids is the stability of the system. When a large penetration of renewable energy sources is present, the stability of the system is heavily impacted and further modifications are required to bring the system back into stable operation. Storage systems can be used in hybrid micro-grids to compensate for the frequency variances in order to improve the reliability of that system (Shahnia et al., n.d.). introduction an energy storage system in this case will play an important role in maintaining power quality, reducing the number of active generators and increasing the overall reliability of the micro-grid.
1.1 Introduction to the Rottnest Island HMG

Currently, Rottnest island depends on 6 generators, a 600 kW Wind Turbine and a 600 kW Photovoltaics system. The island has no grid connection possibilities and has to rely on its hybrid standalone power system. The annual power consumption of the island is approximately 5 GWh and is was previously supplied by five conventional diesel engines, two low-load diesel engines and a single 600 kW wind turbine, installed in 2004 (Hydro-Electric Corporation, 2017). Renewable sources were incorporated into the network to combat the high cost of shipping diesel into the island and to reduce the carbon footprint. The estimated diesel savings were estimated to be up to 43000 litres per annum due to the incorporation of these renewable sources (Rottnest Island Authority, 2017).

The wind energy project was commenced in 1979 when the construction of wind turbines was proposed as a plan to reduce the cost of electricity production to remote locations in Australia. There were two wind turbines that were initially installed on the island on Forbes Hill but were remove in the early 1990s. The 600kW generator currently powering the island was installed in late 2004 (Rottnest Island Authority, 2017).

In January 2001 the Rottnest Island Authority (RIA) reported that its underground water supply was being depleted and the salt levels in the normally fresh water were rising. This was attributed to the overall ongoing lack of rainfall on Rottnest Island over the previous 5-10 years. In response to this, the RIA produced an Integrated Water and Power Development Plan. The philosophy behind the plan was to shift from a predominantly rainfall dependent water source to a majority of potable water being supplied through desalination. A single wind turbine would supplement diesel-generated power in order to make the shift economically and environmentally acceptable (Rottnest Island Authority, 2017).
1.2 Comparison with the activities in the Project Plan

The project plan was laid out such that every 2 weeks, a meeting would be organised to keep the supervisors up to date on the progress made. This was not possible considering that some activities to be discussed where delayed.

The major delay encountered was the organisation of the site visit which was expected to be earlier so that the project plan would be better understood and to have a better understanding of the loads that will be looked at. The required information from the island such as the operation of the micro-grid, the micro-grid structure, and how they have overcome the issues mention above in the control strategy research would have enabled for a more in depth understanding of the micro-grid and any considerations to be taken before any claims were made. One of the more important assumptions made was that the diesel generators are used as the master distributed generation system, this is a logically sound claim as this is the only consistent non-renewable DGs, but it is an unverified claim. This is one of the few examples of claims because not much information is available on the Rottnest island micro-grid and the majority of the available information is before the micro grid was expanded to include the solar panels and the desalination plant.

Load data was received and the chance to address it has been minimal as the software that will be used are still being finalised. The data will be hard to understand at the as a further understanding of the micro grid and the island network will still be required. Once the site visit takes place, then the data analysis can be carried out and more activities can be completed because the lack of major information is quite a big hindrance at the moment. The project has been solely based on research and journals that address various micro grids with different
configurations. This poses as a challenge that (Ma, Yu and Zhou 2015) suggested a solution that states that networks like a micro-grid would require a base model in which further research can be done and in this case, a base configuration in which an understanding could be developed from.

Researching and understanding about the Rottnest micro-grid has proved challenging due the lack of information of the equipment used, the configuration of the micro-grid and the annual load profile data of the island. All this information will be available after the site visit which will help in further research of the project. Further research was intended to be completed on the desalination plant to gain a better understanding. This would not be very productive as I have a limited understanding of chemical engineering. By focusing on it as a variable load that replicates houses and other major loads, it was decided that the desalination plant would not have to be researched.

1.3 Micro grids and remote electrification

Hybrid energy systems have gained popularity in the electrical industry for supplying electrical energy in urban, rural and remote areas to overcome the intermittence of solar and wind resources (Sinha, Sunanda, and S. S. Chandel. 2014). Hybrid Micro-grids (HMG) are networks that combine multiple distributed generation systems (DG) that can co-ordinate local energy generations and demands in a dynamic manner offering flexibility when it comes to the control of both loads and energy sources. Replacing or somewhat supplementing centralised generation with distributed generation has led to the concept of the micro-grid

The DGs and loads can be disconnected from the network with minimal to no disruptions to the overall network and the loads allowing great flexibility during operation if a grid is present. The
Rottnest island grid has no possibility of a grid connection and has to be operated as a stand-alone power supply system or in other words, islanding mode.

For a smooth operation of a micro-grid operating under islanding conditions, the main variables that have to be considered are: power quality, voltage and frequency stability. These variables will affect the operation and reliability of the micro grid. This section of the paper will focus on the stability and reliability of MGs and how they are affected by the nature of the DGs.

Most renewable energy sources are stochastic generators meaning that their energy production is random or very unpredictable. This is due to their dependency on natural energy sources such as the sun and the wind to be able to produce electrical energy. The stochastic nature of renewable energies affects the reliability of MG systems in which they become incorporated into. They also cannot be relied upon as primary sources of energy without any storage capabilities available in the system. Stochastic generation is predicted to play a key role in power generation and thus, islanding operation of these distribution systems is becoming a viable option for economic and technical reasons (Papaeftymiou et al. 2006), (Wang, Sun and Dong. 2011).

Since renewable energy sources require certain conditions for them to produce energy, for example solar panels can only produce electricity under sunny/high irradiance conditions, though research and advances in technology have seen production of panels that can produce some electricity under low irradiance conditions, the fact still remains, for useful electricity to be produced, most panels require high irradiance conditions. The same can be said about wind turbines, certain wind speeds and have to be achieved before a wind turbine can produce electricity and running it before these conditions are means that (loss, cost of maintenance. etc) Operating RDGs without their specific requirements being met could result in overall poor power
quality, instability of the overall system and increased system running costs. (using more money to run system than what the system is producing)

1.4 System Stability

The structure of the network and penetration of RDGs will determine its versatility. One of the main problems with islanded micro-grids is the stability of the network. As the penetration of RDGs is increased, the risk of instability when disconnecting a renewable source. The versatility of the networks and its ability to adapt to sudden changes will play a major role in its overall reliability.

The power quality is also heavily affected when a DG has to be disconnected during islanded operations of MGs considering that the DG has a high penetration in the MG. A disconnected DG could be the result of many reasons such as fault isolation, arc extension, system restoration after a fault isolation (Dewadasa, Ghosh, and Ledwich. 2011). In intentional islanded operation of the MG, the disconnection of a DG could be the result of aforementioned situation where the environmental conditions that allow the operation of an RDG are not enough to produce any useful electrical energy or the conditions are too harsh for the DG to keep operating e.g. The wind speeds exceed the rated WT speed triggering the safety mechanism that protects the WT from damaging the internal components.

In grid tied MGs, the disconnection of a renewable source will not heavily affect the system as the renewable sources are secondary sources used to charge up storage devices and provide power whenever possible. In isolated MG operations where diesel generators are the main sources, RDGs play an important role depending on their penetration in the system. This means
that if a fault occurred or a disconnection was required, there could be instability issues before the required generators start up to compensate for the disconnected RDG.

Micro-grids have many advantages that make them very appealing such as increased reliability, efficiency and minimised levelized costs of electricity generation, but they also have many problems concerning reliability and power stability and configuration (Sinha, Sunanda, and Chandel. 2014). As their applications become larger, from residential applications to large applications such as Rottnest island, due to lack of optimum designing or proper sizing, a hybrid energy system, is over-sized or not properly planned or designed, which makes installation cost high. The technical and economic analyses of a hybrid system are essential for the efficient utilization of renewable energy resources.

Further research into micro grid has unveiled new problems in such as voltage flicker, harmonics and control issues (Ma, You, and Zhou. 2015.). These issues arise from the structuring of the micro-grids as currently there is no unified model that could be used to design a micro-grid, (Wang et al. 2014) analysed possible micro-grid design methods that would consist of PV modules, wind turbines, hydrogen fuel cell, lead-acid battery and multiple types of loads. For power quality and harmonic compensation, the system design incorporated active filters and would be able to operate both in parallel with the grid and in islanding/ off grid mode. The journal analysed various micro-grid control strategies and the main focus for this paper will be on the off-grid control strategy as the Rottnest island grid is isolated.

This system design had active filters installed that could automatically adjust harmonic compensation of the output to manage the power quality. For this type of typical micro grid system, the design would have to ensure that the system could operate either in parallel with
the grid or operating independently and that the system would operate cooperatively with the control strategy (Wang et al. 2014).

1.5 Energy Sources & Storage

There are multiple energy resources that can be incorporated into standalone hybrid micro-grids ranging from diesel powered systems, wind, hydro to bio-gas powered networks. Diesel generators are usually used to supply the base demand required by the loads. Renewable energy sources are used to provide cleaner and energy and reduce not only the cost of generating electricity but also reduce the emissions into the environment. The renewable sources are also an easier method to provide remote areas where a distribution network does not reach.

1.5.1 Wind Turbines

Wind turbines convert wind/kinetic energy into electrical energy. They are built in 2 particular forms, Vertical Axis & Horizontal axis. In Rottnest island, a 50 meter, 600kW horizontal Axis Wind Turbine (HAWT) is installed. Horizontal axis wind turbines have the main rotor shaft and generator at the top of the tower in the nacelle. In the nacelle, depending on the wind turbine type, there is either a squirrel cage induction generator or a synchronous generator which produces the electrical energy.

Synchronous generators have a stationary and rotating part known as the stator and rotor.
Depending on the design of the generator, the rotor or stator can be the power producing component and is known as the armature. The magnetic field is provided by the electromagnets mounted on the stator or the rotor, whichever is the stationary part. The synchronous generator is where the permanent magnet is used instead of a coil to provide the excitation field (Agarwal, 2017).

Asynchronous (induction) generators were originally designed as electrical motors. The difference between synchronous and asynchronous generators is the fact that the rotor of an asynchronous machine is out of sync with system voltages. Asynchronous machine operates with ‘slip’ which is simply a measure of how much out of synch the rotor runs compared to its synchronous speed. The machine acts as a motor when the rotor is rotating slower than synchronous speed and acts as a generator when the rotor is rotated faster than synchronous speed (Anthony, 2017). Asynchronous generators require a gear box that converts the torque from the blade into higher RPMS required by the generator. Asynchronous generators are the most common type of generators used in wind turbines due to its very reliability and inexpensive compared to synchronous generators.

Most wind turbines are up wind machines which means that upwind machines have the rotor facing the wind. The main advantage of this design is that wind shade that occurs being the tower can be avoided, some wind shade can also occur at the front of the tower. Wind shade is the phenomena where by the wind is obstructed by an object which inevitably causes ‘shading’ causing less amount of wind to come into contact with the wind turbine blades therefore less power is generated. The major drawback is the rigidity of the rotor. The deflection of the blades has to be quite minimum because if the blades are too flexible, the distance between the tower and the rotor blades is reduced during operation as the wind comes into contact and forces the
blades in its direction. This may result in very costly and quite catastrophic damages to the wind turbine (Drømstørre.dk, 2003).

1.5.2 Solar Photovoltaic energy sources

Photovoltaic cells convert sunlight directly into DC electricity. Current and Voltage are produced when the sunlight comes into contact with a PV cell. When the sunlight is absorbed by the cell, the solar energy forces electrons loose from their atom thus allowing the electrons to flow the materials, in turn producing electricity. This process of converting photons into electricity is known as the photovoltaic effect hence the term photovoltaic cells. PV cells are combined to form arrays, to obtain applicable amount of electricity. These arrays can be mounted in any configuration as required by the consumer. They can be mounted on a fixed angle facing the direction of the sun or on movable platforms connected to a tracking device that will allow the arrays to follow the position of the sun for maximum electrical output. These arrays can be customised such that they can provide power ranging from small house holds to large commercial applications. One of the advantages with PV arrays is that a large number of arrays can be connected to form a very large PV system. Thin film technology has advanced allowing for more robust solar cells that can doubles as roofing tiles or building facades increasing not only the aesthetic but also the overall application of PV arrays.

The main properties that distinguish PV arrays is their ability to convert sunlight into electricity efficiently. The efficiency of an array will determine how much sunlight is absorbed and turned into electricity or reflected. Lower efficiencies mean that the size of the array must be increased which in turn means that the overall cost is increased as well. The current average solar panel efficiencies are between 11-22%.
The components involved in PV systems are usually PV – panels, inverters, and sometimes batteries. Charge controllers used to me one of the primary components, but now modern inverters have built in charge controllers. For DC loads, the load can be connected directly to the PV system without any converting component. With such a connection, the load can only operate if the PV – panels are producing electricity. When selecting PV – Arrays and building the PV system, it is important to understand the environmental effects that might hinder or improve the performance of the arrays or reduce their life cycle. It is also important to understand the conditions they will be operating under such as the required output can be significantly reduced under certain conditions. Certain conditions that can reduce a solar array’s output are dirt, shading, temperature derating roof tilt and angle (Solar Calculator, 2017). Components of the system will also affect the overall output of the system factors such as manufacturer’s output tolerance, inverter losses, DC and AD cable losses will have a significant impact on the overall performance of the PV system.

1.5.3 Storage

Energy storage is required for off grid/ standalone applications if the load requires constant power during the night or when the PV system is not producing any electricity. Batteries are usually the most common form of storage system and can be arranged in strings to form battery banks (Frisk, 2017). Charging the battery or battery bank requires a charge controller to and if the load requires AC power, then an inverter is compulsory. In networks like Rottnest island where the load is usually residential, most of the appliances in residential houses use AC power, therefore the best configurations for such systems would include an inverter and a charge controller for the battery storage.

When choosing the battery, the most important aspect is the rated capacity that is given in Ah (Amp Hours). The battery capacity depends on the discharge current hence why the nominal
battery capacity is given with a nominal charge current. To calculate the storage capacity of the battery in kWh, the rated capacity in Ah and the operating voltage are required. A very important parameter that has to be considered with battery storage devices is the depth of discharge (DOD). The depth of discharge describes discharge depth relative to the battery's total capacity. Depth of discharge plays an important role in the cycle life of a battery. All batteries have a cycle life, which is the number of complete charge and discharges that the battery completes before its capacity falls below a certain percentage (usually 80%) of its rated capacity. The life cycles of a battery depend on multiple factors, the DOD, the average temperature of the battery, the recharge voltage, the rate of recharge and most importantly, the number of times a battery is run flat i.e. discharged below its minimum, state of charge.

Efficiency in battery storage is a significant variable that has to be considered. The efficiency varies with each manufacturer. The efficiency determines how much of the stored energy can actually be used. There are a number of losses when dealing with electrical systems and having high efficiencies means that most of the generated and stored power is used and not lost.

### 1.5.4 Dynamic Resistor

Also known as the dump load, the dynamic resistor plays a very important role in the stability of the network at Rottnest island. It is used to quickly divert any surplus energy produced by the RDGs into a load bank. This manages the stochastic energy production nature of the RDGs.
1.6 Control Strategies

1.6.1 Supply Side Control strategies

The control hierarchy is made up of generally 3 levels:

1. Primary Level:
The primary level controls seek to stabilise the grid and to establish power sharing between the generators. This control is usually localised to individual generators and their points of contact with the grid. Droop controllers are usually used as primary controllers. If a change in loading occurs, the droop controllers will stabilise the network at a new operating point causing a shift in frequency and voltages across the system which may be undesirable (Simpson-Porco et al. 2015).

2. Secondary Control
The main goal of secondary control is to remove the deviations in frequency and voltage caused by primary control. A centralised strategy is used that determines new set-point values for all local controllers (Simpson-Porco et al. 2015).

3. Tertiary Control
Tertiary control seeks to optimize the economic dispatch of generators across the network. In islanding mode, the micro grid is required to stabilize voltage, supply the power for the important load, reduce the dependency on the storage device and keep the storage device working as optimal as possible (Wang et al. 2014). Usually the storage device is switched to VF mode (Voltage Frequency mode) to use it as the reference as the micro grid will lack the reference value of frequency and voltage in the islanding mode, which will compromise the
stability of all the distributed generation systems (Wang et al. 2014). All the controllers that will be control strategies that will be presented today will be based on the secondary control level. The two methods that will be presented are based on the droop control method. The difference between the two is the reference component in the micro-grid.

One of the most common methods used in micro-grids is known as the droop based V/F control method. In this method, the droop coefficients are defined with respect to the DG’s capacities. This would include all the renewable sources, battery storage systems and diesel generators in the island.

### 1.6.1.1 Droop control V/F Method using a master DG as a reference

In the case of Rottnest Island’s current setup, to balance the power and to maintain the voltage and frequency of the micro-grid, a master distributed generation system must be selected within the micro-grid, where the control strategies will be implemented due to the lack of a storage system. There are multiple distributes generation (DG) sources that can be selected but the required sources must be stable and not affected by environmental changes. Choosing PV and wind sources as master DGs would be disadvantageous as the performance is likely to be affected by any environmental changes.

The master DG which can be the diesel generators in this case, provide reference for the voltage and frequency that all the other DGs refer to. The major problems facing this mode are the stability of the DG both reference and the other DGs connected to the micro-grid, power quality problems such as voltage flicker and harmonics and control issues. (Ma, Yu and Zhou 2015) proposed structural and power control solutions that could help overcome these
disadvantages. The first proposal is to unify the definition and structure of micro-grid to enable
the individual research of micro-grids based on a unified model rather than researching one type
of micro-grid knowing that the all the rest might not apply to the research conducted. The
second proposal was to research power control technology. Power quality in micro-grids is
known to be affected by the system, the suggestion was that by combining the active power
filter with the micro power resource, researching more on power quality and regulating that
power quality would possibly enable the micro-grids to provide users with safe and reliable
electricity (Ma, Yu and Zhou 2015).

1.6.1.2 Droop control V/F Method using storage devices as a reference

Another feasible solution is the integration of batteries/ storage systems into the micro grid
system. In an off-grid states, storage devices can be controlled using V-F mode to help maintain
a stable output voltage to the loads and help in stabilising the power fluctuations (Ustun et al.
2011). Energy storage systems can play a vital role in off grid micro grid control as they can be
used as reference systems in the micro-grid to combat the stability problems experienced by
other DGs during off grid/ islanding operations.

The major problem experienced by the droop based V/F control method in this case is that the
state of charge (SOC) of the battery is not considered when determining the power delivered by
the storage systems, meaning that the storage devices might quickly get depleted and as a
result, disconnect from the micro grid (Hosseiniemehr. 2017). To combat this issue,
(Hosseiniemehr. 2017) suggests that the droop control be modified such that the power ratios of
each storage device correlate with their state of charge as opposed to the device’s capacity.
1.6.2 Demand Side Management Techniques

1.6.2.1 Load Shifting

Load shifting is a demand side management technique that is used to ‘shift’ the load and average it out throughout the day. The consumption of high wattage loads is usually the major focus and customers are usually given incentives to use their high wattage loads at various times during the day or even within a week. It must be noted that Load shifting does not reduce the overall consumption but simply changes the time of consumption (Ratha, 2015).

One of the most common incentives is the cost of electricity for different periods. Usually electricity suppliers will have different tariffs for different periods of the day i.e. off-peak period and on peak period. The off-peak period will usually have a lower price tag as compared to the on peak period. The price differences are an effective incentive that encourages customers to alter the times of day in which they use their high demand loads thus in turn shifting their load profiles. With such different load profiles, the benefits can be experienced in both demand side and supply side of the network. For the demand side, especially commercial consumers, the overall running costs can be reduced due to consuming large amounts of power at a lower tariff rate during ‘off peak periods’ and consuming less during ‘on peak period’. The supply side would experience the benefits in terms of reduced power generation capacity through-out the day, which means that some generators could be potentially turned off remain on stand-by (Sun, Yongjun et al 2013).

With the current HMG, this could be quite beneficial in terms of LCOE. The overall LOCE could be reduced if less generators are operational.
January the month with the highest electricity consumption rates, with a peak registered at 1224 kW at mid-day. Shifting large commercial loads such as the desalination plant to later hours such as 10pm or the early hours of the morning where less consumption is likely to be occurring would see the consumption being averaged to about 800kw to 900 kw in each hour. This could mean that some of the generators could be removed from the system as the load during peak hours could be reduced.

1.6.2.2 Load & generation Forecasting

This is an idea that could also help reduce any excess energy generated in the HMG or help with generating what is needed (Load Following). The idea behind load forecasting is that, data collected in the previous years is revised and analysed to find any trends. This then allows for the prediction of the future load. Generation forecasting is the same as load forecasting differing in that it focuses on the generation of the previous years. The generation considered is the energy generated to meet the load without any excess considered. Discrepancies must then be
considered at later stages to allow for any environmental changes or mechanical failures. The forecasting method helps to reduce the usage unnecessary generation rather than having all diesel generators and the RDGs on at the same time. *Hong, Tao, and Shu Fan. 2016* extensively reviewed multiple load forecasting methods ranging from very short load forecasting, short term load forecasting, medium term load forecasting and long-term load forecasting. The focus in this thesis paper is mostly on long term load forecasting where factors such as weather data, time factors, customer classes, and economic and end use factors affect the accuracy of the outcome (*Hahn, Heiko, Silja Meyer-Nieberg, and Stefan Pickl. 2009*).
1.6.2.3 Smart grids Advanced metering infrastructure & Adaptive Dynamic Islanding

Usually a method used in grid connected MGs, ADI is whereby the MG has the ability to switch on and off non-critical loads by using advanced metering infrastructure (AMI) such as smart meters (Nourai, A., and D. Kearns. 2010). AMIs allow dynamic control of the MG, increasing the overall reliability and versatility of the system.

ADI in conjunction with AMIs could present the opportunity to reduce the overall LCOE in the Rottnest island HMG because of the dynamic control ability introduced by AMIs. Even though there currently is a large amount of excess energy produced by the MG, there is a predicted exponential growth in electricity consumption and as the community expands, so does the need for electricity (Rottnest Island Authority, 2017). If AMIs were to be introduced during the expansions and all new buildings included AMIs, this could open up multiple opportunities such as demand side management control methods such as Load Shedding. AMIs would enable the control of each single load and if the HMG is experiencing high demands some low priority loads could be remotely ‘shed’ to free up some generation for high priority loads.

Currently ADIs research is leaning towards the remote control of every house meter but the initial costs could be very high. Economically, the long-term benefits would outweigh the initial cost. The reliability of the network would increase as loads could be connected and disconnected as required. In this study, the smart meters can be installed on the large loads such as the desalination plant and the dump load. This will allow any future expansion of the island’s load to be easily incorporated into the system, meaning that all major loads could be remotely accessed, increasing the network’s versatility.
Currently the island has an automated demand side management system incorporated which is limited to the desalination plant with future prospects of being extended to the rest of the island. The objective is to reduce the diesel-based energy intensity of desalinated water through smart control of the desalination process and water storage. If possible, the desalination plant will run only when there is excess renewable energy generation available, effectively utilising desalinated water as a form of battery (energy storage) (Hydro Tasmania, 2016).

2 Methodology

The simulations were conducted in Homer, a software built for the optimisation of various micro-grid designs. The Initial simulation considered the bases case to be comprised of the seven 200 kW generators. This allowed a case for comparison to see the differences in the LOCE and any other factors as components are included or excluded from the MG. All costs were calculated in Australian Dollars (AUD) The project lifetime was assumed to be 25 years at an interest rate of 7% with an inflation rate of 2%.

It has to be noted that HOMER software does not limit the size with respect to the considered component, when a component is considered in the system regardless of its size, the software sizes each component according to its optimiser to obtain the most feasible solution.
### Table 1: Cost & parameters of components

<table>
<thead>
<tr>
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<th>Solar</th>
<th>Wind Turbine</th>
<th>Diesel Generators</th>
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<td>Initial capital cost ($/W)</td>
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<td>Initial capital cost (k$)</td>
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<td>Battery</td>
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<tr>
<td>--------------------------</td>
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<table>
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<td></td>
<td>O&amp;M cost ($/kW/year)</td>
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<td>Lifetime (year)</td>
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<td></td>
<td>Rectifying efficiency (%)</td>
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<tr>
<td></td>
<td>Inverting efficiency (%)</td>
<td>96</td>
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</table>

![Figure 2: Hybrid MG setup](image-url)
2.1 Diesel Generators

The diesel generators used were the CAT C9 generators with an estimated maximum power output of 200 kW AT 0.8 pf, an estimated CO₂ emission of 1.62g/L of diesel.¹ There is a total of seven diesel generators in the system the total generation capacity is 1.4MW when operating at rated power outputs.

2.2 Wind Turbine

The wind turbine used was the Vistas V47 rated at a maximum power output of 660 kW, the wind turbine output characteristics were modified to replicate the maximum power output of the installed turbine in Rottnest island which is rated at 600 kW. It is assumed that the WT is producing A.C. electricity. Figure 3 shows the power curve of the Vestas V47 WT after the modifications were applied.

![Wind Turbine Power Curve](image)

Figure 3: WT Power Curve

¹ Generator data sheet
2.3 Solar PV

Generic flat plate panels were used with a maximum power output of 630 kW. All the required data such as the GHI & SCI were obtained from the Atmospheric Science Data Centre of NASA. Figure 4 shows that the annual average irradiance of the island is 5.51 kWh/m²/day.

![Figure 4: Shows the Average daily radiation of each month and the clearness index](image)

2.4 Inverter

The RDGs were used in conjunction with a Leonics converter rated at 680kW. The converter had both inverting and rectifying capabilities at 98 % & 96% efficiencies respectively. The relative capacity on the rectifying side was 10%. This inverter is bi-directional allowing for integration of storage devices into the network, Figure 2 illustrates the configuration of the considered network and how the converter is incorporated.
2.5 Battery/Storage

The current set up of the HMG, does not include any storage devices, but multiple battery storages have been simulated to show the effects storage devices have on the overall LCOE of the network. The battery storages considered range from 1kWh capacity to above 1 MWh. They were also considered to improve the power quality in the network due to the stochastic nature of the RDGs.

2.6 Load

![Annual Generation Vs Annual Average Consumption](image)

*Figure 5: Annual Generation Vs Load Consumption*

*Figure 5* shows the load consumption of the island vs the generation from the HMG. The figure shows that for most month, there is large amounts of excess generated. The simulations conducted aim to reduce this excess and to reduce the amount of generation from the diesel generators.
2.7 Thermal Load, Boiler & Controller

A thermal load simulates the idea of a “water battery”, which is heating up the water stored in the water storage facilities using the surplus renewable energy, a boiler is also connected into the system that heats up the water when the RDGs are not producing any excess power. The boiler like the diesel generators uses diesel fuel to provide the heat energy. The thermal load controller allows for the load to be connected to the AC, DC or both sides of the HMG, without the controller, the boiler would provide the required energy to the heat load. The thermal controller has 3 different modes, AC connected, DC connected and AC/DC mode where by the controller draws electricity from both ends of the HMG. This allows us to see which connection could provide the lowest LCOE while minimising the operational cost of the HMG and reducing the excess energy. The estimated hot water daily usage is 5000L/day maximum and the reasoning and calculations behind this value is shown in the appendices.
3 Results & Analysis

To find the most feasible solution for the standalone Hybrid micro-grid in Rottnest island, the LCOE, NPC, & the operational costs will be considered. There are multiple cases that will be compared with the base case (7 diesel generators without any renewable energy sources incorporated into the system), this will allow for a suitable system to be selected and to see if that system is economically feasible. The analysis was undertaken in HOMER software which utilises provided electrical load consumption of the island over a year, the previous year’s solar radiation and wind speed. The costs of each component is also included in the simulation results which HOMER takes into account to allow for economically feasibility comparisons.

Tables 2-4 show the results of the optimisation. Table 2 shows the optimisation results when different dispatch methods were used. The micro-grid controller in the Homer Software can either be load following (LF) or Cycle charging (CC) or the simulation can be set such that both controllers are active, and the software chooses the optimal controller that produces the most feasible solution. Table 3 shows the optimisation results when the only controller used was the cycle charging controller. The cycle charging controller focusses on charging the battery if any surplus energy is present. Table 4 are the results of controlling and extra heat load connected into the HMG. Table 4 is the results of including a thermal load into the network to simulate a “water battery”.

### Table 2: Optimisation Results using different dispatch methods

<table>
<thead>
<tr>
<th>Case</th>
<th>Configuration</th>
<th>PV (kW)</th>
<th>WT (kW)</th>
<th>Gen (200 kW)</th>
<th>Batt (kWh)</th>
<th>Leon (kW)</th>
<th>Disp</th>
<th>LCOE ($/kWh)</th>
<th>NPC (M$)</th>
<th>Operational Cost (k$/yr.)</th>
<th>Capital Cost (M$)</th>
<th>Fuel Cost (k$/yr.)</th>
<th>O&amp;M (k$/yr.)</th>
<th>Ren Frac (%)</th>
<th>Excess (kWh/yr)</th>
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<td>A1</td>
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<td></td>
<td></td>
<td>CC</td>
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<td>91.4</td>
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<td>6</td>
<td></td>
<td></td>
<td>CC</td>
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<td></td>
<td>CC</td>
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### Table 3: Optimisation Results using cycle charging dispatch methods

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<th>Case</th>
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<th>WT (kW)</th>
<th>Gen (200 kW)</th>
<th>Batt (kWh)</th>
<th>Leon (kW)</th>
<th>Disp</th>
<th>LCOE ($/kWh)</th>
<th>NPC (M$)</th>
<th>Operational Cost (k$/yr.)</th>
<th>Capital Cost (M$)</th>
<th>Fuel Cost (k$/yr.)</th>
<th>O&amp;M (k$/yr.)</th>
<th>Ren Frac (%)</th>
<th>Excess (kWh/yr)</th>
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<td>-</td>
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<td></td>
<td></td>
<td>CC</td>
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<td>34.99</td>
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3.1 Case 1: Base System

The first case that will be considered is the base system, which assumes 7 x 200kw generators are in operation. Figures 6 & 7 respectively show the cost summary of each generator and the annualised cost type in the considered base system. In all the cases run, the LCOE of the base case was found to be $0.371/kWh. This system has a net present cost of approximately $35.1 Million and an operational cost of $2.5 Million. In Figure 6, the highest cost is the diesel fuel costs of approximately $2.23M per year.
The annual cost of each generator ranges from $2M to $8Million which impacts the overall cost of energy production per year. The 2 low load generators that are required as reserves have lower costs per annum due to the low usage rates but still provide spinning reserve during high consumption periods. In this case, generators 1 to 5 are the primary generators, providing most of the power throughout the year and generators 5 and 6 always on standby to provide the required power.

**Figure 8:** Monthly average electricity production for each generator

**Figure 9:** Average monthly diesel consumption for case A1

**Figure 9** shows the combined average monthly diesel consumption of the generators and the daily diesel consumption and the highest consumption corresponds to the high load requirement as shown in **Figure 5**. The diesel consumption shown in **Figure 9** is on average 350L/hr during the month of January where the load also has a peak consumption of 1200kW at approximately
780kW/h with an average daily consumption of 18200 kWh. The total fuel cost per year is M$2.2, with an operational cost of M$2.5 per year.

### 3.2 Case 2: Generator/PV

Cases A2 and B2 include a PV component into the network, the renewable fractions of each optimisation are 46.13% and 46.12% respectively. In both these cases, the renewable fraction is high enough to cause stability problems within the network, thus proper design and control would be required before this optimisation could be implemented.

#### 3.2.1 Case A2:

![Figure 10: NPC summary for DGs case A2](image1)

![Figure 11: Average monthly diesel consumption for case A2](image2)
Figures 10 & 11 show the cost summary of each DG into the system and the average monthly consumption of the diesel generators. Compared to the base case, it can be seen that when the PV system is incorporated into the network, the overall costs of the system experience a dramatic reduction. The NPC of the system is estimated at $24.33M with the LCOE reduced to $0.258/kWh compared to the $0.371/kWh of the base system. The fuel consumption on the highest load month reaches a peak of 315 L/hr but averages 127 L/hr. The operating costs of this system are approximately $1.5M which is almost half the operational cost of the base case.

3.2.2 Case B2:

Figure 12 shows the cost summary of the components in Case B2, it can be seen that the diesel generators costs has reduced with the highest cost being approximately $6M. The PV components cost $3.5M per year and the converter (Leonics 680) costs around $2.2M. The annual costs LCOE for this system is 0.27 $/kWh which is 10c/kWh less than the base case and the NPC is estimated at $25.17M. The operational cost for this system and the capital costs are $2.5M and $3.92M respectively.
Figure 13 shows the average monthly generation for case B2, the generation from the PV system can be seen that it exceeds the generation from the diesel generators. The generators are still required to cover the base load of the island. The solar generation cannot be used to cover the base generation due to the stochastic nature of renewable energy sources hence why this case has such a high excess generation of 2323 MWh/yr.

Both Case A2 and B2 have reduced LCOE, NPC and Operations costs. The disadvantages experienced by these systems are the excess electricity being generated, as can be seen from the Tables 2 & 3, the base cases A1&B1 does not produce any excess energy and when the RDGs are introduced, excess energy is to be expected because the generation from RDGs cannot be accurately forecasted.

3.3 Case 3: Generator/WT

Cases A3 & B3 are very similar, the overall LCOE for both cases is $0.194/kWh. In comparison to both the base case and cases 2 (A1&B2), the LCOE of case 3 has experienced a significant reduction. Compared to case B2 which has the lowest LCOE for the Generator/PV cases, the LCOE has reduce by $0.76 /kWh, this is mainly due to the reduction in the components required and the increased generation of the WT throughout the year.
Figure 14: NPC Cost summary for case 3

Figure 15: Monthly Average Generation Case A3&B3

**Figure 14** shows the cost of each DG in the generator; the highest diesel generator cost is $4.2M which is approximately $1.2M less than the diesel generators in case 2. The NPC of the WT is close to $5.1M and as shown in **Figure 15**, the WT produces the majority of the electricity in this case. The renewable penetration in this case is 65.9%. The excess energy generated in this case is around 8200 MWh/year with the operational cost almost $1M per year. **Figure 16** shows the annual diesel consumption and when compared to the base case and case 2, the average is down to only 87L/hr. and about 200L is consumed per day with the fuel costs predicted at $816000 per year.
The overall NPC for the system is $18.32M which is $16.67M less than the base case NPC. One of the costs that increases when RDGs are introduced into the system is the O&M costs, compared to the O&M costs of the base system, case 3 experiences an increased O&M cost of $15000 per year.

3.4 Case 4: Generator/PV/WT

Case 4 shows the results of optimising all the DGs. The combination of diesel generators, PV system and WT are the current setup of the HMG this simulation gives an idea of how the current network system can be altered in order to reduce the overall LCOE of the system. Cases A4 & B4 show varying results with case A4 having the lowest LCOE of $0.181/kWh between the two cases. Case A4 requires that the current system be upgraded to include a 1081 kW PV system, 5 of the 600 kW wind turbines a 734-kW converter and the controller to be setup as cycle charging. This system has an NPC of $17.1M and an estimated operational cost of $856k.
Figure 17 and 18 show the NPC of each DG and the annualised cost with respect to the cost type. In Figure 17, the diesel generators have the highest combined NPC followed by the WT with an NPC of $3.4M. The highest cost type remains as the diesel fuel costs with an annualised cost of almost $670k per year which does not include the transportation costs into the island. This means that the total annual cost for the diesel fuel will be much higher than the optimisation value.
Figure 19 shows the generation of each DG in the HMG network of Case A4, the highest generation is from the suggested 4 WT which generate more than 63% of the total electricity, followed by the PV system which is estimated to contribute 22.3% of the total generation. The total RDG penetration in the HMG network is approximately 72.5.

Figure 20 shows the annual diesel consumption of the HMG. Due to the high penetration of renewables in the network, the average annual consumption is low compared to the previous cases. The average diesel consumption is around 70 L/hr and around 1600 L per day. This case has an operational cost of $856k per year and an annual operation and maintenance cost of $61k. The excess produced by this case is around 6500 MWh per year because of the increase amount of electricity generated by the RDG and isn’t consumed by the load.
3.5 Case 5-8: Battery integrated MG cases

3.5.1 Cases 5-7:

Cases 5-7 are the results of when a storage device is added into the previous cases. The chosen battery was a generic 1kWh battery from the Homer software. The software then simulates regardless of the selected components sizes, the most optimal size of each component in that simulation.

In these optimisations, Cases A5 to A7 and B5 to B7 have LOCEs that vary from very high to very low. Case A5 and B5 are similar to the base case with battery storage capabilities and the LCOE actually slightly increases due to the additional components. Based on just the LCOE, case A7 would be the optimal case between these four cases as the LCOE for case A7 is $0.180/kWh. This case requires that 5 WTs be installed and 5 diesel generators to be operational.

Figure 21: NPC Cost summary for case A7
Figures 21 show the NPC of each DG in the HMG. Figure 22 shows the annualised cost of the HMG divided in cost types. The WT has the highest NPC in this case, but it is to be expected as it produces 83% of the total electricity production as shown in Figure 23.

The annual excess electricity is estimated to be 47.2% of the annual generation which means that with the 307-kWh battery suggested by the optimisation, a large number of the generated electricity will still be wasted in this case. The only cases that do not have any excess electricity are case A5 & B5 due to the fact that the base case only produces enough electricity to meet the required load. Case A7 has the lowest operational and fuel costs between these cases estimated at $863k per year with a fuel cost of $713k per year. This case is highly dependent on wind energy and further simulations and research would be required to confirm the economic
feasibility and if this case would manage to provide electricity even when the wind resource is low.

### 3.5.2 Case 8:

Cases A8 & B8 have the overall lowest LCOE in all the optimizations conducted with case A8 having levelized costs of $0.163/kWh and 0.172/kWh respectively. The systems both require that the network have 4 x WT (600kW) but case 8 has the lowest number of diesel generators in operation of 4 x 200Kw. Most of the electricity in case A8 is then produced by the PV system which is required to be sized at 973.3 Kw, case B8 requires 5 x 200kW diesel generators and a reduced PV generation of 780kW. The batteries in both cases are sized at 825 kWh and 698kW respectively.

![Figure 24 : NPC Cost summary for case A8](image)

![Figure 25 : Annualised Cost type for Case A8](image)
Figures 24 & 25 respectively show the NPC summary of each component in Case A8 and how the annualised costs are divided within the network. The highest NPC in this case is the combined cost of the diesel generators followed by the WT costing $3.38M. The diesel fuel cost is close to $500k without including transportation costs. The operational cost is approximately $690k and an expected O&M cost of $65.61k.

![Figure 26: Monthly Average Generation Case A8](image)

**Figure 26** shows the average monthly generation of each DG in the system. Case A8 has the highest renewable fraction in all the optimisations of 77.26% followed by cases B8 & B4. The WT produces close to 67% the total generation followed by the PV system at 21%. The excess electricity that would be generated by case A8 annually is around 5.9 MWh/year.

![Figure 27: Fuel Consumption Case A8](image)
**Figure 27** shows the estimated diesel fuel consumption of case A8, the average hourly usage is down to 51.7 / Hour compared to the 350l/hr. of the base case. The average diesel consumption per day is down to 1242 L. As seen from the results, case A8 is the most economically feasible of all the cases if the Rottnest island authority aims to reduces the LCOE down to the amount of $0.163/kWh. It also has to be noted the MG controller used. For case A8, the load following (LF).

### 3.6 Case C1-3: Thermal Load

Cases C1-3 are expansions of previous cases to include a boiler and a thermal Load controller, the average LCOE for Cases C range is $0.13/kWh with the case C3 having the lowest LCOE of $0.128/kWh. **Figure 28** shows the NPC of each component in these cases in comparison to **Figure 29** which shows the NPC of each component for Case C2 which has the highest overall NPC.

![Figure 28: NPC Cost summary for case C3](image)
As is shown by the Figures 27&28, the systems have very similar component NPCs with just slight variances, which is reflected in the LCOE. Figure 30 also shows the cost of Case 3 and how it is divided annually. The fuel cost still constitutes the largest cost in the network compared to any other cost.

Figure 31 shows the monthly generation of each sources in Case C3, as can be seen, the PV system is estimated to contribute about 88.7 % of the overall electricity production from the recommended 28000 kW system to be installed. The 4 WTs only produce close to 10% of the overall annual generated electricity.
Figure 31: Monthly Average Generation Case C3

Figure 32, on the other hand, shows the annual thermal production of the system and as shown, the boiler produces approximately 420 000kWh/yr in thermal energy, this constitutes only 0.5% of the annual thermal energy production. Figure 33 shows the boiler power output throughout the year.

Figure 32: Thermal Energy produced by Boiler

Most of the power output used to produce the thermal energy using diesel fuel is shown in Figure 33. The majority of the power produced for thermal energy production using diesel fuel occurs before sunrise and after sunset when the PV system is no longer capable of producing any electricity and the boiler has to use diesel fuel to produce the required thermal energy.
Figure 33: Boiler Power output

Figure 34 tells a different story, it shows the power produced through the thermal controller that is connected to both the AC and DC sides of the HMG. For Cases C1-3, the power output from the TLC looks very similar to Figure 33. The average excess energy that is generated by the HMG and used to produce thermal energy for the thermal load is approximately 10000kW. This power output makes 99.5% of the overall thermal energy production of the system. Figure 31 only shows the 0.5% of the thermal energy produced, there is no graph to show the 99.5% from the TLC as it is in the form of electrical energy which is then converted to thermal energy.

Figure 34: TLC Power Output
As can be seen from Figures 33&34, both graphs show complimentary outputs, when the excess energy from the RDGs is lo, the broiler takes the responsibility and produces the required power to support the thermal load.

3.7 Case C4:

Case C4 shows the results of simulating the thermal load without any connection to the HMG, that is, the boiler uses diesel fuel to generate all the thermal energy required by the thermal load. The LCOE for this case is $0.371/kWh, which is similar to the base case (Cases A1 & B1).

Figure 35: NPC Cost summary for case C4

Figure 35 shows the NPC of case C4 and it has similar trends as the base case, most of the diesel generators provide the island’s load and the broiler’s NPC is significantly high as well.

Figure 36: Average monthly diesel consumption for Case C4
Figure 36 shows the diesel fuel consumption of the entire system including the boiler. The average fuel consumption is 250l/Hr with peaks of above 450l/Hr during the month of January. On average, the estimated fuel consumption demand is close to 6kL per day with an approximate total consumption of 2.2ML per year. This case including the base case, reflect why the overall LCOE is high due to the amount of diesel fuel being consumed. These values do not include the transportation cost of the fuel cost into the island, meaning that the costs including the transportation could be a lot higher than expected.
4 Conclusion

The presented suggestions to problems currently experienced by micro grids still have a lot of further research to be carried out due to the ever-changing configuration of micro-grids. These solutions are very specific to a certain type of micro grid configuration which only considers a few renewable sources and diesel generators. When more sources are added into the system, new challenges may be faced, and the performance of the system based on these suggested solutions cannot be guaranteed because every energy source will present more challenges.

By reviewing and understanding all these scenarios, a better understanding was developed on remote/off grid systems and how to possible work around any problems that could occur while running an off grid micro grid. Many of the journal sources were analysing configurations that were somewhat similar with a few extra renewable sources or included storage capabilities. This made them relevant to the project as all these configurations presented problems and solutions that were applied into this paper. The suggested solutions presented by the journals all presented the same method (droop based V/F control method) with slight variations when it came to the controlled component in the system.

The LCOE of the different systems presented reflect a possibility of increased savings if certain amounts of RDG penetration is incorporated into the island’s HMG. Even though is noted that the HMG could experience stability problems when operating with such a high degree of renewables, corrective measures could be taken to avoid any instability issues. Battery integration is one of the methods that seems favorable in HMGs to combat stability and also to reduce the amount of diesel generation within the HMG. The dynamic resistor will still be required in the HMG’s operation as most of the presented cases still produce a large amount of excess and the dynamic resistor would be required to dissipate that excess energy.
For the thermal load cases, a stand-alone case is not advisable in the sense that more diesel fuel will be consumed. Other cases show promising results if any further upgrades are to be carried out into the system and the overall cost of upgrades is to be reduced. The results show that for the stated LCOEs to be achieved, there is a large amount of capital required and usually capital cost is a contributing factor when large system upgrades like these are being considered.
5 Recommendations

When further research is conducted for real world application of these models, it is to be advised that the software used be changed to a more powerful program such as MATLAB or similar, that will adhere to the stated constraints. HOMER does not use the given values per say as it uses them as guides to find the lowest LCOE without considering real world limitations such as practicality of recommended systems and whether the Capital cost is too high. HOMER software allows too much versatility thus the results can be variable to the point where the system does have a low LCOE but is practically and economically not feasible. Some of the results from Homer, though economically feasible do not take into account extra costs such as diesel transportation. This could be a feature that could be helpful.

Site visits are very important for students conducting research on a particular place/land as this will give the researcher a clear idea of what they are working with, and it also gives them the chance to engage with the people that could answer any questions and clarify any misconceptions that the researcher might have. Without having the opportunity to visit the actual plant, there were many assumptions that had to be made in order to begin the research, which some of them still stand due to the research close to completion when some of the assumptions were disproven.

It is to be further recommended that more time be spent explaining to the student the clear objective of the project in the beginning for projects that do not appear on the thesis list as this will help the student and supervisor to understand what is expected out of the project. When working with big corporations, the required DATA and any excursions need to also be planned out prior to the student beginning the project rather than everything being organised while the project is under way as this puts a lot of pressure on both students an any supervisor involved. Further studies were conducted for thermal energy production and the LCOE for the thermal cases using system advisor modelling software (SAM) but the results were not feasible enough.
to be included into the research paper. The results were not consistent and kept changing as slight changes were made to some of the variables. It is recommended that more studies be carried out in SAM due to the detail that is required on flow rates and financial variables. The SAM program allows for more variables to be controlled and there is a wide variety of solar thermal panels to be chosen from. In HOMER, there is no solar thermal component, hence why the focus of this research was more concentrated on consuming the excess energy produced from the HMG and the only recommended upgrades were based on the already existing components. It is recommended that further research be carried out on this section using SAM or a similar software for a more detailed and comprehensive study on including solar thermal technology into the HMG to see how it affects the LCOE of the system.
6 References


7 Appendices

Thermal water heating calculations

1. Estimated supply water to the Island

\[ 110000 \text{ kL /yr} \]

\[
\text{Hourly supply} = \frac{110000 \text{ kL}}{8760 \text{ hrs/yr}} = 12600 \text{ L/hr of hot & cold water}
\]

2. Assuming 1/3 of supplied water is hot water

\[ \frac{1}{3} \times 1600 \text{ L/hr} = 4200 \text{ L/ hr of hot water supplied} \]

\[ \therefore \text{Round up to 5000l/hr} \]

3. System flow rate:

Assuming 1L = 1kg

\[ \therefore 5000 \text{ L/hr} = 5000\text{kg/hr} = 85\text{kg/s} \]

4. Using heat equation

**Using**: \( Q = C_{\text{water}} \times m \times dT \)

Where \( C = \) Specific heat

\( M = \) mass of measured fluid

\( dT = \) change in temperature (K)

\( Q = \) Heat Energy (Joules)

5. \( C_{\text{water}} = 4186 \text{ Joules/gram ° K} \)

\[ \text{Mass} = 5000\text{kg} = 5 \times 10^6 \text{ mg} \]

\[ dT = 18^\circ\text{C} - 50^\circ\text{C} \]

\[ = 292\text{K} - 324\text{K} \]

\[ = 32\text{K} \]

\[ \therefore Q_{\text{required}} = 4.186 \times 5 \times 10^6 \times 32 \]

\[ = 66.976 \times 10^7 \text{ Joules is required to raise the water temperature from 18^\circ\text{C} - 50^\circ\text{C}}. \]

\[ \therefore Q (\text{kW/hr}) = \frac{66.976 \times 10^7}{3600} = 186.04 \text{ kW/ hr (System size)} \]