INVESTIGATION INTO IMPROVING THE OPERATION OF THE EXISTING WIND DIESEL POWER SYSTEM AND CONSIDERATIONS FOR FUTURE GRID TIED SOLAR PV ON THE ISLAND OF NEVIS, WEST INDIES

Murdoch University
School of Engineering and Energy

Project report submitted in partial fulfilment of the requirements for the degree of
Master of Science in Renewable Energy

By
Jonathan Augustine Kelly
2015
Declaration

I declare that this dissertation is an account of my own research except where other material was referenced in the literature reviews and case studies. In instances where material from other sources have been used, they have been explicitly referenced throughout the dissertation and listed in the appended bibliography.

The dissertation contains as its main content, work which has not been previously submitted for a degree at any tertiary education institution.

Signed: Jonathan Augustine Kelly

Date: 4/12/15
Acknowledgements

Without the help of God, nothing would be possible.

I will take this opportunity to express my gratitude to the Australian Government Department of Foreign Affairs and Trade (DFAT) Australia Awards Scholarship program for affording me this opportunity to pursue this degree at Murdoch University.

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Finally I thank my family and friends for their unwavering support and encouragement through it all.
Abstract

In 2010, Nevis became the first Eastern Caribbean Island to have a grid tied wind farm operating in tandem with an existing diesel generator fleet. However, due to the old age of the existing diesels and the lack of a unified automated control system to govern the wind diesel system operation, the full possible fuel savings are not being realised.

The following report examines the existing Nevis Island wind diesel system, and uses literature reviews and a case study of the high penetration wind diesel system at Coral Bay Western Australia, to derive possible solutions for improving the Nevis Island wind diesel system. Through the use of HOMER simulations based on an automated Nevis Island wind diesel system, the project research shows that the existing 2.2MW wind farm can achieve a maximum annual wind energy penetration of 10%. This is a 2% increase over the present average annual wind energy penetration and translates into an annual fuel savings of approximately 2,039 kL.

Further investigations carried out in this report, looked at the benefits to be derived from installing new diesel generators. The HOMER simulation results show that the annual wind energy penetration level remains the same for the existing wind farm capacity, however with the use of more fuel efficient diesel generators that have lower minimum loadings and better part load efficiencies, the annual diesel fuel consumption is further reduced.

As Nevis has a good solar radiation resource, the project investigated the combined benefits of increasing installed wind power generation capacity and the addition of grid-tied roof top solar PV on government buildings. Simulations were also done with the inclusion of battery storage which would act as short term spinning reserve to maintain grid frequency stability during rapid variations of the renewable energy resources or sudden load changes.
Overall, each of the scenarios which were simulated in HOMER, indicate that the Nevis Island wind diesel system can be much improved through the deployment of a unified automated control system, new diesel generators and some energy storage, which then allow for an increase in renewable energy penetration into the Nevis Island grid, while maintaining good power quality.
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<tbody>
<tr>
<td>AMI</td>
<td>Advanced Metering Interface</td>
</tr>
<tr>
<td>BMEP</td>
<td>Brake Mean Effective Pressure</td>
</tr>
<tr>
<td>CARICOM</td>
<td>Caribbean Community</td>
</tr>
<tr>
<td>CC</td>
<td>Cycle Charging</td>
</tr>
<tr>
<td>COE</td>
<td>Cost of Energy</td>
</tr>
<tr>
<td>CREDP</td>
<td>Caribbean Renewable Energy Development Program</td>
</tr>
<tr>
<td>DNI</td>
<td>Direct Normal Irradiation</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>ESBNG</td>
<td>Electricity Supply Board National Grid (Ireland)</td>
</tr>
<tr>
<td>ESS</td>
<td>Energy Storage System</td>
</tr>
<tr>
<td>G3</td>
<td>Generator 3</td>
</tr>
<tr>
<td>G4</td>
<td>Generator 4</td>
</tr>
<tr>
<td>G5</td>
<td>Generator 5</td>
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<tr>
<td>G6</td>
<td>Generator 6</td>
</tr>
<tr>
<td>G7</td>
<td>Generator 7</td>
</tr>
<tr>
<td>G8</td>
<td>Generator 8</td>
</tr>
<tr>
<td>GFC</td>
<td>Global Financial Crises</td>
</tr>
<tr>
<td>GFC</td>
<td>Global Financial Crises</td>
</tr>
<tr>
<td>GHI</td>
<td>Global Horizontal Irradiation</td>
</tr>
<tr>
<td>GM</td>
<td>General Motors</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>HOMER</td>
<td>Hybrid Optimisation of Multiple Energy Resources</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------------------------------------</td>
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<tr>
<td>HRES</td>
<td>Hybrid Renewable Energy Systems</td>
</tr>
<tr>
<td>IADB</td>
<td>Inter-American Development Bank</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>IPP</td>
<td>Independent Power Producer</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized Cost of Energy</td>
</tr>
<tr>
<td>LLD</td>
<td>Low Load Diesel</td>
</tr>
<tr>
<td>MB</td>
<td>Mirrlees Blackstone</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>NEVLEC</td>
<td>Nevis Electricity Company</td>
</tr>
<tr>
<td>NIA</td>
<td>Nevis Island Administration</td>
</tr>
<tr>
<td>NIWDM</td>
<td>Nevis Island Wind Diesel Model</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrous Oxides</td>
</tr>
<tr>
<td>NPC</td>
<td>Net Present Cost</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and Maintenance</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OHL</td>
<td>Overhead Line</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>PPA</td>
<td>Power Purchase Agreement</td>
</tr>
<tr>
<td>PPS</td>
<td>Prospect Power Station</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable Energy</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control And Data Acquisition</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>SCIG</td>
<td>Squirrel Cage Induction Generator</td>
</tr>
<tr>
<td>SEN</td>
<td>Sustainable Energy Now</td>
</tr>
<tr>
<td>SIDS</td>
<td>Small Island Developing States</td>
</tr>
<tr>
<td>SOx</td>
<td>Sulphurous Oxides</td>
</tr>
<tr>
<td>USAID</td>
<td>United States Aid</td>
</tr>
<tr>
<td>WDHS</td>
<td>Wind Diesel Hybrid System</td>
</tr>
<tr>
<td>WNL</td>
<td>Wind Watt Nevis Ltd</td>
</tr>
<tr>
<td>WOIS</td>
<td>Wartsila Operator Interface System</td>
</tr>
<tr>
<td>WTG</td>
<td>Wind Turbine Generator</td>
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Chapter One: Introduction

1.1 Overview of Nevis

Nevis is a 93km² Caribbean island located in the Lesser Antillean island chain, which together with the island of St Kitts, forms the federation of St Christopher and Nevis (St Kitts and Nevis). Figure 1.1 illustrates the geographical location of St Kitts and Nevis. Both islands were former British colonies which gained their independence in 1983. The Nevis island economy is tourism and offshore banking services based, and is heavily dependent on imported goods and fuels.

Figure 1.1 Geographical location of St Kitts and Nevis (worldatlas 2015)

In similitude to other small island development states (SIDS), Nevis is prone to the negative environmental impacts of climate change such as rising sea levels and devastating tropical cyclones. However, along with the concerns of climate change, Nevisians are burdened with high electricity cost as the island largely depends on imported fossil fuels to power the economy and society. Presently the electricity tariff which includes a variable fuel surcharge averages $0.35 per kWh.
1.2 Nevis Island Electrical Utility Structure

The Nevis Electricity Company (NEVLEC) is a vertically integrated utility and is a wholly state owned subsidiary of the Nevis Island Administration (NIA). NEVLEC is the sole provider of electrical utility services on the island of Nevis. In 2010 NEVLEC entered into a power purchase agreement (PPA) with Wind Watt Nevis Ltd (WNL) which is an independent power provider (IPP) operating a 2.2 MW wind farm. Figure 1.2 illustrates the electrical utility structure of Nevis.

![Figure 1.2 The Nevis Island Electrical Utility Structure](image)

The island power system has the following key characteristics:

- 60 Hz mains frequency.
- Five overhead line (OHL) 11kV distribution feeders.
- Average peak daily load demand approximates 9MW (2011).
- Base load of approximately 5MW.
- Annual energy demand 57 GWh (2011).
• 13.3MW diesel power station owned by NEVLEC.

• 2.2 MW wind farm owned by WNL.

1.3 Nevis Island Load Profile

The Nevis island diurnal load profile typically follows the pattern as illustrated in Figure 1.3 with little seasonal variation. As the island is located within the tropics, peak power demands are observed during the summer months when there is increased usage of air conditioning systems. Figure 1.4 illustrates this pattern.

![Figure 1.3 Typical daily load profile of Nevis Island (NEVLEC 2011 data)](image-url)
1.3.1 Electricity Consumption by Sector

Sectoral consumption of electricity on Nevis is largely dominated by commercial/industrial activities which account for approximately 65% of the total system demand. Residential and street lighting account for the remaining 35% as illustrated in Figure 1.5.

Figure 1.4 Nevis Island Monthly Maximum Power Demand Profile (NEVLEC 2011 data)

Figure 1.5 Nevis Electricity Consumption by Sector (Espinasa.et.al 2015)
1.3.2 Net Generation Forecast

According to World Bank 2010 estimates, the projected net energy generation growth rate for Nevis was 5.2 percent per annum from 2009 to 2028 (Espinasa.et.al 2015).

Table 1.1 Nevis Island Projected Net Generation in GWh (Espinasa.et.al 2015)

<table>
<thead>
<tr>
<th>Year</th>
<th>Projected generation</th>
</tr>
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<tr>
<td>2015</td>
<td>94.3</td>
</tr>
<tr>
<td>2017</td>
<td>102.5</td>
</tr>
<tr>
<td>2019</td>
<td>110.6</td>
</tr>
<tr>
<td>2021</td>
<td>119.4</td>
</tr>
<tr>
<td>2023</td>
<td>128.9</td>
</tr>
<tr>
<td>2025</td>
<td>139.2</td>
</tr>
<tr>
<td>2027</td>
<td>150.2</td>
</tr>
</tbody>
</table>

Table 1.1 shows the projected net energy to be generated over this period as per the estimated rate of increase. However, actual figures of 2013 revealed that growth was slower than forecasted as net generation totalled 56 GWh for that year (Espinasa.et.al 2015).

1.3.3 Installed Generation Capacity Forecast

Based on the World Bank 2010 forecasts, it was projected that Nevis’ installed generation capacity would require expansion by the year 2015 (Espinasa.et.al 2015). However, due to a retardation in energy demand growth after the onset of the global financial crisis (GFC), the 2010 forecast has proven to be slightly too aggressive. Present day peak demand has not yet reached the projected 13MW which required 18MW installed capacity as shown in table 1.2.

Table 1.2 Nevis Island Projected Capacity Needs and Peak Demand in MW (Espinasa.et.al 2015)

<table>
<thead>
<tr>
<th>Year</th>
<th>Projected capacity needs</th>
<th>Projected peak demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>2017</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>2019</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>2021</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td>2023</td>
<td>29</td>
<td>21</td>
</tr>
<tr>
<td>2025</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td>2027</td>
<td>36</td>
<td>27</td>
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</tbody>
</table>
1.4 Description of the Nevis Island Wind Diesel System

The Nevis Island wind diesel system comprises of the NEVLEC owned Prospect Power Station (PPS) and the WNL Wind Farm which both contribute to a total island power system installed capacity of 15.5 MW. Figure 1.6 shows the layout of the system including the distribution network. As shown the wind farm is connected to an 11kV OHL distribution feeder.

![Figure 1.6 Nevis Island Wind Diesel Power System Layout (NEVLEC)](image-url)
Figure 1.7 shows the energy contribution of the wind farm and diesel plant to the island load demand for the period July 2010 to July 2011.

![Graph of electricity generation on Nevis July 2010-July 2011 (NEVLEC)](image)

Figure 1.7 Graph of electricity generation on Nevis July 2010-July 2011 (NEVLEC)

Since it’s commissioning the wind farm meets on average 8% of the islands’ annual energy needs. It has an average instantaneous power penetration of 24% of the instantaneous system peak demand and can reach a maximum of 40% during night time hours when system load is lowest.

1.4.1 NEVLEC Prospect Power Station

Since the inception of electrical utility services on the island of Nevis, medium speed diesel generators have been used for electric power generation. The existing power plant was commissioned in 1983 and has had incremental increases in installed capacity to reach the present day total installed capacity of 13.3 MW spread across six generators. Table 1.3 shows that the power station comprises of varying sized diesel generators from three different manufacturers. The generators also vary in age with the oldest and smallest installed in 1983 and the largest and most recent installed in 2002.
Table 1.3 NEVLEC Prospect Power Station diesel generator data (NEVLEC 2011)

<table>
<thead>
<tr>
<th>Diesel Plant</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Year of Commission</th>
<th>Expected year of retirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 3-900 kW</td>
<td>Mirrlees Blackstone</td>
<td>ESL-8-MKII</td>
<td>1983</td>
<td>2008</td>
</tr>
<tr>
<td>Generator 4-2200 kW</td>
<td>Mirrlees Blackstone</td>
<td>ESL-16-MKII</td>
<td>1989</td>
<td>2009</td>
</tr>
<tr>
<td>Generator 5-2500 kW</td>
<td>Mirrlees Blackstone</td>
<td>ESL-16-MKII</td>
<td>1996</td>
<td>2014</td>
</tr>
<tr>
<td>Generator 6-2500 kW</td>
<td>Mirrlees Blackstone</td>
<td>ESL-16-MKII</td>
<td>1995</td>
<td>2015</td>
</tr>
<tr>
<td>Generator 7-2500 kW</td>
<td>General Motors</td>
<td>16-645-HF4B</td>
<td>1997</td>
<td>2013</td>
</tr>
<tr>
<td>Generator 8-2700 kW</td>
<td>Wartsila</td>
<td>9R32LN</td>
<td>2002</td>
<td>2019</td>
</tr>
</tbody>
</table>

Table 1.3 also shows that most of the existing generator fleet is approaching, and in some cases already passed, their projected age of retirement. However, all generators are in active service.

**Plant Operational Characteristics**

Over the years, the Mirrlees Blackstone (MB) and General Motors (GM) gensets have become increasingly costly to operate due to increases in cost of spare parts, and decreases in efficiency in terms of fuel and lubrication oil consumption per kWh of energy generated.

To date, the Wartsila engine continues to be the most efficient genset meeting an average of approximately 40% of the islands’ energy demand, operating at an average load factor of 90.2%. Table 1.4 presents the operational characteristics of all the engines.

Table 1.4: PPS Generator operational characteristics (NEVLEC 2011)

<table>
<thead>
<tr>
<th>Diesel Plant</th>
<th>Average Loading (kW)</th>
<th>Average contribution to load (%)</th>
<th>Capacity Factor</th>
<th>Load factor</th>
<th>Average Fuel Efficiency (kWh/Litre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 3</td>
<td>412</td>
<td>1.1%</td>
<td>7.7%</td>
<td>45.8%</td>
<td>3.7</td>
</tr>
<tr>
<td>Generator 4</td>
<td>864</td>
<td>6.1%</td>
<td>16.8%</td>
<td>39.3%</td>
<td>3.2</td>
</tr>
<tr>
<td>Generator 5</td>
<td>1,398</td>
<td>14.8%</td>
<td>36.0%</td>
<td>55.9%</td>
<td>3.6</td>
</tr>
<tr>
<td>Generator 6</td>
<td>1,449</td>
<td>18.6%</td>
<td>45.1%</td>
<td>58.0%</td>
<td>3.9</td>
</tr>
<tr>
<td>Generator 7</td>
<td>1,862</td>
<td>19.8%</td>
<td>48.1%</td>
<td>74.5%</td>
<td>3.7</td>
</tr>
<tr>
<td>Generator 8</td>
<td>2,436</td>
<td>39.5%</td>
<td>88.7%</td>
<td>90.2%</td>
<td>4.6</td>
</tr>
</tbody>
</table>
Plant Operational Cost

Significant financial budgetary allocations have to be made towards the operation of the PPS with approximately 90% of the plant annual operating budget being allocated towards purchasing fuel and lubricants.

Plant Operation and Control

Since its commissioning in 1983, the PPS has had several advancements in the area of generator operation and control systems as new generators were added to the existing fleet. One of the key advancements has been from purely mechanical engine governing systems as shown in Figure 1.8 to using electronic governing systems as shown in Figure 1.9. In addition, improvements were made in the area of generator protective devices from utilising electromechanical relays to numerical and digital relays.

These advancements however, were not in the form of a retrofit of all generator systems to meet the latest industrial standard, but rather with each individual engine being installed as per the latest operation and control system being issued with the engine from the original equipment manufacturer (OEM). The Mirrlees engines use mechanical and electronic governors with generator 3 governed mechanically and generators 4 - 6 utilising electronic governors. Generators 7 and 8 have similarities in their control systems which utilise electronic governors interfaced with programmable logic controllers (PLC) human machine interfaces (HMI), and supervisory control and data acquisition (SCADA) systems.
Figure 1.8 Generator 3 Woodward UG-8 mechanical governor

Figure 1.9 Generator 8 Woodward 723 digital governor and ABB Unitrol AVR
To date no effort has been made to install a unified centralised automated control system to dispatch the PPS generators to meet the daily Nevis island power system load. The plant is therefore manually controlled on a 24 hour basis. Present day operation requires extensive operator input to regulate and manually adjust parameters for voltage, power-factor, active and reactive power as per changes in the power system demand.

In their daily tasks, the PPS power plant operators continuously monitor and adjust a combination of analogue displays and controls as shown in Figures 1.10 and 1.11 along with digital HMI systems and controls as shown in Figure 1.12.

*Figure 1.10* Generator 6 analogue power parameter displays

*Figure 1.11* Generator 6 manual power factor control
Disadvantages of manual operation

Continuous monitoring and adjustment of generator parameters throughout an eight hour shift places significant stresses on the operator. When needing a break, the operator must ensure that there is sufficient online capacity to absorb any sudden decreases in wind farm output. The operator then overcompensates for such changes while away by increasing online spinning reserve.

Generator Dispatch

With the exception of planned or forced outages, the normal genset priority dispatch to meet island load is as follows:

- Generator 8 operates in fixed kW mode with a normal set point of 2,500 kW.
- Generator 7 is loaded with the remaining load from generator 8, with an average loading as shown in Table 1.4.
- Generator 6 is loaded with the remaining load from generators 7 and 8 with an average loading as shown in Table 1.4.
Generators 5 to 3 are brought online and loaded as needed throughout the day as per the daily load profile illustrated in Figure 1.3.

The dispatch scheme as described is adjusted to cover load variations as per the daily load profile and the wind farm power variations if it is in operation. In all cases 100% of the wind farm output is covered by online diesel generator spinning reserve. Due to the sizing of the generators, often there can be more spinning reserve capacity online than actually needed.

1.4.2 WNL Wind Farm

In July 2010, the WNL 2.2MW grid-tied wind farm was commissioned on the island of Nevis. To date, this wind farm is the only grid-tied renewable energy generator on the island. For the year 2011 the 2.2MW wind farm operated at a capacity factor of 24.8%. Figure 1.13 shows that the wind farm is located on a NIA owned cattle paddock in Maddens Estate on the South Eastern coast of the island. Figure 1.14 shows that the wind farm faces the prevailing wind direction.

![Figure 1.13 Nevis wind farm and cattle paddock at Maddens Estate (Jargstorf 2011)]
Wind Farm Specifications

The WNL Wind Farm consists of eight Vergnet 275kW GEV MP C wind turbine generators. The Vergnet GEV is a downwind 2 bladed wind turbine generator (WTG) with a 2 stage planetary gearbox attached to a 2 speed asynchronous squirrel cage induction generator (SCIG). Figure 1.15 shows the dimensions and structure of the Vergnet GEV WTG.
Figure 1.16 shows the power curve of the Vergnet GEV turbine at a standard air density of 1.225 kg/m³. As shown the turbine has a cut in speed of 3.5 m/s and a cut out speed of 25 m/s. Aerodynamic braking through pitch regulation is used to prevent rotor overspeed, and allow rapid stoppage of the turbine if needed (Vergnet 2015).
As Nevis lies within the tropical region which is prone to hurricanes during the months June to November, the Vergnet GEV WTG was chosen due to its titling mast functionality which allows the WTG to be lowered into a prone position and strapped to the ground when a hurricane is approaching the island.

**Figure 1.16** Vergnet GEV MP C 275 kW wind turbine power curve  (Vergnet 2015)

**Figure 1.17** Vergnet WTG in lowered position at WNL wind farm Nevis (Jargstorf 2011)
Figure 1.17 shows one of the turbines in the prone position. According to the Vergnet technical description (See Appendix A) the turbines can withstand wind speeds up to 85 m/s in the lowered position.

Active power regulation is achieved through hydraulic blade pitch control and each turbine has a capacitor bank to provide reactive power adjustment. Each turbine is also equipped with a soft starter to reduce in-rush currents as the induction generator starts operating. A detailed technical description of the Vergnet GEV WTG can be viewed in Appendix A.

1.5 Problems with The Existing Nevis Island Wind Diesel System

The power purchase agreement (PPA) between NEVLEC and WNL allows for 2.2MW of wind power to be fed into the grid depending on load conditions, diesel spinning reserve and the grid stability impact of the wind power. So far the operation of the Nevis Island wind diesel system faces two main challenges, as outlined below.

1.5.1 Frequency Instability

Fixed speed WTG’s such as the Vergnet GEV have their rotor speed determined by the grid supply frequency, gear ratio and generator design, thus the rotor speed remains within a fixed operational range irrespective of the wind speed (Hansen 2012).

Use of these type of turbines provides advantages as they are tried and proven, cost effective, simple and of a robust design. However, fixed speed induction generator wind turbines have the disadvantages of limited power quality control, uncontrollable reactive power consumption and large mechanical stresses on components. In addition due to their fixed speed operation, fluctuations in wind speed produce fluctuations in mechanical torque and electrical power output which can lead to large voltage and frequency fluctuations in weak electrical grids (Hansen 2012).
To date, the Nevis Island wind-diesel system has had instances where undesirable fluctuations in power grid frequency resulted in the curtailment of the wind farm output by the NEVLEC SCADA operator.

1.5.2 Aged Diesel Engines

In many cases such as in Western Australia, wind diesel systems are able to achieve high wind power penetration through the utilisation of automated low load diesel (LLD) generators. In the Nevis wind diesel system however, the existing engine diesel technology results in the wind farm output being curtailed for several reasons:

1. With no energy storage present in the existing system, any reduction in wind farm output has to be compensated for by diesel generators at the PPS to continue meeting the island loads. Starting, synchronizing and loading the existing diesels under the present manual operating scheme, averages approximately 3 minutes. If reductions in wind farm output cannot be compensated for by diesels already online, the NEVLEC power system will experience an underfrequency situation. Considering that the present underfrequency load shedding settings are at 57 Hz for 2 seconds, it is highly likely that not running sufficient spinning reserve to cover the wind farm can result in underfrequency load shedding. One down side of this conservatism, is that possible diesel savings are not fully realised.

2. In addition, as diesels must be operated above their minimum loadings to avoid adverse effects of bore glazing which would reduce performance and shorten maintenance intervals, the wind farm is often curtailed to maintain diesel engine loadings above their minimum value.

1.5.3 Reliance on Manual Control

As outlined in section 1.4.1, the PPS operates with a combination of modern and legacy diesel generator control systems which are all manually tuned. An operator cannot adjust diesel generator power parameters as fast as computer and PLC based systems can, hence with the wind farm attached to the
grid, there will be occurrences of frequency variations until diesel generators set points are modified to
regain stability.

1.6 Formulation of Research Questions

Based on the challenges being experienced in the operation of the Nevis Island wind diesel system as
described in section 1.5, the following thesis research questions were formulated:

I. How can the existing Nevis Island wind diesel system be improved to realise increased wind
   energy penetration and reduced diesel fuel consumption?

If time permitted, the dissertation project would have then proceeded to a second stage and seek answers
to the following question:

II. Should Nevis Island invest in more wind farms and allow grid-tied solar PV rather than
    increasing diesel generation to meet future electricity demands?

If time permitted, the dissertation project would then have proceeded to a third stage and seek answers
to the following question:

III. What infrastructural, regulatory and operational implementations would be needed in the
    Nevis power system to permit more wind farms and grid connected solar PV?

1.7 Research Methodology

The project research followed the methodology outlined below and as illustrated in Figure 1.18:

- **Stage 1**: Formulation of research questions.
- **Stage 2**: Hourly average load data for the year 2011 was obtained from NEVLEC and analysed in
  Excel to determine operational patterns.
- **Stage 3**: Hourly average wind data for the Maddens Estate site was obtained from NREL with the
  help of Mr. Angus King from Sustainable Energy Now (SEN) Australia.
- **Stage 4**: Literature review and case study analysis of wind diesel systems was conducted to find solutions to increasing wind penetration.

- **Stage 5**: Conducted literature review of hybrid energy optimisation software to perform energy flow analysis.

- **Stage 6**: Simulations of the Nevis Island wind diesel system performed in HOMER to observe system technical and economic performance with various changes in technology.

*Figure 1.18 Flow chart of research methodology*
1.8 Limitations

Financial data with respect to fuel, operation and maintenance and other general cost associated with the operation of the NEVLEC PPS were not made available for this research project. In addition, financial data for the WNL Wind Farm capital and operational cost was not made available.

Attempts were made to obtain capital cost estimates from certain original equipment manufacturers (OEM) of the various technologies utilised in high penetration wind diesel systems. These costs were not made available, hence the project simulations conducted in section three do not perform an economic feasibility and cost benefit analysis for the various options but rather focuses on increasing the renewable energy penetration levels and savings in diesel fuel.

Also the project does not include an analysis of measurements of the Nevis Island power system frequency fluctuations induced by the wind farm as such measurements were not available.
2 Chapter Two: Literature Review

2.1 Frequency Control in Power Systems

**Primary and secondary frequency control**

Primary and secondary frequency control are used to restore power system frequency to normal operation after an imbalance has occurred between production and consumption.

Primary frequency control relates to the ability of a power system to maintain an instantaneous balance between supply and demand within a time frame of 1-30s. Wind turbines do not contribute to primary frequency control reserve margins as they cannot retain rotational energy for later utilisation if there is a sudden decrease in wind. Hence, as power system frequency fluctuations occur as a result of an imbalance between power supply and demand, wind power generation increases the need for primary control reserve margins to counteract the frequency variations which wind power introduces into the power system (Soder 2012). In instances of frequency instability, primary control units increase or decrease their power output until frequency has been stabilised and the balance between production and consumption has been restored (Matevosyan 2012).

Secondary frequency control relates to the ability of a power system to maintain the balance between supply and demand after primary control events and extending up to a period of one hour. In the event of a decrease in wind power, primary control reserve margins would be used up and, if frequency stability has not been restored within the primary control margin, the system frequency would rapidly degrade unless secondary reserve margins are rapidly ramped up or brought online. Wind power does not contribute to secondary control margins but rather creates the need for additional secondary reserves as variations in wind power output are continuous (Soder 2012).
Wind farms are not capable of contributing to primary and secondary frequency control in the same manner as conventional thermal power plants. However, some electrical utilities such as the Electricity Supply Board National Grid (ESBNG) in Ireland require wind farms to have primary frequency control capabilities of 3-5% and also be able to participate in secondary frequency control. As wind is an uncontrollable resource, during instances of overfrequency, pitch control or shutting down turbines can contribute to primary and secondary frequency control (Matevosyan 2012).

Due to the lack of technical regulations to govern wind farm operations on Nevis, WNL was not required to provide primary or secondary frequency control while connected to the NEVLEC grid. The present day operational regime whereby NEVLEC operators adjust the wind farm output via the SCADA to maintain power system stability, was implemented due to frequency instability experiences after the commissioning rather than a technical stipulation. The PPA did not explicitly state that NEVLEC will be allowed to reduce the wind farm output via SCADA, if the wind farm operation is deemed disruptive to normal grid and diesel power plant functioning.

2.2 Methods for Improving Grid Frequency Stability in Wind Diesel Systems

2.2.1 Variable speed wind turbines

In an autonomous wind diesel power systems, the frequency is normally not as stable as that of a large interconnected grid due to limited online spinning reserve. Consequently sudden increases or decreases in wind will affect the power balance and result in frequency variations. However, frequency stability in wind diesel systems can be significantly improved through the use of variable speed wind turbines (Ackermann 2012).

Although variable speed turbines are a proven solution to improving frequency stability in wind diesel systems, for this project analysis, consideration has been given to the fact that the existing fixed speed Vergnet WTG’s were commissioned on Nevis in 2010 and with an estimated life span of 20 years and with
an existing 20 year PPA between NEVLEC and WNL, it is unlikely that these turbines will be replaced in the near future. The project analysis therefore accepts variable speed turbines as a valid solution but will further investigate other options that can work with the existing fixed speed turbines to improve frequency balance of the Nevis Island wind diesel system.

2.2.2 System Automation

A hybrid energy system such as the Nevis Island system that has no unified automation and control system, has the typical architecture as illustrated in Figure 2.1. Hybrid energy system automation interfaces the controllers of each energy producing component such as the diesel engine governor and wind turbine pitch control with a centralised controller which monitors the power quality parameters and adjusts each energy system power outputs to adhere to power quality standards.

![Figure 2.1](image)  
*Figure 2.1 Typical configuration of Hybrid energy system without automation and storage (Zimmerman 2014)*

Figure 2.3 illustrates a conceptual layout of an automated hybrid energy system that utilises the ABB MGC600 series of PLC’s (as shown in Figure 2.2) to interface the various energy system components with a central SCADA system.
Automating a wind diesel energy system provides the benefits of automatic power control and optimisation of renewable energy and diesel plant while significantly improving grid stability (Zimmerman
OEM suppliers of hybrid energy automation systems such as ABB and Siemens, are able to retrofit to existing diesel power plants and tailor the system according to customer requirements. Such installations now offer a web page based control interface enabling SCADA operators and system engineers to easily modify the system configuration. Figure 2.4 shows a screen shot from an example of a hybrid energy system automated control interface.

**Figure 2.4 Screen shot from an automated wind diesel system (Zimmerman 2013)**

### 2.2.3 Energy Storage Systems

Along with automated system dispatch, incorporating energy storage systems (ESS) into wind diesel and solar PV systems can provide grid stabilisation by reducing frequency and voltage fluctuations resulting from rapid changes in wind and solar resources.
Figures 2.5 and 2.6 illustrate how the ESS improves grid stability by absorbing excess energy that would otherwise cause system frequency rise, which can later be injected into the grid to provide frequency and voltage support when the wind variable resource decreases. The ESS is normally sized to maintain system frequency and voltage until diesel power compensates for the renewable resource reduction. Figure 2.6 also shows that the ESS provides load levelling throughout the day as demand changes.
Figures 2.7 and 2.8 illustrate the components and configurations of the ABB “PowerStore” battery and flywheel ESS, that have been used in high penetration wind diesel systems around Australia such as at Coral Bay and Denham. These energy storage devices have also been used in high penetration solar PV diesel systems at Marble Bar and Nullagine in Western Australia.
Figure 2.7 Grid stabilising system – ABB Power Store Li Ion Battery system (Luyster 2014)

Figure 2.8 Grid stabilising system – ABB Power store Flywheel System (Luyster 2014)

Figure 2.9 shows a snapshot of the grid stabilisation response of the Coral Bay “PowerStore” flywheel ESS. As shown the wind speed constantly fluctuates between 6.4 and 7 m/s over the snapshot five minute period. It can be seen that the ESS charges and discharges power from and into the grid to mitigate the impact of wind variation on grid stability.

Advances in ESS technology such as the ABB “PowerStore” enable storage systems to provide additional power quality improvement functionality including; voltage reference for renewables only mode, step load capabilities, fault ride through, voltage control, frequency control, spinning reserve and grid forming (Luyster 2014).
The benefits provided by energy storage are evidenced by several hybrid energy systems around the world that have been able to achieve high renewable energy penetration while maintaining grid stability. Table 2.1 presents the performance of several hybrid energy systems around Australia and other parts of the world, where it can be seen that the systems that have achieved the highest levels of renewable energy penetration, utilised either battery or flywheel energy storage technology.
### Table 2.1 ABB On and Off grid Micro grid Technology Reference list (Zimmerman 2014)

<table>
<thead>
<tr>
<th>Wind/Diesel Power Stations (11)</th>
<th>Country</th>
<th>wind / solar/other</th>
<th>power/ renewable/kW</th>
<th>Microgrid Plus System</th>
<th>PowerStore Battery or Flywheel</th>
<th>Peak renewable penetration</th>
<th>Customer / Operator</th>
<th>Year of start of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denham</td>
<td>AU/WA</td>
<td>Wind</td>
<td>4x250/330</td>
<td>x</td>
<td></td>
<td>90%</td>
<td>Verve Energy</td>
<td>2004</td>
</tr>
<tr>
<td>Rottnest Island</td>
<td>AU/WA</td>
<td>Wind</td>
<td>600</td>
<td>x</td>
<td></td>
<td>85%</td>
<td>Rottnest Island board</td>
<td>2005</td>
</tr>
<tr>
<td>Coral Bay</td>
<td>AU/WA</td>
<td>Wind</td>
<td>3x220</td>
<td>x</td>
<td></td>
<td>95%</td>
<td>Verve Energy</td>
<td>2008</td>
</tr>
<tr>
<td>Ross Island</td>
<td>Antarctica</td>
<td>Wind</td>
<td>3x330</td>
<td>x</td>
<td></td>
<td>60%</td>
<td>Mandalin Energy</td>
<td>2010</td>
</tr>
<tr>
<td>Flores</td>
<td>Azores</td>
<td>Wind</td>
<td>2x330</td>
<td>x</td>
<td></td>
<td>100%</td>
<td>EDA</td>
<td>2006 &amp; 2010</td>
</tr>
<tr>
<td>Graciosa</td>
<td>Azores</td>
<td>Wind</td>
<td>2x330</td>
<td>x</td>
<td></td>
<td>80%</td>
<td>EDA</td>
<td>2006</td>
</tr>
<tr>
<td>Mawson</td>
<td>Antarctica</td>
<td>Wind</td>
<td>2x330</td>
<td>x</td>
<td></td>
<td>90%</td>
<td>Australian Antarctica Div</td>
<td></td>
</tr>
<tr>
<td>Esperance</td>
<td>AU/WA</td>
<td>Wind</td>
<td>15x225/600</td>
<td>x</td>
<td></td>
<td>35%</td>
<td>Verve Energy</td>
<td>2004</td>
</tr>
<tr>
<td>Hopetown</td>
<td>AU/WA</td>
<td>Wind</td>
<td>600</td>
<td>x</td>
<td></td>
<td>85%</td>
<td>Verve Energy</td>
<td>2008</td>
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<td>Bremer Bay</td>
<td>AU/WA</td>
<td>Wind</td>
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<td>x</td>
<td></td>
<td>85%</td>
<td>Verve Energy</td>
<td>2005</td>
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<td>Faial</td>
<td>Azores</td>
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<td>5x650</td>
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<td>40%</td>
<td>EDA</td>
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<td><strong>Solar PV/Diesel Power Stations (2)</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Marble Bar</td>
<td>AU/WA</td>
<td>PV</td>
<td>300</td>
<td>x</td>
<td></td>
<td>100%</td>
<td>Horizon Power</td>
<td>2011</td>
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<tr>
<td>Nuligine</td>
<td>AU/WA</td>
<td>PV</td>
<td>200</td>
<td>x</td>
<td></td>
<td>100%</td>
<td>Horizon Power</td>
<td>2011</td>
</tr>
<tr>
<td><strong>Other Renewable (1)</strong></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Legion House, Sydney</td>
<td>AU/NSW</td>
<td>Syngas</td>
<td>200</td>
<td>x</td>
<td></td>
<td>100%</td>
<td>KLM/Groco</td>
<td>2013</td>
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<tr>
<td><strong>Other Microgrid Stabilisation and Energy Storage (5+)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leinster Nickel Mine</td>
<td>AU/WA</td>
<td>Peak Lopping</td>
<td>x</td>
<td>x</td>
<td></td>
<td>BHP</td>
<td>2004</td>
<td></td>
</tr>
<tr>
<td>Zurich, Battery smoothing</td>
<td>Switzerland</td>
<td>PV</td>
<td>x</td>
<td>x</td>
<td></td>
<td>EKZ</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>Long Island, Gas station</td>
<td>US/NY</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td></td>
<td>NYPA</td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>La Gomera, Stabilisation</td>
<td>Spain</td>
<td>Wind</td>
<td>x</td>
<td>x</td>
<td></td>
<td>Unesco Endossa</td>
<td>2013</td>
<td></td>
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<tr>
<td>La Palma, Stabilisation</td>
<td>Spain</td>
<td>Wind</td>
<td>x</td>
<td>x</td>
<td></td>
<td>RIE</td>
<td>2013</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Case Study of the Coral Bay Wind Diesel System in Western Australia

Coral Bay uses the same type of wind turbines as the Nevis island wind diesel system and with the combination of several technologies identified in section 2.2 of the literature review, has been able to obtain a peak wind power penetration of 95% as identified in Table 2.1.

The Coral Bay wind diesel system utilizes an innovative approach of increasing wind penetration through a combination of intelligent automation, advanced diesel engine technology, energy storage and refined wind turbine blade pitch control. The combined optimised functioning of all system components results in a continuous electricity supply, with voltage and frequency stability meeting the power quality requirements of the regional electricity utility Horizon Power.
2.3.1 Coral Bay Wind Diesel System Structure

The system is comprised of seven containerised Detroit 320 kW “low load” diesels (LLDs) generators, three Vergnet 275 kW wind turbines and a 5 kWh 500 kW kinetic energy storage unit (Verve-Energy 2007). LLDs is a terminology and concept developed by Power Corp (now ABB) in Darwin Australia, which describes diesel generators that are optimised for running at loads of 10% or less to avoid curtailing wind power penetration in wind diesel systems.

Automated control of the energy storage, power generation and feeder management systems is provided by the Station Management System (SMS) which optimises the interfacing of consumer loads with the power supply according to design and operational requirements and constraints. Figure 2.10 illustrates the Coral Bay automated system key control node points.

---

**Figure 2.10 Structure of the Coral Bay Wind Diesel Automation System (Verve-Energy 2007)**

The control nodes of the automated system as illustrated in Figure 2.10 serve the following functions (Verve-Energy 2007):

- **Station Management System (SMS)**: Governs and interfaces with all other control nodes of the power system to achieve automated functionality according to the system operational configurations and parameters.
- **Black Box Interface (BBI):** Controls the operation of the WTGs and kinetic energy storage system.

- **Generator Supervisory system (GSS):** Schedules the operation of the LLDs to meet consumer loads.

- **Boiler Grid Interface (BGI):** Dynamic dump load assisting in frequency and power regulation.

- **Feeder Management System (FMS):** Controls low voltage (LV) feeder circuit breakers connecting to consumer loads.

2.3.2 Frequency and Voltage Regulation

Utilization of wind energy characteristically involves the issue of variability in wind power supply due to the stochastic nature of the wind resource. This variability can be translated into grid voltage and frequency fluctuations due to incurred mismatching of energy supply to load demands.

Frequency regulation of the Coral Bay wind diesel system complies with the Horizon Power frequency control standards with steady state limits of ± 1Hz, transient limits of ± 5 Hz, returning to and staying within ± 1Hz after 5 seconds. The power station LV busbar is operated at 480V with a ±1% steady state limit and ±4% transient limit (Verve-Energy 2007).

In the case of the Nevis Island power system, operational voltage and frequency steady state and transient limits are not as clearly stipulated as is the case in Western Australia. To date the Nevis Island electrical ordinance that has been in operation since the inception of electrical power on the island, has not been ratified to stipulate power quality requirements for grid tied distributed power generators and IPPs.

Several mechanisms contribute to frequency and voltage regulation in the Coral Bay operation:
- **Isochronous frequency control:** The LLDs are operated in isochronous control therefore as wind power output increases the diesels reduce power to maintain dynamic system frequency variations within limits and steady state frequency at 50 Hz.

- **Energy storage unit:** Short term fluctuations in wind turbine power output are smoothed by the kinetic energy storage unit acting as an energy buffer. During periods of wind energy bursts, the unit absorbs the excess wind energy which it can later export to the load during lulls of wind.

- **Dynamic dump load:** In the event of a sudden wind gust providing excess energy beyond the buffering capacity of the kinetic energy storage device, an inverter controlled 100 kW resistive device can be ramped on over one second to prevent the LLDs from going into reverse power.

- **Blade Pitching:** By using a rapid response blade pitch control algorithm, the Vergnet wind turbines are able to vary blade pitch in an effort to maintain power and frequency set points as best as possible and minimize over or undershoot during wind gusts. Although by itself this may not be capable of providing adequate frequency stability, when operated in tandem with the above mentioned power and frequency control mechanisms, the overall result is a wind diesel system that meets the Horizon Power requirements for power quality.

Based on the case study of the Coral Bay wind diesel system, it is likely that these four key frequency control mechanisms in conjunction with an automation system, which have allowed Coral Bay to achieve high levels of wind penetration, can be used to achieve similar results in Nevis.
2.4 Improvements in Diesel Engine Technology

Diesel generators are a reliable effective source of electric power generation that are ubiquitous in global utilization. They are scalable in size, robust and reasonably cost effective. In recent years the global push towards averting the negative impacts of climate change on the environment has resulted in diesel engine manufacturers increasing investment in research and developing into methods of improving diesel engine part load and full load efficiencies while reducing NOx and SOx emissions. Additionally with increasing global utilisation of wind diesel and solar PV hybrid energy systems, diesel generator OEMs have adapted to the need for engines and generators that can work well with variable renewables, and are now supplying diesel generators that have good part load efficiencies, dual fuel flexibility and rapid start functionality.

Wartsila is one such diesel engine manufacturer who is continuously working to further improve the efficiency and environmental performance of their diesel engines (Wartsila 2015b). Extensive research and testing has led to the development of combustion chambers capable of withstanding higher cylinder temperatures and pressures. This development of advanced combustion cylinder technology in conjunction with research and development of two stage turbocharging has contributed to the production of fuel efficient environmentally sound diesel engines (Wartsila 2015a). Figure 2.11 shows the fuel efficiency improvement of Wartsila engines from 1960 to 2014. Additionally, Wartsila has developed a portfolio of engine based power plants that have fast start up and high ramping capabilities, and can therefore contribute to power system frequency stability by providing primary and secondary reserve power faster than conventional power plants (Dekker.et.al 2012).
2.4.1 Two Stage Turbocharging

Two stage turbocharging as illustrated in Figure 2.12 utilises high and low pressure turbochargers that function according to the engine loading. Under low load conditions the modulating high pressure turbine bypass valve and the high pressure compressor bypass valves open thereby allowing the low pressure turbine and compressor to operate only. Under high load conditions the bypass valves close thereby operating the high pressure and low pressure turbines sequentially.
Utilising series-sequential arranged turbocharging systems on diesel engines offer the benefits of increases in boost pressures, improved low speed torque and reduced turbocharger lag in comparison to single turbocharged system (Sweetland and Schmitt 2004).

**Figure 2.12** Illustration of Two Stage Turbo Charging (Jääskeläinen 2013)

**Figure 2.13** Comparison of Diesel Engine performance with Single and Two Stage Turbocharger Arrangements (Jääskeläinen 2013)
Figure 2.13 illustrates that higher brake mean effective pressures (BMEP) can be achieved with two stage turbo charging systems at lower RPMs, which results in improvement in torque over a range of engine speeds and improved dynamic response to load changes. This flexibility and improvement in operation over a range of loads allows for improved fuel economy, better power density and lower emissions of diesel engines (Codan and Huber 2012).

Two stage turbocharging could be considered a technological option for improving the performance of the existing Nevis island wind diesel system, whereby retrofitting the existing engines with two stage turbo chargers could allow for loading flexibility and achieve improved fuel economy and combustion performance under low load conditions. However, considering that the present diesel engine fleet is significantly in need of replacement as shown in Table 1.3, it would be best to replace these diesel generators with new and improved diesel engines that have improved part load efficiencies and fuel economies such as the newer Wartsila engines now on the market.

2.5 Summary of Investigation Grid Stability Improvements for Wind Diesel Systems

The literature review and case study investigation into methods of improving grid stability in wind diesel systems shows that all high penetration wind diesel systems that are presently in operation in Australia and other parts of the world, utilise some or all of the following key technologies:

- Unified automated control of all components
- Energy storage systems for grid stabilisation
- Advanced diesel engine technology
- Automated load control
- Wind turbine blade pitch control

Table 2.2 illustrates that renewable energy annual average contribution and peak power penetration increases significantly with the inclusion of automation and energy storage components.
Table 2.2 Impact of Various Hybrid Energy System Integration Technologies on Renewable Energy Penetration (Luyster 2014)

<table>
<thead>
<tr>
<th>Wind/Solar/Diesel Systems</th>
<th>Annual Average Contribution</th>
<th>Peak Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Integration</td>
<td>7%</td>
<td>20%</td>
</tr>
<tr>
<td>Automated Dispatch (MGC600)</td>
<td>10%</td>
<td>22%</td>
</tr>
<tr>
<td>Grid Stabilizing (PowerStore)</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>Automated Demand Response</td>
<td>60%</td>
<td>100%</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Presently the Nevis Island wind diesel system does not include any of these components. Hence Chapter three of this report details a system simulation analysis that was performed using HOMER to investigate the possible impacts of including some of these technologies into the Nevis wind diesel system.

2.6 Considerations for Increasing Wind Generation Capacity on Nevis Island

Holttinen et al. note that there are no technical limits to the integration of wind power into an electricity grid, however, with increases in wind capacity, measures must be taken to ensure that variations in wind power do not compromise the reliability of a power system. They further state that increasing wind power penetration beyond 10 percent increases the economic impact on operation of a power system (Holttinen 2012).

Assimilation of wind power into a power system can be influenced by the system size, mix of power generation technology and demand load profile. If the proportion of wind power production is small and spread over a wide geographical area, integration of wind power becomes easier as geographical diversity in the wind resource will increase predictability and decrease the likelihood of near zero or peak wind output (Holttinen 2012). However, on small island grids such as Nevis, there is not enough geographical diversity in wind resources to achieve a reduction in the likelihood of zero wind power output occurrences.
Furthermore the current wind diesel system topology and mismatch of technology, provides no incentive to increasing installed wind power capacity, as the issue of curtailing wind power to maintain grid stability and load on the existing diesel engines has not been eliminated. Therefore, significant technological modifications to the existing Nevis Island wind diesel system would be required, before making increasing wind power generation capacity a worthwhile investment.

2.6.1 Wind Resource Assessments

For several decades, international lending agencies and institutions such as the USAID have been conducting wind energy potential assessments in various Caribbean islands. Table 2.3 summarises the findings of four different organisations that conducted investigations into potential wind energy utilisation on the island of Nevis. Between 1984 and 2000, eleven potential sites on the island were identified and assessed. By 2006 the majority of these sites were occupied by residential dwellings and therefore are no longer suitable for wind park development (Jargstorf 2011). As the island is only 36 square miles in area, land usage for housing and agriculture supersedes that for developing wind farms.

*Table 2.3 Proposed Nevis Island Wind Park Sites from Wind Energy Missions 1984 – 2000 (Jargstorf 2011)*

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of Location</th>
<th>Elevation</th>
<th>Annual Wind Speeds</th>
<th>Remarks</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zetlands</td>
<td>310 m</td>
<td>8.5 m/s in 10 m</td>
<td>site now with housing</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Cole Hill</td>
<td>300 m</td>
<td>8.0 m/s in 10 m</td>
<td>site now with housing</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Indian Castle</td>
<td>30 m</td>
<td>6.7 m/s in 10 m</td>
<td>directly on the coast</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Newcastle</td>
<td>20 m</td>
<td>6.8 m/s in 10 m</td>
<td>Airport</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Cole Hill</td>
<td>300 m</td>
<td>8.0 m/s in 10 m</td>
<td>8 x 30 kW AEROMAN</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Cole Hill</td>
<td>300 m</td>
<td>8.0 m/s in 10 m</td>
<td>site now with housing</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Zetlands</td>
<td>310 m</td>
<td>8.5 m/s in 10 m</td>
<td>site now with housing</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Indian Castle</td>
<td>30 m</td>
<td>6.7 m/s in 10 m</td>
<td>directly on the coast</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Beaumont</td>
<td>900 m</td>
<td>8.9 m/s in 10 m</td>
<td>site now with housing</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>New River</td>
<td>40 m</td>
<td>6.5 m/s in 30 m</td>
<td>23 x 60 kW GEV 15/60</td>
<td>16.5%</td>
</tr>
<tr>
<td>11</td>
<td>Potwork</td>
<td>20 m</td>
<td>7.6 m/s in 30 m</td>
<td>48 x 60 kW GEV 15/60</td>
<td>21.6%</td>
</tr>
</tbody>
</table>
Figure 2.14 Cross Section of Nevis Island Showing Location of Potential Wind Park Sites (Jargstorf 2011)

The North to South cross section of the island as shown in Figure 2.14, illustrates that areas which are at higher elevations with flat terrain (and thus would be suitable for wind park development) are presently all densely populated. Other good sites are located in hilly regions which would prove challenging for wind farm development.

In 2006 a wind energy study conducted by the Caribbean Renewable Energy Development Program (CREDP) identified four other potential wind farm sites of which Maddens Estate was considered to be the most promising (Jargstorf 2011). Wind speeds at this site averaged 7.6 m/s at 30m above ground.

The Maddens Estate site has been a long standing government owned cattle paddock. However, with the wind farm being able to co-exist with the cattle as illustrated in Figure 1.13, WNL was able to utilise Maddens Estate for developing a wind farm.

The conclusion that can be drawn from these wind resource assessments is that although the island has several sites with a good wind resource, due to the majority of the land space at these sites being presently occupied by residential dwellings, there is limited scope for large scale wind power generation capacity on the island of Nevis.
2.7 Considerations for Grid-Tied Solar PV on Nevis

Figure 2.15 shows the solar map of St Kitts and Nevis. Both islands have good solar resources with a global horizontal irradiation (GHI) value averaging in the excess of 5.7 kWh/m²/day, thus the low lying areas of the islands are suitable for solar PV and solar hot water systems. However, the direct normal irradiation (DNI) resource is significantly less than the GHI, which is an indicator that concentrated solar would perform poorly in this region (LCCC 2011).

Although the island has a good solar resource, there has not been a major uptake in solar PV systems for several reasons. These include:

- There are no incentivising mechanisms such as rebate schemes or feed-in tariffs to stimulate investment into solar PV by average households.
- NEVLEC has not established technical regulations to govern connection of solar PV systems to the existing grid.

![Solar Resource Maps of St Kitts and Nevis (LCCC 2011)](image)

*Figure 2.15 Solar Resource Maps of St Kitts and Nevis (LCCC 2011)*
Figure 2.16 shows that St Kitts and Nevis are amongst several other countries in the Caribbean Community (CARICOM) that presently do not have grid interconnection policies in place for distributed renewable power generators. Until these challenges are addressed, the NIA remains best suited to reap the benefits of introducing roof top solar PV or a solar farm in Nevis. Although NEVLEC is owned by the NIA, monthly electricity consumption by government buildings such as schools has to be paid for. Hence installing roof top solar PV on government buildings provides a suitable opportunity for NEVLEC and the NIA to learn how this technology can impact grid performance while developing standards and regulations to govern grid-tied PV systems on the island.

**Figure 2.16 Status of Distributed-Scale Grid Interconnection Policies in Caribbean Community (CARICOM) Countries (Samuel 2013)**
2.8 Use of Computer Simulations in Optimizing Hybrid Renewable Energy Systems

A Hybrid energy system is one which incorporates two or more electric power generation technologies such as wind turbines and diesel-electric generators (Sinha and Chandel 2014). These systems provide several advantages over those based on a single technology including:

- Better reliability
- Higher efficiencies
- Reduced energy storage capacity especially where different sources have complementary behaviour (Sinha and Chandel 2014).
- Minimum levelized life-cycle electricity generation cost, when optimum design technique is used (Sinha and Chandel 2014).

All of the above listed benefits, present attractive financial incentives for power generators to hybridize their power generation asset base. However, as outlined by Sinha and Chandel, such benefits are realized with the application of optimization techniques to the system design.

The development and utilization of hybrid renewable energy systems (HRES) is a complex discipline that requires in-depth economic and technical analysis, to ensure the system design performs satisfactorily to justify investment. Present day renewable energy modelling software packages provide tools that enable this feasibility analysis to be performed and allow for eliciting the optimal design that would meet project technical requirements and economic expectations while increasing the utilization of renewables.

The performance of the individual HRES components can be modelled by either probabilistic or deterministic approaches (Deshmukh and Deshmukh 2008).
2.9 Review of Various HRES Modelling Software

In their analysis of nineteen popular renewable energy modelling software, Sinha and Chandel present a comprehensive comparative review of the global utilisation of those software. Of the nineteen software packages, the advantages and disadvantages of four popular freely available software are assessed as shown in Table 2.4. As shown each software has its relative merits and demerits, however, as programs such as RETScreen and HOMER are continuously updated and improved, they provide a useful platform for launching a feasibility analysis into an optimal hybrid renewable energy system design.

Table 2.4 Comparative Analysis of Freely Accessible Renewable Energy System Modelling Software (Sinha and Chandel 2014)

<table>
<thead>
<tr>
<th>Softwares</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOMER</td>
<td>User friendly</td>
<td>“Black Box” code used</td>
</tr>
<tr>
<td></td>
<td>easy to understand</td>
<td>first degree linear equations based models used</td>
</tr>
<tr>
<td></td>
<td>provides efficient graphical representation of results</td>
<td>time series data in a form of daily average can’t be imported</td>
</tr>
<tr>
<td></td>
<td>hourly data handling capacity</td>
<td></td>
</tr>
<tr>
<td>RETScreen</td>
<td>Strong product database and meteorological database from NASA only</td>
<td>No time series data import options</td>
</tr>
<tr>
<td></td>
<td>financial analysis is the main strength</td>
<td>less data input options</td>
</tr>
<tr>
<td></td>
<td>easy to use as it is EXCEL based software</td>
<td>limited options for search, retrieval and visualization features</td>
</tr>
<tr>
<td>HYBRID 2</td>
<td>User friendly</td>
<td>Does not work on Windows platforms later than Windows XP</td>
</tr>
<tr>
<td></td>
<td>multiple electrical load options</td>
<td>some simulation errors shown although project is written successfully</td>
</tr>
<tr>
<td></td>
<td>detailed dispatching option</td>
<td></td>
</tr>
<tr>
<td>HOGA</td>
<td>Use multi or mono objective optimization using Genetic Algorithm and sensitivity analysis</td>
<td>Free EDU version has some limitations in analysis</td>
</tr>
<tr>
<td></td>
<td>required low computational time</td>
<td>internet connection is required to activate license</td>
</tr>
<tr>
<td></td>
<td>purchase and selling energy options to the electrical grid with net metering system available</td>
<td></td>
</tr>
</tbody>
</table>

Sinha and Chandel illustrate such usefulness in an analysis of case studies of hybrid energy systems research studies that were conducted using some of the software listed in Table 2.4. Table 2.5 shows that the software analysis provided useful results toward an optimal design for each case.
Table 2.5 Summary of Hybrid Energy System Research Studies Conducted Using Various Software Tools (Sinha and Chandel 2014)

<table>
<thead>
<tr>
<th>Software used</th>
<th>Hybrid system studied</th>
<th>Location</th>
<th>Type of analysis</th>
<th>Highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOMER</td>
<td>Biomass-solar PV–pico-hydel system</td>
<td>Kakkanad, Kerala, India</td>
<td>Feasibility study and cost analysis</td>
<td>Carried out system sizing and optimization.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>COE of proposed hybrid system found economical than diesel based hybrid system</td>
</tr>
<tr>
<td>HOMER</td>
<td>Wind–diesel system</td>
<td>Algeria</td>
<td>Techno-economic assessment</td>
<td>Evaluated energy production, life-cycle costs, greenhouse gas emissions reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wind-diesel hybrid system found feasible at a wind speed of 5.48 m/s or more with fuel price of 0.162 S/L or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40% pollutant reduction found in wind–diesel hybrid system in comparison to diesel system</td>
</tr>
<tr>
<td>HOGA</td>
<td>PV–diesel–battery storage system</td>
<td>Zaragoza and Jaca, Spain</td>
<td>Levelized Cost of Energy (LCOE) and the equivalent CO₂ life cycle emissions (LCE)</td>
<td>Optimization of hybrid systems in different locations with different load profiles has been done</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Photovoltaics has been found as the essential component for hybrid systems in Spain</td>
</tr>
<tr>
<td>HYBRID2</td>
<td>Solar–Wind–Fuel Cell–Electrolyzer–Hydrogen system</td>
<td>Chicago, USA</td>
<td>Design and simulation</td>
<td>Hybrid2 is used to predict long-term performance using site-specific resource data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The results indicate that renewable energy resource of the site is sufficient to meet the load requirements and the fuel cell integration may not be needed for such locations</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>Photovoltaic–thermal (PV/T) hybrid system</td>
<td>Nicosia, Cyprus</td>
<td>Modeling and simulation</td>
<td>PV/T hybrid system is found to produce more electrical energy than PV system for applications</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reduction in initial and running costs make PV/T hybrid system economically viable</td>
</tr>
<tr>
<td>RETScreen</td>
<td>Wind–PV–battery–fuel generator system</td>
<td>Shanghai, China</td>
<td>GHG emissions, costs, financial viability and risk analysis</td>
<td>Feasibility analysis of off grid wind–PV–battery system is carried out</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electricity generation contribution in the proposed hybrid system by wind turbines and PV are found to be 82.1% and 10.2%, respectively</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Annual greenhouse gas emission reduction is predicted</td>
</tr>
</tbody>
</table>

Within all HRES modelling software, there is still room for improvement in areas including user friendliness, control technique flexibility, demand side management and incorporation of a wider range of renewable resources (Sinha and Chandel 2014). However, of the software analysed by Sinha and Chandel, HOMER was found to have been the most widely utilised globally.

Connolly et al. in their review of 68 different HRES computer tools, conclude that there is no singular tool that can address all issues relating to integrating renewable energy, but rather the perception of an ‘ideal’ tool is highly dependent on the extent to which it fulfils the specific design objectives (Connolly et al. 2010).

2.10 Considerations for HRES Optimization

Software such as HOMER derive an optimal hybrid energy system design based on financial factors of net present cost (NPC) and levelized cost of energy (LCOE), wherein the design that has the lowest NPC and LCOE is nominated as the most optimal. In reality however, the optimal option nominated by the software
calculations may not prove to be the most practical due to other design requirements or customer specifications that may not be able to be incorporated into the software parameters. In such cases, the system designer can use the software modelling result as a guide but ultimately must meet the complete system design requirements.

Optimization of an existing wind diesel system, cannot only be based on financial performance but must also give considerations to improving overall system performance. In the case of the Nevis island wind diesel system, one of the key technical consideration for optimisation is maintaining the system frequency at the 60 Hz standard with a minimal variation, while achieving the maximal level of wind penetration possible.

As the wind farm has proven to have added benefit of boosting system end of line voltages, another technical point for consideration is seeking to have the wind farm operational whenever possible to provide voltage support.

In conducting the literature review, it was found that most authors referred to HRES optimization designs for green fields projects rather than providing case studies of existing systems that have been optimized after being designed built and operated for several years. For example Erdinc and Uzunoglu in their investigation into the different design approaches to achieve an optimal HRES, state that HRES can be developed and optimized to meet the load demands of a given area by deriving the optimal size of HRES components that will achieve minimal investment and operating cost. They then conclude that different sizing methodologies can be utilized in software tools to obtain a techno-economically optimum HRES (Erdinc and Uzunoglu 2012).

The existing Nevis island wind-diesel system therefore presents a unique challenge for optimisation, considering that it comprises of a mix of mature diesel generator technology and modern wind power tech that is already in use rather than a new project for development.
The techniques therefore described in the literature such as optimal sizing of new HRES cannot therefore be directly applied as a methodology to the existing Nevis island situation. This project has therefore taken a novel approach in establishing baseline considerations for optimization of the existing system. Such considerations can be broadly categorised as follows.

- **Economic optimisation**: Wherein modifications can be made to the existing system to achieve a reduction in the operational and maintenance cost of the PPS, primarily through a reduction in diesel fuel consumption.

- **Technical optimisation**: Wherein modifications can be made to maintain primary and secondary frequency control without curtailing wind farm output and running excess spinning reserve.

Modifications to be considered under each of these categories are based on techniques that have been proven to work such as in the case of the Coral Bay wind diesel system.
3 Chapter Three: Simulation of the Nevis Island system in HOMER

3.1 Choice of HOMER for Simulation

After conducting a literature survey into methodologies of optimising hybrid energy systems, the HOMER software was noted to be the most utilised renewable energy optimisation program and has rapidly become an accepted bankable feasibility analysis tool. HOMER performs simulation, optimization and sensitivity analysis of hybrid energy system hourly performance for a year to determine its life-cycle cost and technical feasibility (Lambert T 2006).

Optimisation of renewable energy systems takes into consideration the economic and technical performance of the chosen design. HOMER permits the comparison of the technical and economic merits of different design options including a power system’s physical behaviour and life-cycle costs (Lambert T 2006).

There were several other factors that influenced the choice of HOMER for conducting the project analysis. These included:

- **Flexibility of systems**: HOMER can be used to model systems comprising of wind, diesel, solar and storage inputs which were within the project scope for analysis. Software such as the System Advisory Model (SAM) considers many renewable options but presently does not include diesel engines in its models.

- **Outputs**: HOMER generates results in numerical and graphical format which enables ease of analysis.

- **Scalability**: HOMER can perform an analysis of a range of system sizes to find the optimal solution.

- **Familiarity**: The Murdoch University Master’s in Renewable energy program teaches HOMER as one of the main renewable energy project analysis tools.

- **Affordability**: HOMER 2.68 Beta is free to download and use.
Precise replication of the existing manual operation of the Nevis Island power system proved to be beyond the capability of HOMER and Excel. Excel was used to analyse the existing system data to extract the PPS average online diesel spinning reserve capable of covering the wind farm and instantaneous hourly load changes. The analysis showed that at all times 100 percent of the windfarm output could be covered by online diesel capacity, and the plant operated with a reserve margin averaging 36 percent of hourly peak loads. These values were entered as constraints into the HOMER model.

3.2 Limitations of HOMER 2.68 Beta

Although HOMER has several benefits as described above, inherently it has limitations and for the Nevis Island system analysis, the following limitations were made evident:

- Unable to perform instantaneous system frequency and voltage analysis.
- Unable to input suggested cost of energy (COE) to represent present energy cost in Nevis to observe economic performance.
- Unable to set wind farm as IPP owned with energy purchase arrangement.

Nonetheless the HOMER simulations described in this report have been able to show the technical and economic benefits achievable with various technological advancements to the Nevis Island wind diesel system.

3.3 Simulation Methodology

The research has shown that it is possible to utilise available wind energy in wind diesel systems without comprising grid stability, and degrading voltage and frequency regulation. The following simulation scenarios use HOMER to perform an energy flow analysis for Nevis Island using some of the key components that were observed to assist high wind energy penetration while maintaining grid stability, in the Coral Bay wind diesel system case study.
It must be noted however, that due to the limitations of HOMER as summarised in Section 3.2, a detailed analysis of system frequency response could not be performed. However, Grid frequency stability was assessed based on the match between electricity supply and demand. Overall the HOMER simulations mainly focused on the derived fuel and financial savings of each option.

3.4 Scenario 1: Existing Wind Diesel System with Automated Control

Scenario 1 investigated how automated control of the existing Nevis Island wind diesel system could impact wind energy penetration and diesel fuel consumption. The existing diesel power station, wind farm, wind resource and island load data were entered into HOMER and the system performance was modelled. Figure 3.1 shows the system configuration in HOMER.

![Figure 3.1 The Existing Nevis Island Wind Diesel System Layout in HOMER](image)
3.4.1 HOMER Inputs

PPS engine and fuel data

Each of the existing PPS diesel engine power rating and specific fuel consumption data was entered into HOMER according to the plots shown in Appendix B. The minimum load ratio for each engine was set to 30% of their nominal rated power. Diesel fuel cost was set at $0.84 per litre under the diesel inputs section as shown in Figure 3.2.

![Diesel Inputs](image)

*Figure 3.2 Diesel Inputs Section of HOMER*

Generator Schedule

- G8 being the most efficient engine was set to always be online as shown in Figure 3.3.
All other engines operating schedule were optimised by enabling the HOMER diesel engine optimisation setting as shown in Figure 3.4, which automatically brings engines online according to the most economical dispatch.

**Figure 3.3 Generator 8 Dispatch Schedule: Always On**

**Figure 3.4 All Other Generators Schedule: Optimised by HOMER**
Wind resource and WTG data

As per the existing wind farm configuration, the HOMER model was set to use eight Vergnet GEV MP C 275 kW turbines based on the power curve shown in Figure 1.16 of Section 1.4.2. The wind resource data obtained from NREL was also entered into HOMER. Appendix C details the manipulation of the NREL wind resource data in HOMER.

Nevis Island Load profile

The 2011 Nevis Island hourly load data obtained from NEVLEC was entered into HOMER which produced a seasonal profile plot as shown in Figure 3.5.

System Control

Figure 3.6 shows the system control settings in which the simulation time step was set at 60 minutes, the dispatch strategy was set for load following and the generator control allowed multiple generators to operate simultaneously.
Constraints

- Online diesel capacity reserve set at 36% of hourly load according to the operating trend observed from analysis of the 2011 NEVLEC PPS generator hourly load data.

- 100% of wind farm was set to be covered by online spinning reserve: Although automation can start and bring diesels online, this first scenario does not assume any mechanical modifications to the existing diesels apart from the governing and control systems. As Generator 8 is the only generator that presently has an engine block pre-heating system it therefore means that all other generators must be warmed up before being fully loaded which causes a delay in bringing generators online. Taking this delay into consideration to avoid underfrequency occurrences it was decided to set the
constraint of online diesel capacity covering the wind farm output at 100 percent hence some diesel savings is lost. Figure 3.7 shows the settings entered in the HOMER constraints section.

![Figure 3.7 System constraints inputs section of HOMER](image)

3.4.2 Scenario 1 Simulation Results

When compared with 2011 actual Figures, the HOMER simulation of an automated version of the existing Nevis Island wind diesel system results in a 2% increase in the annual wind energy penetration and a 14.4% decrease in the annual diesel fuel consumption. Table 3.1 compares the system performance in 2011 with the scenario 1 HOMER simulation where it can be seen that the wind farm mean power output increased by 24.6% and its capacity factor increased by 6.2%.
Figure 3.8 shows the average monthly energy contribution of the energy system components and Table 3.2 shows that no excess energy was generated or capacity shortage incurred. Hence it can be assumed that the grid frequency was kept stable and balance was maintained between the overall energy demand and supply.

![Figure 3.8 Scenario 1 Monthly Average Electric Production by Constituents](image)

**Table 3.1 Comparison of Scenario 1 Simulation Results with 2011 Actuals**

<table>
<thead>
<tr>
<th>Variable</th>
<th>2011 Actuals</th>
<th>Scenario 1 HOMER Simulation</th>
<th>Difference</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumed (KL)</td>
<td>14,163.68</td>
<td>12,125.71</td>
<td>(2,037.98)</td>
<td>(14.4%)</td>
</tr>
<tr>
<td>Annual wind energy penetration (%)</td>
<td>8</td>
<td>10</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Wind farm mean output (kW)</td>
<td>548.2</td>
<td>683</td>
<td>134.80</td>
<td>24.6%</td>
</tr>
<tr>
<td>Wind farm Capacity factor (%)</td>
<td>24.8</td>
<td>31</td>
<td>6.2%</td>
<td></td>
</tr>
</tbody>
</table>
At the average diesel fuel price of $0.84 per litre, the savings of 2,037.98 kilolitres achieved through installing an automation system translates into an annual savings of approximately $1.7 million.

Although the fuel savings are significant and the overall system performance improvement could justify the investment in an automation system, considering that the majority of the existing gensets are approaching and in some cases already exceeding their end of life cycle, the automation retrofit can be deemed an uneconomic investment as the existing diesels will still prove increasingly costly to maintain and operate hence the diesel savings will be negated by these costs.

Based on this point of view, the project then moved to a second scenario in which the existing wind farm operation was simulated with a new fleet of Wartsila diesel generators.

### 3.5 Scenario 2: Existing Wind Farm with New Diesel Generators

Wartsila 32 diesel engines were chosen for the replacement fleet and their specific fuel consumption characteristic were set as that used for G8 as shown in Appendix B. This fuel consumption data was loaded into HOMER along with the existing wind farm and island load data as used in scenario 1. Figure 3.9 shows the general system layout in HOMER.

#### Table 3.2 System Supply and Demand

<table>
<thead>
<tr>
<th>Quantity</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess electricity</td>
<td>0</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0</td>
</tr>
</tbody>
</table>
3.5.1 Replacement Diesel Engine Choice

Although there are numerous diesel generator manufacturers available, the choice of a replacement diesel generator is influenced by several factors:

- **Regional support**: The product must have support infrastructure located in the Caribbean region capable of providing 24 hour rapid response product support.

- **Familiarity**: Plant operators and maintenance staff should have familiarity with the product type to enable rapid and ease of integration into the existing system.

- **Fuel efficiency**: The diesel engine must have fuel efficiency at the same level or greater than the existing engine.

*Figure 3.9 HOMER Layout of the Nevis Island Wind Diesel System with New Diesels*
- **Cost**: The product must be cost effective.

- **Reliability**: The product and balance of systems must be proven to have robust performance and flexibility required to work in an island hybrid energy system.

- **Environmental considerations**: The diesel engine emissions must not have a negative impact on the flora and fauna of Nevis as it’s a prime tourist destination.

- **OEM Acceptance of renewables**: The global push towards increasing the use of renewables requires diesel engine OEM’s to provide flexible solutions that can work in tandem with wind and solar power systems.

- **Considerations for low load operations**: The replacement diesels sought after must have the ability to operate efficiently at reduced loadings to increase wind farm penetration and reduce fuel consumption.

Section 2.4 of the literature review shows that recent advancements in diesel engine technology, automation and control allows Wartsila diesel generators to operate efficiently at low loads while providing spinning reserve, voltage and frequency support for hybrid power system operations.

Since its installation in the year 2002, G8 has proven to be a sound investment with the best fuel and lubrication oil economy of all installed generators at the PPS. In addition Wartsila over the years has provided stellar technical support to NEVLEC as needed. Also as plant operators and maintenance staff are already familiar with the Wartsila 32 model diesel engines, replacing the existing PPS diesel generators with Wartsila 32 engines, will require less training of operation and maintenance staff, which will decrease overall project costs.

Taking these benefits into consideration, the scenario 2 simulation uses the Wartsila 32 generator for the new fleet of diesels.
3.5.2 Replacement Diesel Engine Sizing

Sizing of diesel generators for power plant applications must give consideration to several factors. These include:

- Daily and seasonal load changes
- Projected load growth
- Capacity and load factors
- Being able to meet load demands while one or more diesels may have to be out of service for planned or unplanned maintenance.

It was therefore decided to keep the replacement diesels in a range not exceeding 3 MW individually, which allows for the loss of one or more diesel generator while online without incurring significant load shedding. Also keeping the diesels within this size range increases the loading of individual engines thereby improving overall plant fuel economy. As shown in Table 3.3 the total installed capacity of the new diesel fleet totals 15.7MW which provides sufficient generation capacity to meet future load demands exceeding the present 9MW peak.

<table>
<thead>
<tr>
<th>Existing engine</th>
<th>Size (kW)</th>
<th>Replacement name</th>
<th>Replacement Wartsila Model</th>
<th>Size (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 3</td>
<td>900</td>
<td>Generator 14</td>
<td>6L26</td>
<td>1,870</td>
</tr>
<tr>
<td>Generator 4</td>
<td>2,200</td>
<td>Generator 13</td>
<td>6L32</td>
<td>2,760</td>
</tr>
<tr>
<td>Generator 5</td>
<td>2,600</td>
<td>Generator 12</td>
<td>6L32</td>
<td>2,760</td>
</tr>
<tr>
<td>Generator 6</td>
<td>2,600</td>
<td>Generator 11</td>
<td>6L32</td>
<td>2,760</td>
</tr>
<tr>
<td>Generator 7</td>
<td>2,500</td>
<td>Generator 10</td>
<td>6L32</td>
<td>2,760</td>
</tr>
<tr>
<td>Generator 8</td>
<td>2,700</td>
<td>Generator 9</td>
<td>6L32</td>
<td>2,760</td>
</tr>
<tr>
<td>Total</td>
<td>13,500</td>
<td></td>
<td></td>
<td>15,670</td>
</tr>
</tbody>
</table>

Table 3.3 Replacement Diesel Generator Sizing
3.5.3 HOMER Inputs

**Engine data**

The minimum load ratio for each engine was set to 10% of their nominal rated power as the new engines would have better part load efficiencies as discussed in section 2.4 of this report.

**Generator Schedule**

- All engines were set to be scheduled according to the HOMER optimisation algorithm.

**Wind resource and WTG data**

The wind resource data and wind farm configuration remained the same as in scenario 1.

**Nevis Island Load profile**

The island load profile remained the same as in scenario 1.

**System Control**

The system control settings and dispatch strategy were set to be the same as in scenario 1.

**Constraints**

- Online diesel capacity reserve set at 18 percent of hourly load as the new diesels in conjunction with the automation system provides automatic rapid start and synchronisation functionality hence excess online spinning reserve was halved.
- 100 percent of the wind farm power output was still set to be covered by online spinning reserve. It is assumed in this scenario the new diesels would be configured in isochronous frequency control hence diesel engines would automatically adjust their set points to assist in maintaining grid frequency stability. Isochronous frequency control however, cannot be modelled in HOMER.
3.5.4 Scenario 2 Simulation Results

Table 3.4 presents the comparison of 2011 actual Figures with the scenario 2 HOMER simulation results where the Figures show that replacing the existing diesel fleet with new diesel generators in an automated Nevis Island wind diesel system results in a 20.14% decrease in annual diesel fuel consumption. Values for annual wind energy penetration, average wind farm power output and capacity factor remain the same as in scenario 1.

Figure 3.10 shows the average monthly energy contribution of the system components and Table 3.5 shows that no excess energy was generated or capacity shortage incurred. Hence in similitude to scenario 1, it can be assumed that the grid frequency was kept stable and balance was maintained between the overall energy demand and supply.

![Figure 3.10 Scenario 2 Monthly Average Electric Production by Constituents](image_url)
**Table 3.4** Comparison of Scenario 2 simulation results with 2011 actuals

<table>
<thead>
<tr>
<th>Variable</th>
<th>2011 Actuals</th>
<th>Scenario 2 HOMER Simulation</th>
<th>Difference</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumed (KL)</td>
<td>14,163.68</td>
<td>11,310.46</td>
<td>(2,853.23)</td>
<td>(20.14%)</td>
</tr>
<tr>
<td>Annual wind energy penetration (%)</td>
<td>8</td>
<td>10</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Wind farm mean output (kW)</td>
<td>548.2</td>
<td>683</td>
<td>134.80</td>
<td>24.6%</td>
</tr>
<tr>
<td>Wind farm Capacity factor (%)</td>
<td>24.8</td>
<td>31</td>
<td>6.2%</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.5** Scenario 2 System Supply and Demand

<table>
<thead>
<tr>
<th>Quantity</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess electricity</td>
<td>0</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0</td>
</tr>
</tbody>
</table>

At the average diesel fuel price of $0.84 per litre, the savings of 2,853.23 kilolitres achieved through installing new diesels with a wind diesel automation system translates into an annual savings of approximately $2.4 million.

The results of scenario 1 and 2 showed that automating the wind diesel system and installing new diesels results in increased wind energy penetration and reduced diesel fuel consumption. However, as scenario 2 results showed no further increase in wind energy penetration over scenario 1, the project then moved to a third scenario to investigate the impact of increasing the number of wind turbines operating with the new diesels and in an automated system.
3.6  Scenario 3: Automated Wind Diesel System with New Diesel Generators and Increased Wind Power Generation Capacity

Section 2.6 of this report outlined several considerations for increasing installed wind power generation capacity on Nevis, and identified the main barrier of limited available land space for installing wind turbines. However, it is estimated that there is sufficient land space available in Maddens Estate to accommodate 8 extra wind turbines. Scenario 3 therefore investigated the impact of doubling the size of the existing wind farm.

3.6.1  HOMER Inputs

The HOMER inputs and constraints remain the same as in scenario 2 with the addition of increasing the number of turbines from 8 to 16.

3.6.2  Scenario 3 Simulation Results

Table 3.6 presents the comparison of 2011 actual Figures with the scenario 3 HOMER simulation results where the Figures show that doubling the size of the existing wind farm along with new diesel generators in an automated Nevis Island wind diesel system results in a 28.74% decrease in annual diesel fuel consumption.

Annual wind energy penetration increased to 21% and the average wind farm power output increased to 1,365kW while the capacity factor remained at 31% as in the two previous scenarios. At the average diesel fuel price of $0.84 per litre, the savings of 4,069.95 kilolitres of diesel achieved through doubling the wind farm size along with system automation and new diesels translates into an annual savings of approximately $3.4 million.
Figure 3.11 Scenario 3 Monthly Average Electric Production by Constituents

Figure 3.11 shows the average monthly energy contribution of the system components and Table 3.7 shows that although some excess energy was generated, this value was a minimal 0.03% of the total system annual energy demand. However, this is indicative that there may have been some instances of wind energy oversupply for the given system demand, which could have caused some grid frequency instability. Moreover, considering that the island daily base load approximates 5 MW as shown in Figure 1.3 of section 1.3, doubling the wind farm size to 4.4MW can have an instantaneous peak power penetration level approximating 88% during the late night to early morning hours.

Table 3.6 Comparison of Scenario 3 simulation results with 2011 actuals

<table>
<thead>
<tr>
<th>Variable</th>
<th>2011 Actuals</th>
<th>Scenario 3 HOMER Simulation</th>
<th>Difference</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumed (KL)</td>
<td>14,163.68</td>
<td>10,093.73</td>
<td>(4,069.95)</td>
<td>(28.74%)</td>
</tr>
<tr>
<td>Annual wind energy penetration (%)</td>
<td>8</td>
<td>21</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>Wind farm mean output (kW)</td>
<td>548.2</td>
<td>1,365</td>
<td>846.80</td>
<td>149%</td>
</tr>
<tr>
<td>Wind farm Capacity factor (%)</td>
<td>24.8</td>
<td>31</td>
<td>6.2%</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.7 Scenario 3 System Electricity Supply and Demand

<table>
<thead>
<tr>
<th>Quantity</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess electricity</td>
<td>14,860</td>
<td>0.03</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

However, given the small value of excess energy generated, it can be assumed that during the events of increased wind power penetration, grid frequency would be maintained through a combination of WTG dynamic blade pitch control, diesel generator isochronous frequency control and governor response which would all be under the control of the unified automation system. These responses however, cannot be modelled in HOMER but are accepted based on proven applications in wind diesel systems such as at Coral Bay. The project then moved to a fourth scenario to investigate the impact of adding solar PV power generation to the system design as per scenario 3.

#### 3.7 Scenario 4: Automated Wind Diesel System with New Diesel Generators, Increased Wind Power Generation Capacity and Solar PV

Section 2.7 of this report highlights that as NEVLEC is owned by the NIA, the government is an energy customer of itself hence reducing the energy consumption of government buildings by installing roof top solar PV systems would prove beneficial to the NIA. Based on this reasoning, scenario 4 models a 550 kW solar PV installation to represent the collective average peak day time demand of government buildings. The 550 kW sizing is based on NEVLEC estimates of government buildings average daily peak power demand. Figure 3.12 shows the scenario 4 system configuration in HOMER.
3.7.1 HOMER Inputs

Solar resource data and PV panels were added to the system design and constraints of scenario 3 to form scenario 4. Solar resource data for Nevis was obtained by entering the latitude and longitude coordinates of Nevis Island into HOMER, which then downloads the data from the NASA Surface meteorology and Solar Energy database. The Nevis Island monthly solar resource profile is shown in Figure 3.13.

Figure 3.12 Scenario 4 System Layout in HOMER
As Nevis is located at latitude 17°20’ North and longitude 62°45’ West, the solar PV panels were set at a slope angle of 17.333 which is equivalent to the Island latitude angle. HOMER version 2.68 does not have various types of solar PV panels hence the generic model with no tracking was used, with the output current set to AC. Figure 3.14 shows the properties for the solar PV inputs.

![Figure 3.13 Nevis Island Monthly Solar Resource profile](image)

![Figure 3.14 Solar PV Panels Input Properties in Homer](image)
3.7.2 Scenario 4 Simulation Results

Table 3.8 presents the comparison of 2011 actual Figures with the scenario 4 HOMER simulation where the Figures show that installing 550 kW of solar PV panels on government buildings along with the other system changes previously described in scenarios 2 and 3, results in a 29.96% decrease in annual diesel fuel consumption. The combination of the wind farm and 550 kW of solar PV resulted in 1% increase in annual renewable energy penetration to give a total renewable energy fraction of 22%. At the average diesel fuel price of $0.84 per litre, the savings of 4,244.12 kilolitres of diesel achieved through adding 550 kW of solar PV panels to the scenario 3 system design, translates into an annual savings of approximately $3.6 million.

![Figure 3.15 Scenario 1 Monthly Average Electricity Production by Constituents](image_url)
Table 3.8 Comparison of Scenario 4 simulation results with 2011 actuals

<table>
<thead>
<tr>
<th>Variable</th>
<th>2011 Actuals</th>
<th>Scenario 4 HOMER Simulation</th>
<th>Difference</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumed (KL)</td>
<td>14,163.68</td>
<td>9,919.57</td>
<td>(4,244.12)</td>
<td>(29.96%)</td>
</tr>
<tr>
<td>Annual wind energy penetration (%)</td>
<td>8</td>
<td>21</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>Wind farm mean output (kW)</td>
<td>548.2</td>
<td>1,365</td>
<td>846.80</td>
<td>149%</td>
</tr>
<tr>
<td>Wind farm Capacity factor (%)</td>
<td>24.8</td>
<td>31</td>
<td>6.2%</td>
<td></td>
</tr>
<tr>
<td>Mean Solar PV output (kWh/day)</td>
<td>0</td>
<td>2,252</td>
<td>2,252</td>
<td></td>
</tr>
<tr>
<td>Annual solar PV energy penetration (%)</td>
<td>0</td>
<td>1</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Renewable energy fraction (%)</td>
<td>8</td>
<td>22</td>
<td>14%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.9 Scenario 4 System Electricity Supply and Demand

<table>
<thead>
<tr>
<th>Quantity</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess electricity</td>
<td>15,885</td>
<td>0.03</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3.15 illustrates the energy system monthly contribution by components, and Table 3.9 indicates that the balance between system energy demand and supply remained the same as in scenario 3.

The results of scenarios 1 through 4 indicate that the Nevis Island wind diesel system can be significantly improved through installing a unified wind diesel automated control system, new diesel engines and adding solar PV to the mix. Based on these results the project then moved to a fifth scenario to investigate the impact of adding energy storage to the system design.
3.8  Scenario 5: Automated Wind Diesel System with New Diesel Generators, Increased Wind Power Generation Capacity, Solar PV and Battery Storage

The results of scenario 4 show that increasing the renewable energy fraction by adding more wind capacity and solar PV, can produce some excess energy which can cause instances of grid frequency instability. However, according to the literature review, several high penetration wind diesel and solar PV systems such as Coral Bay, utilize energy storage devices which provide additional grid stabilizing functions as discussed in Sections 2.2.3 and 2.3.2. Scenario 5 therefore adds a generic battery system to the design used in scenario 4 which results in a system layout as shown in Figure 3.16.

![Figure 3.16 Scenario 5 System Layout in HOMER](image-url)

*Figure 3.16 Scenario 5 System Layout in HOMER*
3.8.1 HOMER Inputs

Battery storage

360 kWh of battery storage was chosen from the HOMER battery selection and added to the system design. The batteries were configured in 3 strings consisting of 2 volt Hoppecke 20OPzs 2500 Ah batteries with 24 batteries per string to give a 48V DC bus.

The battery capacity sizing was based on the following calculation:

- Coverage of average wind farm output for 5 minutes = 1,365 kW * 1/12 hr = 114 kWh
- Coverage of solar PV system average output for 5 minutes = 420 kW * 1/12 hr = 35 kWh
- Coverage of 36% of average system load for 5 minutes = 36% * 6,575 kW * 1/12 hr = 197.26 kWh
- Total 346.25 kWh

5 minutes was chosen as the time frame in the calculations shown above to provide sufficient power reserve, while a diesel generator is being brought online in the event of a rapid decrease in solar and or wind resource, or a sudden increase in system load demand.

Converter

The converter interfacing the DC and AC bus was sized at 1500 kW to provide sufficient capacity to charge and discharge the battery according to the AC system demands and sudden fluctuations in wind and solar resources.

System Controls and Constraints

With the battery storage added to the system, it was decided to enable cycle charging (CC) under the system control inputs in HOMER as shown in Figure 3.17. The set point charge was set to 80% to allow some head room to absorb any sudden injection of excess energy into the system by the wind or solar PV
resources. Enabling CC also provides the benefit of increasing the loading of online diesels during the battery charge cycle which in turn increases the fuel efficiency of the diesel engine operation.

![System Control Inputs](image)

**Figure 3.17 Scenario 5 System Control Inputs in HOMER**

With the addition of energy storage, the need for online spinning reserve to cover wind and solar PV along with load variations can be reduced. Hence for this scenario all online diesel operating reserve requirements were set to zero as shown in Figure 3.18.
3.8.2 Scenario 5 Simulation Results

The comparison of 2011 actual Figures with the scenario 5 HOMER simulation as shown in Table 3.10 indicates that adding a 360 kWh battery storage system to the new diesels, increased wind capacity and 550 kW of solar PV on government buildings, resulted in a 31.62% decrease in annual diesel fuel consumption. At the average diesel fuel price of $0.84 per litre, the savings of 4,479.22 kilolitres of diesel achieved through adding a battery storage system to the scenario 4 system design, translates into an annual savings of approximately $3.8 million. The scenario 5 fuel savings clearly show that the battery system provides online capacity reserve and reduces the need for diesel spinning reserve to cover variations in renewables and load demands. It must also be noted that the battery contributed to maintaining grid stability as the excess energy value decreased from scenario 3 and 4 as shown in Table 3.11.
Figure 3.19  Scenario 5 Monthly Average Electricity Production by Constituents

Table 3.10  Comparison of Scenario 5 simulation results with 2011 actuals

<table>
<thead>
<tr>
<th>Variable</th>
<th>2011 Actuals</th>
<th>Scenario 5 HOMER Simulation</th>
<th>Difference</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumed (KL)</td>
<td>14,163.68</td>
<td>9,684.47</td>
<td>-4,479.22</td>
<td>-31.62%</td>
</tr>
<tr>
<td>Annual wind energy penetration (%)</td>
<td>8</td>
<td>21</td>
<td>13</td>
<td>13%</td>
</tr>
<tr>
<td>Wind farm mean output (kW)</td>
<td>548.2</td>
<td>1365</td>
<td>846.80</td>
<td>149%</td>
</tr>
<tr>
<td>Wind farm Capacity factor (%)</td>
<td>24.8</td>
<td>31</td>
<td>6.2%</td>
<td></td>
</tr>
<tr>
<td>Mean Solar PV output (kWh/day)</td>
<td>0</td>
<td>2,252</td>
<td>2,252</td>
<td></td>
</tr>
<tr>
<td>Annual solar PV energy penetration (%)</td>
<td>0</td>
<td>1</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Renewable energy fraction (%)</td>
<td>8</td>
<td>22</td>
<td>14%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.11  Scenario 5 System Electricity Supply and Demand

<table>
<thead>
<tr>
<th>Quantity</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess electricity</td>
<td>6,403</td>
<td>0.01</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
4  Summary of HOMER Simulation Results

The Nevis Island wind diesel system was modelled and the system energy flow simulated under five different configurations in HOMER. The results from the simulations indicate that for each technological modification, there is a reduction in diesel fuel consumption when compared to 2011 actual Figures. Figures 4.1 to 4.3 summarise the impact of the various technological modifications on the annual renewable energy penetration and fuel savings. It can be seen that system configuration of scenario 5 wherein new diesels, increased wind farm capacity, solar PV, battery storage and an automation system, resulted in the greatest reduction in annual fuel consumption and increase in financial savings.

Figure 4.1 Summary Annual Fuel Savings for each HOMER Scenario Analysis
For the existing system configuration the simulation results of scenario 1 and 2 indicate that the maximum achievable annual wind energy penetration with the existing WNL Wind Farm is 10%. However, the renewable energy fraction on Nevis can be increased to 22% by doubling the size of the existing wind farm and installing grid tied roof top solar PV systems on all government buildings as shown in scenarios 3 and 4.
However, increasing the installed renewable power generation capacity with the existing PPS infrastructure will not result in these savings as the existing operational regime will continue and renewables are likely to be curtailed. Hence the conclusion that can be drawn from the HOMER simulation analysis, is that the Nevis Island wind diesel system first needs an upgrade of the diesel engine technology and overall system control technology to capitalise on the diesel fuel savings that can be potentially achieved with the increased use of renewables. Until a unified automated control system along with new flexible and efficient diesel generators are installed, the Nevis Island hybrid energy system will not realise the full possible penetration of renewable energy.

Although the HOMER simulation cannot give much indication in regards to grid frequency stability for each of these modifications, based on the literature review and case study analysis, it can be accepted that installation of an automation system, some form of energy buffering mechanism, along with new diesels configured in isochronous frequency control, will play a major role in improving the Nevis Island
grid frequency performance and allowing for increased renewable energy penetration. In addition with the installation of the automation system, the present day operational procedure of stopping wind turbines at night to maintain grid stability will rather be handled by the automated control system which would adjust WTG blade pitch and also adjust diesel engine governors and voltage regulators to achieve stability.
5 Derived Answers to the Thesis Questions

The five scenarios modelled in HOMER provided insight into the benefits that can be gained through technological improvements of the Nevis Island wind diesel system. Having performed the literature review and HOMER analysis the thesis questions can be answered as follows.

I. How can the existing Nevis wind diesel system be improved to realise increased wind energy penetration and reduced diesel fuel consumption?

Each of the simulation scenarios showed technological advancement of the existing Nevis Island wind diesel system, results in an increased improvement in the system performance in regards to reductions in diesel fuel consumption and increased renewable energy penetration. However, this master’s thesis did not look at the associated cost with installing each system, and perform a cost benefit analysis. The answer to the first thesis question therefore largely depends on the level of investment NEVLEC, the NIA and WNL are willing to make. It can be assumed that the system modification of least complexity will be cheapest. Hence automating the existing system is likely to be the least costly option.

Based on the simulation results, the maximum annual wind energy penetration achievable with the existing wind farm if automated along with the existing PPS diesels is 10%, and the annual fuel savings achievable approximates 2,000 kl. However, given the age of the existing diesels and their poor part load fuel efficiencies, it is recommended to replace them with new diesels that are more fuel efficient and have better part load efficiencies. The results of scenario 2 show that installing an automation system with new diesels and the existing wind farm results in greater financial savings for NEVLEC over installing an automation system only. Ultimately the best improvement would be a combination of all the technologies as demonstrated in scenario 5.
II. Should the island of Nevis invest in more wind farms and allow grid-tied solar PV rather than increasing diesel generation to meet future electricity demands?

The simulation results have shown that Nevis can become largely powered by renewable energy resources with the right combination of renewable energy technologies, energy storage devices and modern flexible diesel generators all linked by an automated control system.

However, due to limited land space on the island and lack of renewable energy incentivising mechanisms large scale wind development is unlikely. Roof top solar PV is therefore the more attractive renewable energy technology to be pursued in the near future but will need the backing of renewable energy policy and incentivising mechanisms. Until such policies, regulations and incentivising mechanisms are in place, the NIA remains best suited to gain the benefits of installing roof top PV system on government buildings as simulated in scenario 4 of this report.

Ultimately a Hybrid energy system comprising of wind, efficient diesels with low minimum load requirement, solar PV and energy storage is the best mix for Nevis and provides the greatest savings and operational flexibility for NEVLEC.
6 Possible Further Investigation

Due to time and word limit constraints, the project was not able to move into the third stage as per the original project proposal. However, this leaves room for possible further analysis into other improvements that can be made for the Nevis Island wind diesel system and scope of renewable energy proliferation in general. Some of the key areas that can be further explored include:

- Impacts of demand side management (DSM) and energy efficiency measures.
- Deployment of smart grid technology such as advanced metering interfaces (AMI).
- Review of tariff structure to compliment DSM.
- Load growth analysis
- Economic analysis
- LCOE analysis
- Necessary policy, regulations and mechanisms to increase renewable energy uptake on Nevis Island.
7 Conclusions

Wind diesel systems provide a reliable flexible energy system option which is ideal for islands such as Nevis, where there is a desire to increase the use of renewable energy to reduce the dependence on fossil fuels. As wind is a variable resource, wind power can introduce undesirable fluctuations in grid frequency as has sometimes been the case on Nevis Island.

Nevis has made a step in the direction of reducing its dependency on fossil fuels by installing a wind farm. However, due to a lack of technical guidelines to govern grid-tied renewable energy generators, primary and secondary frequency control was not required of the wind farm. This omission has resulted in the NEVLEC operators resorting to stopping turbines during instances of grid frequency instability. In addition due to the existing diesel engines not being capable of sustained low load operation without incurring maintenance and operational issues, the wind farm in some instances is curtailed.

Based on the literature reviews, case study analysis and results of the HOMER simulations conducted in this research project, the overarching conclusion is that the Nevis Island wind diesel system would require a technological upgrade to improve frequency stability performance, achieve maximal wind energy penetration and realise increased diesel savings.

The scenario analysis presented in this project shows that each option of technological advancement merits increased savings in fuel savings for the diesel power plant. Furthermore, with an abundant daily solar irradiation resource, the island is well suited for grid tied roof top solar PV utilisation that can further reduce the dependency on diesel fuel.

However, the project analysis has shown that the lack of clearly defined renewable energy targets, incentivising mechanisms, technical regulations and standards are major barriers to renewable energy proliferation on the island. It can therefore be concluded that the optimal future hybrid energy system for
Nevis will be achieved through the deployment and amalgamation of renewable energy technologies, modern diesel generator technology, energy storage, automated control, load management, policies and regulations as illustrated in Figure 7.1.

Figure 7.1 Components of the Future Optimal Nevis Island Hybrid Energy System


8 References


Appendix

9.1 Appendix A: Vergnet GEV MP C Technical description

Figure 9.1 Vergnet GEV MP C Technical Description (Vergnet 2015)
9.2 Appendix B: Scenario 1 PPS Existing Diesel Engine Fuel Curves

**Figure 9.2 Generator 3 Fuel consumption curve**

**Figure 9.3 Generator 3 Fuel efficiency curve**

**Figure 9.4 Generator 4 Fuel consumption curve**

**Figure 9.5 Generator 4 Fuel efficiency curve**
Figure 9.6 Generator 5 Fuel consumption curve

Figure 9.7 Generator 5 Fuel efficiency curve

Figure 9.8 Generator 6 Fuel consumption curve

Figure 9.9 Generator 6 Fuel efficiency curve

Figure 9.10 Generator 7 Fuel consumption curve

Figure 9.11 Generator 7 Fuel efficiency curve
9.3 Appendix C: Nevis Island Wind Resource Data Manipulation in HOMER

\[ u = u_r \left( \frac{z}{z_r} \right)^\alpha \]  

(1)

Where  
- \( u \) = calculated windspeed (m/s)
- \( z \) = height (m)
- \( u_r \) = reference windspeed (m/s)
- \( z_r \) = reference height
- \( \alpha \) = empirical coefficient (1/7 or 0.143)

Using the power law as shown in equation 1 the Nevis Island wind resource data obtained from NREL was entered into the HOMER model. As the NREL data anemometer height was 50M and the Vergnet GEV MP C hub height is 55 m, the wind speed profile variation with height was set to the power law in HOMER and the power law exponent was set at 0.143 as per equation 1. The resulting wind speed profile of the wind farm location is shown in Figure 9.14.
Figure 9.14 Wind Speed profile of Maddens Estate on Nevis

Figure 9.15 Maddens Estate Monthly Average Wind Speeds
The Maddens Estate wind resource has the following characteristics as illustrated in Figures 9.15 and 9.16:

- Annual average wind speed: 7.024 m/s
- Hour of peak wind speed: 03:00
- Weibull: $k = 3.43$, $c = 7.80$ m/s

According to the Wind Resource Atlas of the United States, a class 4 wind site is one which has mean speeds between 6.5 - 7.0 m/s at 30 m. A site which fits this classification is considered to be economically viable for developing a wind farm (NREL 1986). The wind speed profile of the Nevis wind farm shown in Figure 3.14 shows the wind speed at 30m to be 6.5 m/s hence the site can be classified as economically viable.
Figure 9.17 Maddens Estate Monthly Average Wind Speed Variance