Republic of the
Marshall Islands
Energy Future

Electricity Roadmap

Technology Pathways

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Preface

MFAT NZ has commissioned an electricity roadmap to assist the Republic of the Marshall Islands (RMI) and its development partners to determine a path forward for the RMI electricity sector, which will enable the RMI to meet their communicated intended Nationally Determined Contributions (NDC) to global greenhouse gas (GHG) emissions reductions.

This report documents interim modelling analyses which have been performed by the RMI Electricity Roadmap consultant team as an input to developing this Roadmap, and suggests the most cost-effective technology pathways for Majuro, Ebeye, and other RMI island power systems to contribute to GHG emission reduction. Reference is made to prior findings and assumptions in the form of technical notes.

NEW ZEALAND
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The development of the Marshall Islands Electricity Roadmap
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Table of Contents

Executive Summary

This report presents the results of techno-economic analysis to identify high-level technology pathways for the RMI electricity sector to contribute to achieving the NDC targets of reductions in economy-wide national greenhouse gas emissions from 2010 levels by 32% by 2025, 45% by 2030, and 100% by 2050[1] .

The required contribution from the electricity sector to reduce economy-wide national emissions below 2010 levels depends on:

- the proportion of national emissions attributed to the electricity sector in 2010;
- the contribution of other sectors to emissions reductions; and
- the future demand for electricity (including demand-side initiatives and moves to replace fossil fuels with electricity in other sectors, such as transport).

A number of assumptions and estimates have been applied to these variables in order to determine required reductions in diesel fuel consumption [6] . Based on these assumptions, a significant contribution to the economy-wide targets will be required by the electricity sector – a reduction in emissions (and hence diesel consumption) from 2010 levels by 50% by 2025, 65% by 2030 and 100% by 2050. These reductions are despite a forecast increase in electricity demand due to increased commercial activities, and also due to potential electric vehicle charging as an initiative to concurrently reduce transport emissions.

Electricity consumers in the RMI are connected to one of three types of power systems, each with unique recommended technology pathways:

- Stand-alone power systems without connection to a distribution network. The recommended technology pathway for electricity generation on small outer islands without electricity distribution networks is continuation of the current rollout of 100% renewable solar/battery household systems (solar home systems);
- Reticulated island power systems providing energy to up to several hundred people. Drawing on the findings of previous studies, the recommended technology pathway for electricity generation on medium sized islands with existing distribution networks, such as Wotje and Jaluit, is the installation of centralised PV/battery systems. These should be sized such that almost all electricity is supplied from these solar/battery systems, with diesel generators and fuel supplies retained for periods of extended bad weather or periods of unusual demand. This represents a direct near-term transition to systems with very low emissions;
- Large reticulated island power systems (on the islands of Ebeye and Majuro). For large island power systems the HOMER energy modelling tool was used to identify potential combinations of electricity generation technologies which could contribute to the national emissions targets of 2025, 2030 and 2050.

The pathways for Majuro and Ebeye considered two major scenarios – systems with wind generation and systems without wind generation (this is because a full wind feasibility study has not yet been undertaken). As an additional option, biodiesel technology was considered as a 'last-mile' solution for the period between 2030 and 2050. These highly populated large islands hold the greatest potential to significantly reduce national electricity emissions, representing the vast majority of electricity generation. Assuming a 90% reduction in other islands' fuel consumption,

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[1] http://www4.unfccc.int/ndcregistry/PublishedDocuments/Marshall%20Islands%20First/150721%20RMI%20INDC%20JULY%202015%20FINAL%20SUBMITTED.pdf

Majuro and Ebeye will then each need to reduce diesel consumption from 2010 levels by 48% by 2025, 64% by 2030 and 100% by 2050 [6].

During modelling, the criteria for selecting an optimal solution for each of Majuro and Ebeye (2025, 2030, 2050) was selecting the lowest capital cost solution which achieves the milestone (48% GHG Reduction, 64%, 100% from 2010 levels). For the most part, these pathways also yielded the lowest levelized cost of generation.

Table 0.1 provides a summary of techno-economic modelling results.

Table 0.1 Techno-economic analyses modelling results

		Baseline	**Solar and Battery only Pathway**			**Wind, Solar and Battery Pathway**			**Biodiesel, Wind, Solar and Battery Pathway**		
		2022	**2025**	**2030**	**2050**	**2025**	**2030**	**2050**	**2025**	**2030**	**2050**
Majuro	Diesel generation (MW)	12	-	-	12	-	-	12	-	-	12
	Solar PV (MW)	4	29	34	94	4	13	73	4	13	13
	Wind (MW)	-	-	-	-	12	12	42	12	12	12
	Battery (MWh)	1.5	38	75	1050	20	20	300	20	20	20
	Annual OPEX ($M)[2]	17.1	14.5	13.9	44.0	13.5	12.1	22.5	13.5	12.1	19.4
	Total CAPEX from 2018 ($M)	49.5	149	190	672	118	156	476	118	156	185
	Incremental CAPEX ($M)	49.5	99.1	41.4	482	68.3	38.2	320	68.3	38.2	29.2
	- Diesel Generation ($M)	9.0	-	-	9.0	-	-	9.0	-	-	9.0
	- Solar PV ($M)	21.6	62.5	10.0	120	-	18.0	120	-	18.0	-
	- Wind ($M)	-	-	-	-	39.2	-	165	39.9	-	-
	- Battery ($M)	1.0	14.0	11.1	307	6.9	-	-	6.9	-	-
	- Network and system ($M)	17.9	15.3	20.3	-	15.3	20.3	-	15.3	20.3	-
	- Asset Replacements ($M)	-	0.2	-	46	0.2	-	25.9	0.2	-	20.9
	- Enabling Technologies ($M)	-	6.0	-	-	6.0	-	-	6.0	-	-
	Simple LCOE ($/kWh)[3]	0.29	0.32	0.34	0.93	0.29	0.29	0.55	0.29	0.29	0.35
	Renewable energy fraction (%)	9	51	67	100	54	68	100	54	68	100

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[2] This is "Operating Cost" from HOMER and includes fixed overheads, fuel, maintenance, and annualised periodic costs

[3] For the purposes of this analysis Simple LCOE is defined as LCOE using a discount rate of zero, that is total cost divided by total electricity.

		Baseline	Solar and Battery only Pathway			Wind, Solar and Battery Pathway			Biodiesel, Wind, Solar and Battery Pathway		
		2022	2025	2030	2050	2025	2030	2050	2025	2030	2050
Ebeye	Diesel generation (MW)	2.6			2.5			2.5			2.5
	Installed solar PV (MW)	0.6	6.6	6.6	17.0	0.6	2.6	7.6	0.6	2.6	2.6
	Wind (MW)	-	-	-	-	3	3	7.5	3	3	3
	Battery (MWh)	0.6	10.5	17.0	225	6	6	150	6	6	6
	Annual OPEX ($M)	5.6	4.7	4.5	11.3	4.5	4.1	8.8	4.5	4.1	5.0
	Total CAPEX from 2018 ($M)	15.7	36.2	40.1	139	29.4	35.5	115	29.4	35.5	43.9
	Incremental CAPEX ($M)	-	20.6	3.8	99.4	13.7	6.1	79.1	13.7	6.1	8.4
	- Diesel Generation ($M)	1.9	-	-	1.5	-	-	1.5	-	-	1.5
	- Solar PV ($M)	8.8	15.0	-	20.8	-	5.4	10.0	-	5.4	-
	- Wind ($M)	-	-	-	-	9.4	-	13.4	9.4	-	-
	- Battery ($M)	1.0	3.3	3.1	65.4	2.0	-	47.8	3.3	-	-
	- Network and system ($M)	4.0	0.5	0.7	-	0.5	0.7	-	0.5	0.7	-
	- Asset Replacements ($M)	-	-	-	11.7	-	-	6.4	-	-	6.4
	- Enabling Technologies ($M)	-	1.8	-	-	1.8	-	-	0.5	-	-
	Simple LCOE ($/kWh)	0.37	0.39	0.43	1.12	0.36	0.38	0.90	0.36	0.38	0.44
	Renewable energy fraction (%)	5	51	62	100	51	68	100	51	68	100
Wotje Jaluit Rongrong Santos Rongelap and Kili[4]	Total CAPEX from 2018 ($M)	0	22	22	22	n/a	n/a	n/a	0	22	22
	Annual OPEX[5] ($M)	3.3	2.4	2.4		n/a	n/a	n/a	3.3	2.4	2.5
Small island stand-alone power systems	Installed systems	3000 SHS		Schools, health clinics, fish bases, telecoms			Schools, health clinics, fish bases, telecoms			Schools, health clinics, fish bases, telecoms	
	Capital investment to increase services			3.7			n/a			3.7	
	Annualised Asset Replacements ($M)	1	1	1.8	1.8	n/a	n/a	n/a	1	1.8	1.8

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[4] Santos and Kili capacities and costs are indicative only, lacking firm data, see Section 2.4.4

[5] Including annual contribution to replacement reserve fund, and RepMar subsidy applied to baseline only

The analysis identified that very significant changes to electricity generation will be required by 2025 – a move from manually dispatched aged diesel generators to automated systems which allow stable operation with little or no diesel generation running during periods of high renewable energy resource, along with other enabling technologies such as battery storage to provide operating reserve.

For both Majuro and Ebeye, from a techno-economic perspective, wind energy was found to be a potentially attractive form of generation and could provide a significant portion of the energy generation, reducing emissions as well as the cost of generation. There is very high confidence that a viable wind resource is available on Ebeye based on summary wind data provided by the US Army on Kwajalein Atoll. A robust wind resource assessment and a full assessment of technical, social, environmental and economic factors are, of course, pre-requisites to successful wind projects. Given the imminence of the NDC targets and the typical lead time of wind projects, it is recommended that a wind resource assessment commences as soon as practicable on Majuro. Presuming that these will further highlight the benefits of wind generation, then local social acceptance, environmental impacts, logistical construction challenges and long-term maintenance requirements and capability should all be sought to be better understood in parallel.

A waste to energy (WTE) plant was also identified as being potentially of benefit in reducing national greenhouse gas emissions (particularly waste emissions). However, its viability depends on the composition of the waste feedstock extracted from the waste stream, and the technical feasibility of WTE on Majuro. It is recommended that a feasibility study of the viability of WTE on Majuro is undertaken, including more detailed consideration of the effect on greenhouse gas emissions. As such, WTE is not included in the technology pathways at this time.

In all scenarios, solar PV features. Many of the PV capacities suggested by the modelling would require a significant footprint. This is may require considering of the use of floating arrays in the lagoons. Since demonstration of seawater floating PV systems is still in its infancy, some accelerated focus towards a demonstration in the Majuro lagoon is urgently needed.

At this time, without a full understanding of which renewable energy technologies will be mature and cost competitive in 2050, the use of biodiesel is highly recommended to meet the 2050 target, if the relative price of biodiesel remains at around or below 2018 levels. Biodiesel, as a 'last-mile' technology, caps the capital investment, and consequently, cost of energy.

Finally, it is highly recommended that techno-economic analysis is re-run before each major milestone (i.e. before 2025, 2030, and 2050 targets) based on methodologies outlined in this document, to ensure any recent changes in modelling input data is captured and considered.

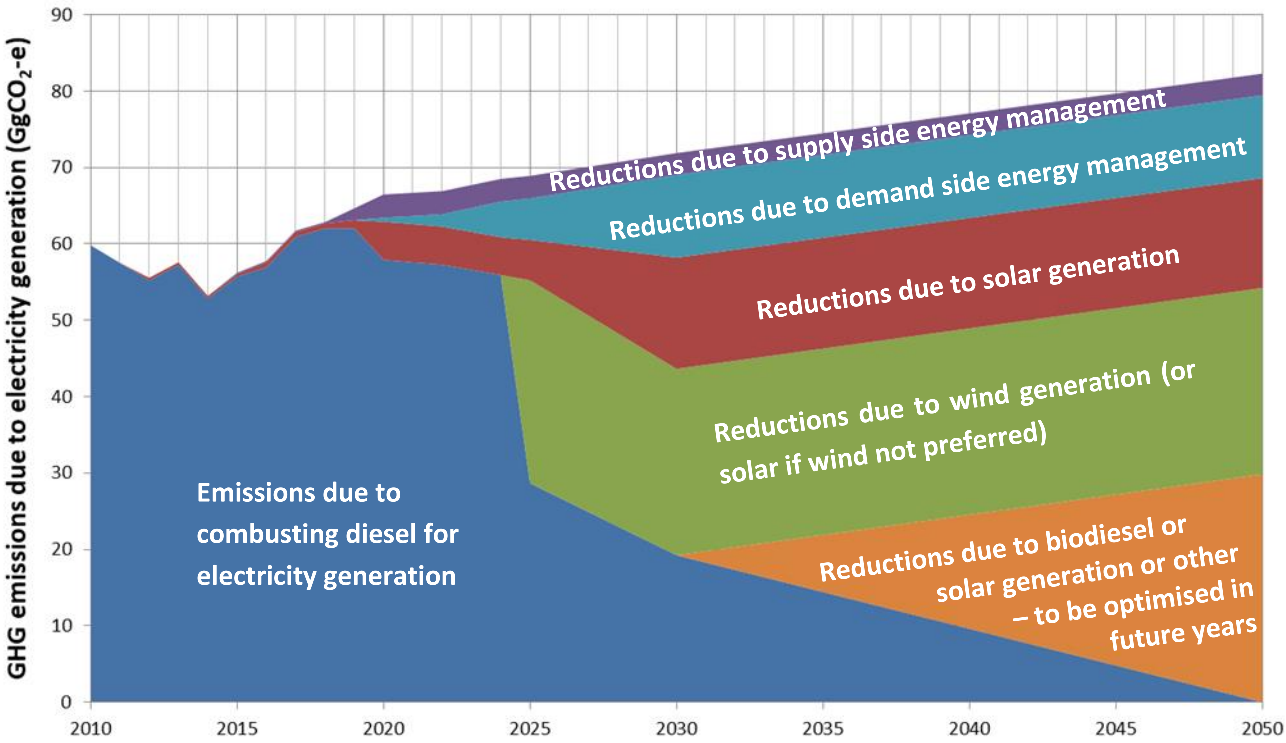

Figure 0.1 Wedge diagram of recommended RMI electricity sector solution to contribute to national emissions targets

1 Introduction

1.1 Rationale

The Republic of Marshall Islands has committed to a bold goal of achieving 100 % reduction of its GHG emissions by 2050. One of RMI's largest GHG emitters is its electricity sector, which heavily relies on fossil fuels. Consequently, the RMI government needs a sound strategy that will transform its electricity sector from the present state to a GHG-free state by 2050.

The '*Support for RMI Renewable Energy Activity'* project financed by New Zealand Ministry of Foreign Affairs and Trade (MFAT) focuses on this question. Its main activity, the RMI Electricity Roadmap, will produce a strategy for the RMI's electricity sector along four themes:

- Technology pathways,
- Human resource strategy,
- Financing strategy, and
- Policy roadmap.

The techno-economic analysis presented in this document is a supporting document for the Technology pathways and focused on modelling an electricity sector transition to an all-renewable, GHG-free future; considering RMI's energy needs, viable technologies, RMI's renewable resources, technology costs and using well-proven methodologies.

1.2 End state

Customers in the RMI live across a number of atolls. Depending on the number of residents on each, there are three basic types of power systems providing electric energy to customers: stand-alone systems supplying a family or a few families or a community facility, reticulated systems supplying power to larger number of families and small businesses in communities, and large-scale reticulated power systems supplying thousands of customers, including RMI's commercial and industrial sectors, on the main islands of Majuro and Ebeye. This techno-economic analysis models a pathway for the renewable energy journey of each of the large systems of Majuro and Ebeye, and uses previous analyses and simple modelling to propose a solution for the other system types.

This techno-economic analysis document will further be used as a basis for preliminary discussions with RMI government representatives and will serve as an input into the final RMI Electricity Roadmap document.

1.3 Aim

The aim of the Techno-economic analysis is to identify high-level technology pathways for the RMI electricity sector to contribute to reductions in economy-wide national greenhouse gas emissions from 2010 levels by 32% by 2025, 45% by 2030, and 100% by 2050. It does not attempt to identify specific projects, project capacities, sites, equipment selection etc. and it is not intended that the capital costs and resultant Levelised Costs of Electricity be taken for budgeting purposes. As a high level pathway development its intention is to be directional rather than specific.

1.4 Method

The techno-economic analysis presented in this document used the following approach:

1. Determine which technologies are suitable for RMI island power systems and determine the pathway for integration of those technologies,

2. Define technology pathways for RMI islands for achieving RMI national targets,

3. Define inputs and assumptions for computer modelling of RMI island power systems, and

4. Analyse, present and discuss modelling results.

1.5 Document flow

Following the outlined Method, this document is structured as follows:

- **SECTION 2 – Background to transitioning from diesel power to renewable energy** – Outlines the approach for modelling a pathway from diesel generation to zero emissions generation for typical island power system types, identifying which technologies are typically used when and why. It also describes the approach taken to choose a mix of appropriate technology to reduce emissions from electricity generation on large and medium islands, as well as individual household systems.
- **SECTION 3– Techno-economic analyses methodology** – Describes the tools and approach used to determine potential mixes of appropriate technology for RMI power systems.
- **SECTION 4 – Modelling Inputs and Assumptions** – Provides or references all inputs used in the techno-economic modelling for Majuro and Ebeye; including each system's energy needs, viable technologies, renewable resources, and costs for proposed technologies.
- **SECTION 5 – Modelling Results** – Outlines the techno-economic analysis results – the mix of technologies expected to meet the targets at lowest cost under the chosen assumptions and scenarios.
- **SECTION 6 – Discussion and Recommendations** – Concludes the document and provides technical pathway for all considered RMI power systems.

2 Background to transitioning from diesel power to renewable energy

Currently almost all GHG emissions from the RMI electricity sector result from the combustion of diesel to generate electricity. A relatively small amount of emissions may also result from lubricating oils which make their way into the cylinders of the generators. The generating technologies considered in this report to displace this diesel combustion are solar photovoltaics (PV), wind turbines,, and replacing the mineral diesel with sustainably sourced biodiesel.

This section outlines the general approach for introducing renewable energy generation into typical island power systems. This approach determines the staging of renewable energy and enabling technologies and determines limits and opportunities for renewable energy penetration. This provides a framework to address the question of which technologies need to be implemented at which stage and why.

Based on this general outline, further review and analysis of the RMI context is presented.

2.1 Typical renewable energy technology pathway in island power systems

Diesel generators (DGs) are a technology developed in the first half of the 20th century. With almost a century-long development and constant improvements, diesel generators provide both necessary electric energy and reliability of power supply to island power systems. The quality of service DGs provide is also somewhat comparable to the service customers in large interconnected systems enjoy. Therefore, any changes to an island power supply must provide the same or better level of service to its customers.

On the other hand, renewable energy generation is still a collection of relatively young technologies. Presently, variable renewable energy (VRE)[6] generators can generate electric energy during favorable conditions, but do not have capability to provide high reliability of service or greater support to power system stability. For this reason, complementary “enabling technologies” often need to be introduced alongside VRE generators to match both the energy generation and the reliability of service traditionally provided by diesel generators.

These enabling technologies are devices which usually do not necessarily generate electric energy but are integrated into hybrid diesel/RE systems to reduce system reliance on the diesel generators to provide all necessary services. As the contribution from VRE sources increases, the contribution from the diesel generator decreases, and so more enabling technologies are required.

The transition to renewable energy power systems from typical island diesel power systems can be broken down into five distinct stages:

1. Diesel only operation
2. Introduction of renewables
3. Expansion of renewables and introduction of enabling technologies
4. Expansion of renewables and enabling technologies, and
5. Zero-diesel operation.

These five stages are explained in detail in the following sections.

2.1.1 Stage 1 – Diesel only operation

Stage 1 is where all island power systems initially based on diesel generation start their renewable energy journey from.

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[6] i.e. solar and wind

As presented in Figure 2.1, island load varies during a day. During all that time, the total capacity of running diesel generators (operating and 'online') is always more than the island load. This approach ensures that any sudden load increase is met with sufficient generation capacity and this approach is practiced across all island power systems. Diesel generators should not be run at very low loads, as this greatly increases maintenance costs and results in poor fuel economy. The dashed red line presents the minimum load the current running diesel capacity could provide; therefore, the running diesel capacity is always planned so that the load curve sits between the 'Diesel capacity' and 'Diesels Min load' lines.

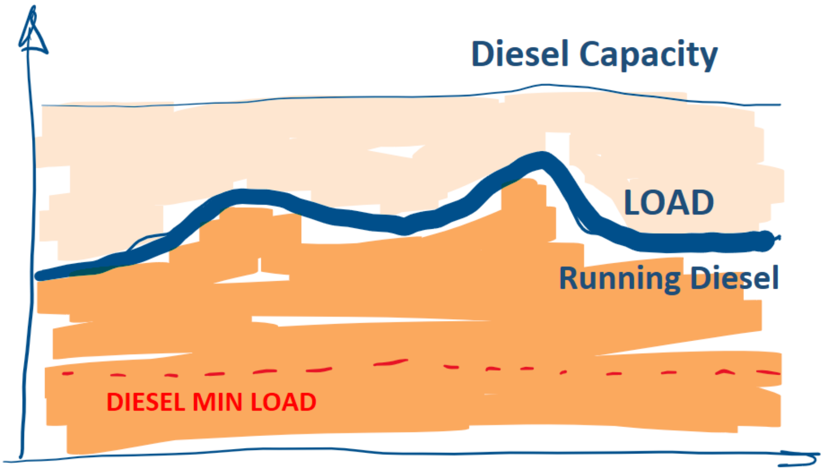

Figure 2.1 - Stage 1 - Diesel only operation

There are zero-to-little renewables present in the Stage 1 system; if there are, their effect is negligible.

2.1.2 Stage 2 – Introduction of renewables

In Stage 2, renewable energy generation is introduced into an island power system. As in Stage 1, island load varies during a day and there is always enough running diesel generation capacity to cover entire island power system load, and any sudden increases. Renewable energy generation effects are usually noticed by diesel generators as reduction of island power system load. Figure 2.2 presents the effect renewables have on diesel generation, where a portion of the load is now supplied by renewables, resulting in a smaller portion by diesel generation.

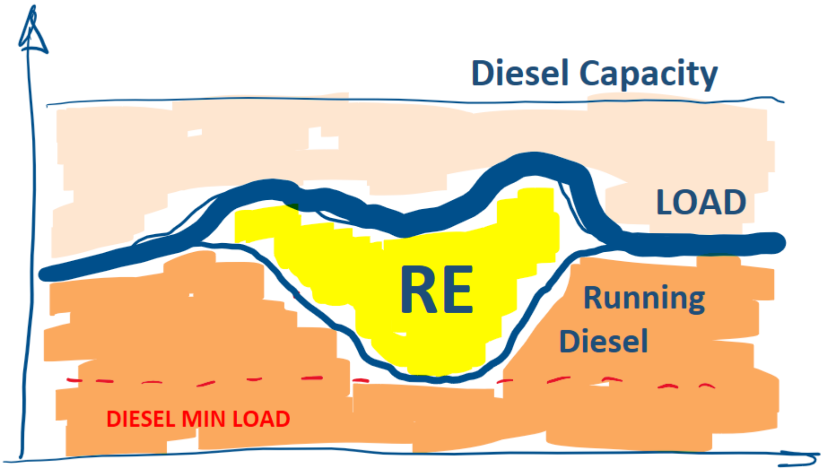

Figure 2.2 - Stage 2 - Introduction of Renewables

As mentioned in the previous section, the load curve must always be planned to sit between 'Diesel capacity' and 'Diesels min load' lines. This minimal loading of diesel generators presents a limitation on the renewable energy generation. This limitation can only be removed by reducing the number of running diesel generators. However, if the number of running diesel generators is reduced, then the total diesel capacity is reduced. This may result in insufficient running diesel generation capacity to supply the current load, or any sudden increase of the load, or compensate for any sudden drop in VRE generation. This may impact the stability and reliability of the island power system supply, which forces introduction of enabling technologies in Stage 3.

2.1.3 Stage 3 – Expansion of renewables and introduction of enablers

Enabling technologies are introduced to solve the problems introduced in Stage 2. When there is not enough running diesel generation to cover the current island load, additional enabling technologies support renewable generation by providing additional power system stability and reliability of power supply.

As before, the island load varies during a day, but in Stage 3 running diesel capacity is most of the time less than the island power system load. It is interesting to note that the 'Diesels minimal load' line is lower than in Stages 1 and 2 due to less diesel machines needing to be in operation. Consequently, there is much more space for renewable generation to fill. As Figure 2.3 demonstrates; renewables are now supplying more of the island load than diesel generation.

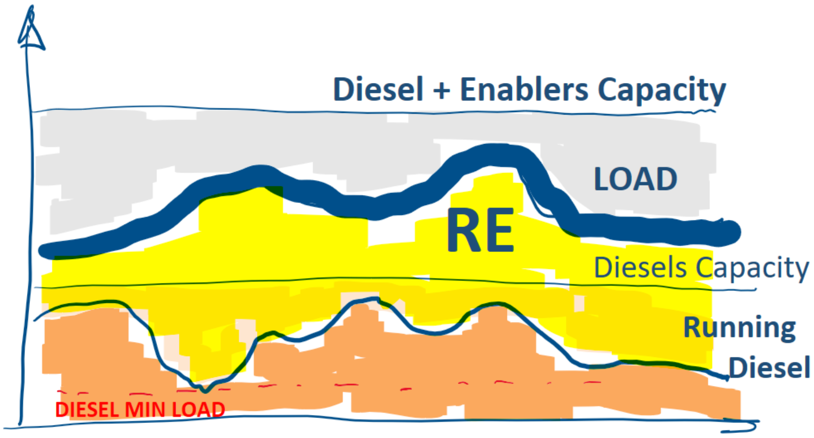

Figure 2.3 - Stage 3 – Expansion of renewables and introduction of enablers

Because of the enabling technologies, generation capacity is still maintained above the island load, with a healthy margin for sudden load increases or sudden drop in VRE generation. Following this approach, higher quantities of renewable energy generation can be integrated into an island system, without compromising island power system stability and reliability of its power supply.

However, diesel generation is still present, albeit with reduced capacity, and provides a backbone for power system stability. It should also be noted that even in Stage 3 the island will still have sufficient diesel genset capacity to cover situation where no RE resource (poor weather/no wind) is available and the enablers are insufficient, however when not switched on it cannot feature in the chart above as "diesel capacity".

2.1.4 Stage 4 – Expansion of renewable energy and expansion of enablers

At this stage, during periods of sufficient renewable energy surplus, a system shall be able to completely switch off entire diesel generation fleet and utilize newly installed enabling technologies to provide required stability services (Figure 2.4). Renewable energy generation is increased even further, with additional solar PV and wind installations. Additional enabling technologies such as larger dump loads, sophisticated control systems and synchronous condensers are added.

At Stage 4, further increasing renewable energy generators are providing most of the energy an island system needs. Diesel generators are run during periods of lower renewable generation availability. Enabling technologies must be fully capable of providing all power system services in the absence of diesel generation. Large battery inverters can provide required real and reactive power and can regulate frequency (and potentially voltage). Dump loads and battery energy storage provide reserve capacity. Synchronous condensers provide required fault levels, system inertia and voltage/reactive power support.

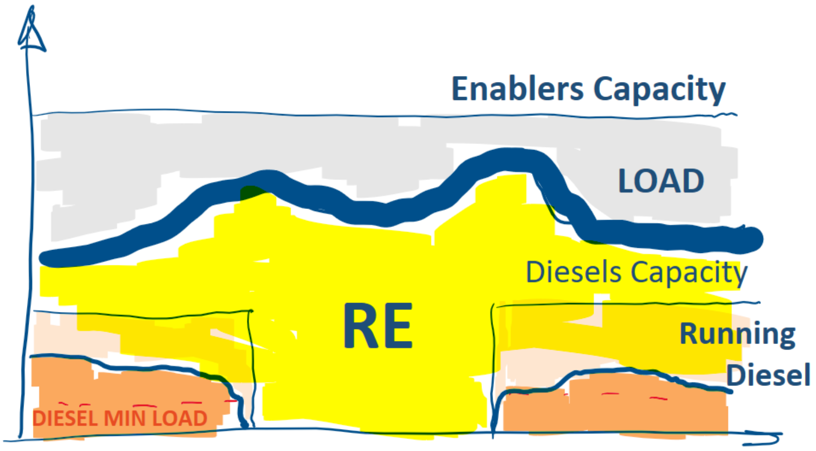

Figure 2.4 - Stage 4 – Expansion of renewable energy and expansion of enablers

The final hurdle an island power system needs to solve on its journey towards 100% renewable energy is to reduce the support of diesel generators even further, to zero, or near-zero -Stage 5.

2.1.5 Stage 5 – Zero-diesel operation

With further increase of renewable generation capacity and some further enabling technologies, sufficient energy is generated from renewable energy sources, potentially stored for low RE periods, and sufficient enabling technologies exist in the island system for its stable and reliable power operation without diesel generation (Figure 2.5).

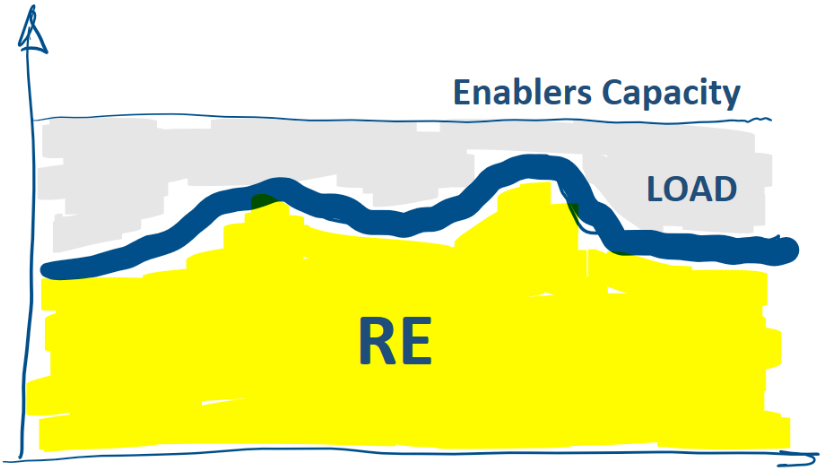

Figure 2.5 - Zero-diesel operation

As always, the load varies during a day, but there is no diesel generation to cover it. The entire load is met by renewable energy generation and supported by enabling technologies. Diesel generators might still be present in an island system but are mostly used in stand-by or emergency situations.

2.1.6 Summary of the transition to renewable energy

The staged process presented in in the previous Sections is summarized in Table 2.1.

Table 2.1 - Renewable energy journey for large-scale island power systems

	Stage 1	*Stage 2*	*Stage 3*	*Stage 4*	*Stage 5*
	Diesel only systems	**Introduction of Renewable Energy**	**Expansion of Renewable Energy**	**Switching off diesels**	**Renewable only energy systems**
Diesel generators (DGs)	DGs are operating at all times	DGs are operating at all times. While they do not supply entire load, running DG capacity is capable of meeting entire load at all times	During high RE generation, some DGs are switched off. Running DG capacity is not capable of meeting entire loads at all times	During very high RE generation, all DGs are turned off for limited periods of time	DGs are almost always turned off and only provide stand-by power.
Renewable energy	RE generation is non-existent or very limited without any larger influence.	RE generation is present and able to deliver up to 70% instantaneous power.	More RE generation is present and capable of providing more than 70 % instantaneous supply.	Further expansion and diversification of RE generation. RE provides 100% for periods.	Further expansion and diversification of RE generation. RE provides 100% supply
Enabling technologies	There are no enabling technologies	Limited presence of enabling technologies	Technologies providing very-short term substitution of DG reliability services are present	Technologies providing multi-hour substitution of DG reliability services are present	Technologies providing long-term substitution of DG reliability services are present
Power system control	Controls are either manual or automatic but very basic.	Controls are necessary to limit penetration of RE and its grids stability impacts.	Sophisticated controls are present to manage multiple energy sources and technologies.	Further sophistication of controls is necessary.	Further sophistication of controls is necessary.

2.1.7 Stability services for island power systems

Diesel generators are capable of providing island power systems with both necessary energy and stability of power supply. Technically, these can be broken down into seven basic services which diesel generators provide; if enabling technologies are used to replace diesel generators, they should not just match the power diesel generators provide, but all other services as well.

Seven basic power services are:

1. ***Provision of real (active) power (kW)*** - Real power is power converted into movement, light or heat that we see and use.
2. ***Provision of reactive power (kVAr)*** - Reactive power supports the conditions for power transfer in transmission and distribution systems but is not consumed.
3. ***Frequency Control*** - As all devices used in RMI are designed for the power frequency of 60 Hz, generation must ensure that the island power system frequency does not deviate much from this value, as it may damage customers' devices.
4. ***Voltage control*** - Similarly, all devices used in RMI are designed for the voltage level of 120 V, and generation must ensure that the customers always receive this or very similar voltage level. Otherwise, higher voltage levels might damage the customers' devices.
5. ***Provision of power system inertia*** - Power system inertia helps the power system quickly recover from transient faults on the grid – the lower the inertia is, the more those faults are felt by the customers on the grid.
6. ***Provision of fault currents*** - Generators provide currents to 'clear the fault' (i.e. blow the fuse or trip the circuit breaker) quickly, as soon as it appears, and before any of the customers attached on other circuits may notice. Not providing currents high enough to clear a fault quickly may result in system-wide blackouts.
7. ***Provision of spinning reserve*** – Generators are generally always operating at less than 100 % of their rated capacity (and some can run above their rated capacity), thereby leaving some 'spinning reserve' in case of sudden load increases. This insures that, if a load does increase for whatever reason, enough generation capacity will be present to meet it, and customers will not suffer an interruption in power supply.

Renewable energy generation can generate clean energy, without (or with very low) greenhouse gas emissions. However, this comes with a high cost – renewables are not capable of providing all necessary services in a power system that are provided by diesel generators.

The two most widely used renewable energy sources, wind and solar energy, can provide Real Power and Reactive Power to their customers, but are only the first two of the previously listed services needed by an island power system.

Other widely used renewable energy generation systems are hydro energy and biomass, as discussed in the RMI Roadmap technical note *Renewable Energy Generation and Enabling Technologies Review*. Traditionally, hydro machines can provide all seven of the necessary stability services. Unfortunately, RMI does not have the topograpghy and surface water necessary for hydro power. Biomass or bio-fuel generators are very similar to diesel generators and can also provide all seven of the necessary stability services. Their downside is that the cost of energy is usually higher than from diesel, and usually much higher than solar and wind cost of energy. Further, they can be challenging to operate due to the inconsistency in their feedstocks.

To supplement renewable energy generation, and to provide necessary stability services, enabling technologies are used. As discussed [1] there are a few enabling technologies which can support a high renewable energy penetration power system. This report will focus on four technologies:

1. ***Inverter - battery technologies*** – Modern inverters with batteries can generate real and reactive power, provide voltage and frequency control. Given a sufficiently large battery capacity, they can provide spinning reserve for any needed amount of time.
2. ***Synchronous condensers*** – can generate reactive power, provide voltage control, provide power system inertia, and provide necessary fault currents.
3. ***Dump loads*** – simply provide some limited but quick access to spinning reserve in an island power system during times of renewable energy generation surplus.
4. ***Control systems*** – enable all the conventional, renewable, and enabling technologies to work together and provide service of sufficiently high quality.

Depending on the system, some or all the above enabling technologies could be used.

2.2 The RMI context

In the case of the RMI, there are three different island system types, which provide electric energy to its citizens:

- Small or household power systems (individual power supplies) – for isolated customers which have very basic power needs and consist of a family or several families living together;
- Medium sized reticulated island power systems – the islands of Jaluit, Wotje, Rongrong, etc, which are home to a hundred or several hundred residents with very limited infrastructure, with loads mostly of residential nature; and
- Large sized reticulated island power systems – the islands of Majuro and Ebeye which are home to thousands of people and have infrastructure with sophisticated needs for electric energy quality.

Each of the three island systems has a different renewable energy implementation approach. The following text therefore describes the approach taken for each of the three system types.

2.3 Individual household power systems technology pathway

2.3.1 Overview

Small home-scale individual power supplies are used for very modest power supply needs in communities with very few households together, or single households. Typical devices used in these small systems are lights, fans, television, computers and small kitchen appliances.

Small home-scale power supplies usually generate and operate on the low or extra-low voltage level, do not have any distribution network or distribution transformers, and the entire amount of produced electric energy is consumed locally.

As described in [2] , the necessary service levels for individual household power supplies are low and interruptions to power supply due to unexpected faults or during adverse weather conditions are acceptable. Therefore, ideal small island power systems consist mostly of renewable energy generation coupled with very basic enabling technologies, mostly in the form of battery energy storage.

2.3.2 Transition goals

Most households in RMI who wish to have access to electricity already do so. For those households not connected to a grid, this means that a solar household system (SHS) has been installed.

The transition goals for SHS should aim to achieve appropriate service level and the ability of locals to maintain and operate installed technologies. Those systems need to provide customers:

- Necessary real and reactive power,
- Sufficient amount of daily energy,
- Reasonable reliability as determined by small island power system service level requirements [2] ,
- Simplicity of operation, and
- Simplicity of maintenance.

There may be justification in increasing access to productive uses of energy for rural development, possibly at community level, although this would need to be balanced with the commensurate increase in costs to replace end of life components such as batteries. This balance requires further investigation beyond the scope of this work.

2.3.3 Proposed Approach

Small home-scale power systems are established technology and can be installed as off-the-shelf systems, either as purely diesel/gasoline or solar/battery installations. Based on the understanding that most rural households that wish to have a solar household system already do so, the approach to increasing renewables and reducing diesel is to improve serviceability, reliability and maintenance of these systems, and in some cases, increasing their capacity.

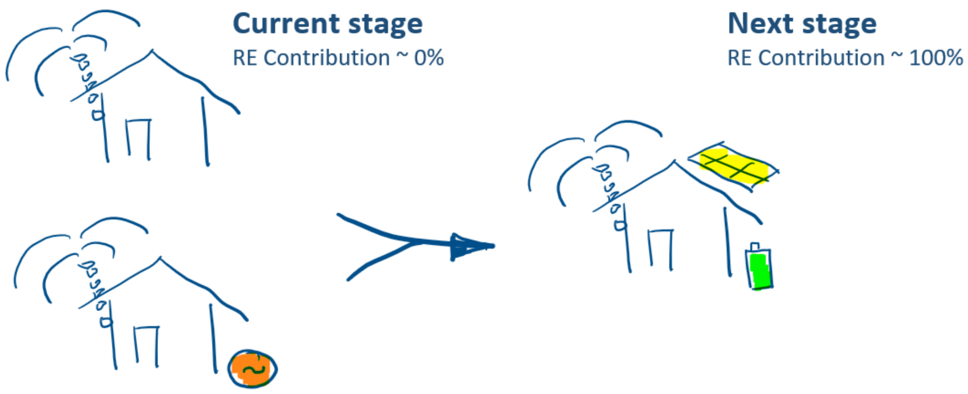

Figure 2.6 - Small island power system transition

Installed systems must be of sufficient capacity to provide the required real power (usually up to few kW), the required energy (usually up to few kWh per day), and adequate energy storage in case of several low-renewable generation days. They must also be easy to operate and maintain.

Table 2.2 – Summary of recommended small island power system approach

Household scale power system			
Services	**Stage 1** 0 % RE generation	**Stages 2, 3, 4**	**Stage 5** Near-100% RE generation
Real power	All provided by small diesel generation	Not suggested	Provided by solar PV and battery energy storage inverters
Reactive power			
Frequency control			
Voltage control			
Inertia provision			Not provided
Fault Currents provision			Not provided – whole inverter may trip off
Spinning reserve provision			Not provided

In lieu of a robust investigation into outer islands energy needs, we have assumed an investment of $3.7m around 2028 to increase energy services provided. This was assumed to lift annual costs to operate and maintain these systems from about $1m per year to about $1.8m per year. See the technical note *Supply of electricity to outer islands* [2] for details of assumptions used.

2.4 Medium island power systems technology pathway

2.4.1 Overview

Island mini-grid power systems are used on islands with communities ranging from a few families up to several hundred people living near to each other. Most of the loads are still of a basic, residential nature; while some of them can be more sophisticated, such as occasional air-conditioners or washing machines. Typical devices used in these small systems are lights, fans, television, computers and small kitchen appliances. Mini-grid power systems can also support small commercial or limited industry operations.

Medium sized island systems usually have distribution networks of a higher voltage level. In RMI, these voltage levels can be 6.42 kV or even 13.8 kV.

As described in the technical note *RMI Islands Suggested Service Levels*, the necessary service level for medium island mini-grids is higher than a required service level for small home-scale power systems, but it is still a long way from a service level required by large grids. So, some interruptions to power supply and some power restrictions are acceptable.

Enabling technologies in medium island power systems rely heavily on inverter-battery enabling technology, which can provide necessary real and reactive power, voltage and frequency control, and can store sufficient amount of energy for use during low-renewable energy generation time periods. While this is very similar to home-scale systems, the difference in inverter-battery systems for mini-grids is in the size of the inverter, which must meet the need of energization of the distribution network, and the size of the battery, which must provide slightly higher energy storage capacity.

2.4.2 Transition goals

Medium-size island power systems such as Jaluit and Wotje depend on a centralized power house and a distribution grid to provide energy to customers across the island. A centralized power house is a shed-type basic building with a couple of smaller diesel generators which run either individually or in parallel. Operation and maintenance requirements for medium-size systems is higher than for small systems, and a higher level of training and electric industry knowledge is required.

Any transition to renewable energy to reduce in greenhouse gas emissions needs to take into the account the necessary service level and ability of locals to maintain and operate installed technologies.

Medium-size power systems need to provide to their customers:

- Necessary real and reactive power,
- A sufficient amount of daily energy,
- Sufficient reliability as determined by the medium island power system service level requirement (see technical note *RMI Islands Suggested Service Levels)*,
- Simplicity of operation, and
- Simplicity of maintenance.

Based on the above criteria, the suggested transition for medium-size island power systems is a direct move from a stage 1 system to a stage 5 system. The existing centralized diesel power house would be modified to a near-100 % centralized renewable power house (Figure 2.7) which generates power from solar panels and potentially, small wind turbines; has sufficient battery storage; adequate LV and HV switching electric systems; a step-up transformer; a simple control system and an adequate building for housing all those technologies (given the corrosive environment).

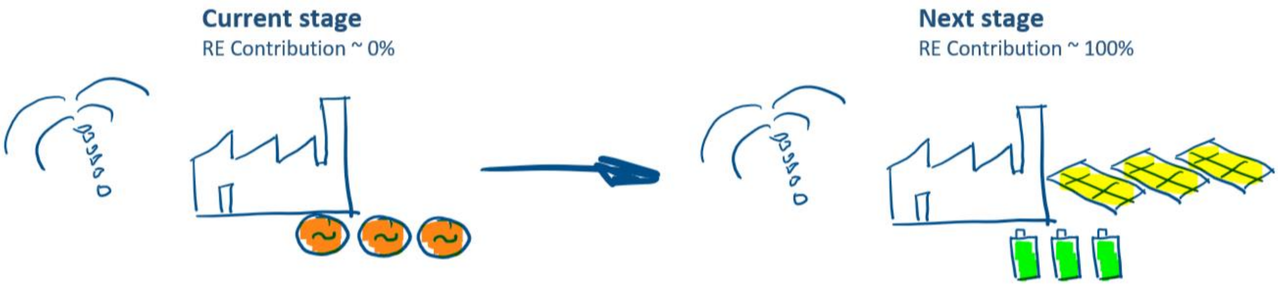

Figure 2.7 - Medium island power system transition

This recommendation for a direct transformation of the system of this scale is based on the following reasoning:

- The current systems are in a state of decay and the entire systems would welcome a change;
- There are numerous examples in the Pacific on effectiveness of this approach (such as Tuvalu or Cook Islands);
- A staged process where diesel generators and renewable generation work in parallel before an exclusively renewable system is installed can introduce unnecessary complications;
- The required service levels are less stringent than those for the large island grids, and allow a system without multiple enabling technologies; therefore, the renewable energy journey for a medium island power system depends on simple renewable generation, battery energy storage and a simple control system;
- Projects of this type are often cost-effective compared to diesel due to the high cost of transporting diesel to these islands;
- Outer island projects tend to incur high fixed logistic costs, reducing the cost effectiveness of multiple staged small projects;
- If a project secures necessary land and builds new renewable power house for storage of batteries and controls, this momentum and mobilization of installers should be utilized for cost-effective finalization of the renewable energy journey; and
- It facilitates adequate service level to its customers.

2.4.3 Previous analyses of RMI medium sized island mini-grids

A number of previous studies have performed techno-economic analyses of three RMI mini-grids in Wotje, Jaluit and Rongrong: JICA [3] , SolarCity [4] and IT Power [5] . These studies each appear to have applied different aims and approaches to the economic decision.

The JICA study appears to have selected the configuration which maximises renewable contributions without requiring energy storage and without curtailing significant quantities of renewable energy. The resulting diesel fuel savings are comparatively low as a result.

The SolarCity approach was to use a fully burdened cost of diesel to these islands, which includes a very high transport cost. In addition, diesel fuel prices are assumed to increase by 6% every year. Under these assumptions, the least cost configurations are predominantly solar/battery systems which basically only retain the diesel generators for occasional back up. The total capital cost each of the three systems is around $5m.

The IT Power approach was to size a system with the aim of producing 90% of the electricity with a solar/battery system and retain the diesel generators for occasional back up. For costing, it is assumed that hybrid systems for these three islands plus another three unnamed islands are implemented as one project, with a combined capital cost of $15M.

Table 2.3 - Previous recommendations for RE projects on Wotje

	PV	Wind	BESS[7]	%RE
JICA	50 kW	0 or 25 kW	none	7 - 14%
SolarCity	450 kW	none	3360 kWh	98%
IT Power	560 kW	none	1400 kWh	90 %

Table 2.4 - Previous recommendations for RE projects on Jaluit

	PV	Wind	BESS	%RE
JICA	50 kW	0 or 25 kW	none	7 - 13%
Solarcity	300 kW	none	1680 kW	91%
IT Power	400 kW	none	1170 kWh	90%

Table 2.5 - Previous recommendations for RE projects on Rongrong

	PV	Wind	BESS	%RE
Solarcity	60 kW		420 kWh	99%
IT Power	105 kW	none	230 kWh	90%

2.4.4 Proposed Approach

Given the high costs and subsidisation of diesel generation in these grids, the ambitious national emissions targets, and the high fixed logistic costs of outer island projects; we agree with the approach suggested by Solarcity and ITPower to move directly to high levels of renewables in the RMI mini-grids rather than small expensive iterative projects. Therefore, detailed techno-economic analysis has not been repeated for these RMI mini-grids. Instead, the assumption was made that RMI mini-grids should move to at least 90% RE by 2025, and to 100% RE by 2050.

A larger solar/battery system will be enough to provide required real power (usually up to a hundred or few hundred kW), required energy (usually around 2-3 MWh per day), adequate energy storage in case of several low-renewable generation days, and will be relatively easy to operate and maintain. Battery inverters would not be able to provide enough fault current to clear all distribution faults, so a system may end up in a blackout from time to time, which is acceptable for a system of this size [2] . Some form of computerized remote support and monitoring and support from a nearby large island is necessary (remote monitoring could be provided by sending automated information to an operations center or even to a smart phone on Majuro. Support could be provided by phone or internet from the main island of Majuro). Finally, one or two small diesel generators should be installed to provide stand-by or emergency generation services to the island

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[7] Usable capacity

if the existing generators are dilapidated or unsuitably sized. The proposed approach is summarized in Table 2.6.

Table 2.6 – Summary of recommended medium island power system approach

Medium Island Power system			
Services	**Stage 1** 0 % RE generation	**Stages 2, 3, 4**	**Stage 5** Near-100% RE generation
Real power	All provided by small diesel generation	Not suggested	Provided by solar PV and battery energy storage inverters
Reactive power			
Frequency control			
Voltage control			
Inertia provision			Not provided
Fault Currents provision			Not provided
Spinning reserve provision			Provided by battery energy storage

The main small or medium sized mini-grids are Wotje Island (Wotje Atoll), Jabor Island (Jaluit atoll), Rongrong Island (Majuro Atoll), Kili Island, and Rongelap Island. In addition, Eniburr Island (Kwajalein Atoll), also known as Santos Island, does not currently have a distribution network but may be a candidate for a new mini-grid system, with around 1,000 residents currently served by private household generation. Establishment of a mini-grid system for Santos would also require establishment of a utility type entity to operate and maintain it.

The previous studies suggest that a high renewables system for Jaluit may cost around $2.5m, around $4m for Wotje, and $0.5m for Rongrong. In 2013 Kili used 155,000 USG of diesel [12], more than Wotje and Jaluit combined (possibly due to no electricity tariff) – more recent data is not available. Implementing a mini-grid on Santos Island would also require the establishment of a distribution network. Without designing and costing these systems, we make the assumption that the combined cost to establish these high renewables mini-grid hybrids (solar/battery/diesel or biodiesel) will be in the order of USD 22 million.

Table 2.7 - Estimated baseline fuel use and costs of RMI mini-grid candidates

Mini-grid	Estimated fuel consumption (USG)	Fuel cost at $2.45/USG plus $4.49/USG outer islands delivery cost[8]	Estimated annual fixed O&M	Estimated annual generation tech O&M[9]	Estimated total annual utility costs
Wotje	49,000 [7]	$340k	$235k	$41k	$616k
Jaluit	50,000 [7]	$347k	$242k [13]	$61k	$650k
Rongrong	5,100 [4]	$13k (no outer islands delivery cost applied)	Assumed incorporated into MEC Majuro costs	$4k	$17k
Santos	Private household generation – ignored	-	-	-	-
Kili	155,000 (2013 MEC data, assume no change in demand)	$1,076k	$242k (based on Jaluit)	$150k (3x Wotje/Jaluit)	$1.5m (speculative)
Rongelap	32,500[10]	$226k	$235k (based on Wotje)	$41k (based on Wotje)	$500k (speculative)
Total					**$3.3m**

Table 2.8 - Estimated fuel use and costs of RMI mini-grid candidates with 90% renewable energy

Mini-grid	Estimated fuel consumption (USG)	Fuel cost at $2.45/USG plus $4.49/USG outer islands delivery cost	Estimated annual fixed O&M	Estimated annual generation tech O&M[11]	Estimated annual deposit in reserve fund[12]	Estimated total annual utility costs
Wotje	4,900	$34k	$235k	$62k	$91k	$422k
Jaluit	5,000	$35k	$242k	$47k	$78k	$402k
Rongrong	510	$1.3k (no outer islands delivery cost applied)	Assumed incorporated into MEC Majuro costs	$11k	$18k	$30k
Santos	5,000 (estimate based on Wotje and Jaluit)	$12k (no outer islands delivery cost applied)	$242k	$62k	$91k	$407k (speculative)
Kili	15,500	$108k	$242k	$164k	$254k	$768k (speculative)
Rongelap	3,250	$22k	$235k	$47k	$91k	$395k (speculative)
Total						**$2.4m**

To expand these systems to 100% renewable energy by 2050 may require replacing the ~10% diesel fuel remaining in use with biodiesel.

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[8] In 2016, a $449k RepMar subsidy was applied to Wotje and Jaluit [13] which used 100,000USG diesel combined.

[9] Lubricants and diesel generator replacements ignored

[10] This was the quantity of diesel sold by MEC to Rongelap local govt in FY2016, assumed to be for electricity generation

[11] Based on annual PV O&M of $60/kW and annual BESS O&M of $20/kWh useable

[12] Based on PV inverter replacement after 10 years @ $200/kW, PV system after 25 years @ $2000/W, BESS after 10 years @ $325/kWh useable

2.5 Large island power systems technology pathway

2.5.1 Overview

There are two large island power systems in RMI; the atoll of Majuro and the island of Ebeye on Kwajalein Atoll. Both islands are home to thousands of residents, businesses and industries (although somewhat smaller in Ebeye). Therefore, loads range from simple residential to sophisticated loads, with high demand for stability and reliability of power supply.

These large systems have high voltage distribution grids with customers distributed across multiple feeders. The distribution voltage level is 13.8 kV.

As described in [2] , the necessary service level for large island systems is much higher than the required service level for medium and standalone home-scale power systems, but it is still a long way from the service level required by large grids. The level of power supply interruptions should be brought to a minimum, and the quality of delivered electric energy should be increased.

Low-emissions large island power systems will rely on multiple renewable energy generation technologies, as well as multiple enabling technologies. These systems use a variety of enabling technologies for their successful transition to 100 % renewable generation.

2.5.2 Transition goals

The large island power systems of Ebeye and Majuro each depend on a sophisticated centralized power house and distribution grid to provide energy to customers across the island. The operation and maintenance requirements will be very high for a high contribution of renewable energy to these large island systems as many cutting-edge technologies will be used and managed at the same time. High levels of training and electric industry knowledge will be required to operate these networks.

The transition to renewable energy (and consequently, reduction in greenhouse gas emissions) needs to take into the account the necessary service level and ability of locals to maintain and operate installed technologies.

These systems need to provide customers:

- The necessary real and reactive power,
- A sufficient amount of daily energy,
- Sufficient reliability as determined by the large island power system service level requirement [2] ,
- The required power quality.

Based on the power system size and the above criteria, the suggested large power system transition is a staged transition, based on the following reasoning:

- Transitioning to 100 % RE in a single step would be both financially and technically tenuous (see technical note *Pathway to 100% RE by 2020* for more details);
- Large systems need more enabling technologies to maintain the required reliability levels. This increased complexity results in a highly complex operation of the system, and requires specialized skillsets, both of which need time to develop;

- Large quantities of renewable generation might be distributed across an island's network and might require new approaches to governing a power system, which needs to happen gradually;
- The number of changes to a large power system is higher, and some of the changes need to happen before the others, hence the staged process;
- While the system is changing, the customers will still expect the same or a better level of service, which would be very hard to manage with a high number of parallel major works.

Therefore, large power systems are likely to take multiple steps before reaching the 100 % renewable contribution goal. This journey, presented in Figure 2.8, might take years or decades to materialize.

2.5.3 Proposed Approach

As presented in Figure 2.8, there are several stages for the transition to 100 % renewable and GHG-free power system:

- **Stage 1** – Planning and preparing the grid for the future renewable energy generation.

  Currently a small amount of renewables have already been installed on the Majuro grid (around 1MW), and imminent projects from the World Bank, JICA and NZMFAT are committed to increasing the contribution from renewable energy on both Majuro and Ebeye. However there remains a need to prepare for variability of future large-scale renewable generation, and its connection to the distribution grid by ensuring diesel generation is renewable-energy-ready and the distribution grid can support bidirectional flow of energy and of sufficient capacity. Therefore, the first stage prior to very significant increases in renewable energy is upgrading diesel generation, distribution grid and any other auxiliary systems and processes.

  At Stage 1, diesel generators are providing almost all of the necessary energy and all required services.

- **Stage 2** – Introducing the renewables.

  While some smaller amount of renewables which do not affect grid stability can be installed in Stage 1, larger-scale renewables are introduced at this stage. In the case of Majuro and Ebeye, solar PV and wind turbines systems are considered. The amount of renewable generation should be determined by economic and power system modelling which will determine the amount of renewable energy which both systems could sustain before any large-scale enabling technologies are introduced.

  At Stage 2, renewable energy generators are providing a small but significant part of the island load, while diesel generators are still providing most of the necessary energy and required power services.

- **Stage 3** – Reducing the number of running diesels.

  To facilitate further renewable energy penetration, a system would start gradually switching off diesel generators. Spinning reserve would then come from the surplus of currently generated renewable energy and installed battery energy systems. This spinning reserve would be required to support a system for few minutes at a time, until the next diesel generator is started and synchronized to the grid. Therefore, this stage will see installation of additional renewable energy generation (solar, wind, waste to energy), and addition of battery energy storage of high power, short storage capacity. Other technologies such as dump load (which provides almost instantaneous access to spinning reserve), and sophisticated control systems are a part of this stage as well.

At Stage 3, increasing renewable energy generators are providing about 50% or more of the energy to an island system. Some enabling technologies are integrated at this stage to assist in reducing the amount of diesel generation by providing some of the power services requirements, such as spinning reserve. Most of the power services are still provided by diesel generators.

- **Stage 4** – Reaching “diesel-off” operation.

  During the period of sufficient renewable energy, the system is able to completely switch off the entire diesel generation fleet and utilize newly installed enabling technologies to provide the required power services for system stability. Renewable energy generation is increased even further in Stage 4, with additional solar PV and wind installations. Additional enabling technologies such as larger dump loads, sophisticated control systems and synchronous condensers are added.

  At Stage 4, renewable energy generators are providing most of energy an island system needs. Diesel generators are run during periods of lower renewable generation availability. Enabling technologies are fully capable to provide all power system services in absence of diesel generation. Large battery inverters can provide required real and reactive power and can regulate frequency (and potentially voltage). Dump loads and battery energy storages provide spinning reserve. Synchronous condensers provide required fault levels, system inertia and voltage/reactive power support.

- **Stage 5** – Reaching near-100% GHG reduction operation.

  This final stage sees mostly further increase in renewable generation and further increase in battery energy storage. The system reaching near-100% GHG reduction is run without diesel generators, during times of both high and low renewable energy generation.

  At Stage 5, solar PV, wind generation and battery energy storage see their final expansion. Other renewable energy generators such as biodiesel generators could be introduced at this stage to avoid the needed exponential increase of battery energy storage. All power system services are provided by renewable and enabling technologies, similar to the previous stage. Diesel generators are still present in the system but are used to provide stand-by/emergency supply only.

The proposed approach is summarized in Table 2.9.

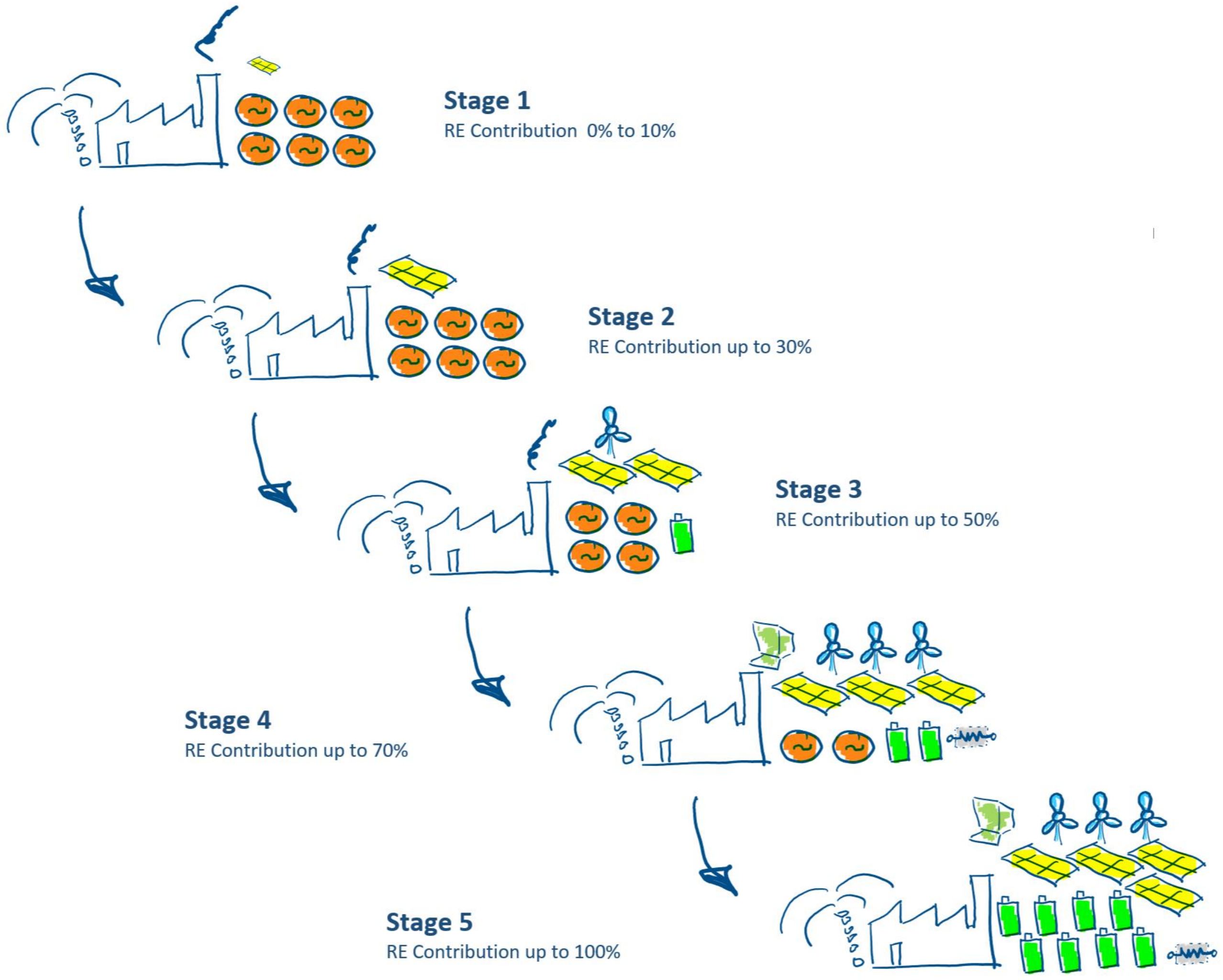

Figure 2.8 - Large island power system transition

Table 2.9 – Summary of recommended large island power system approach

Large Island Power system					
Services	**Stage 1** 0-10% RE	**Stage 2** Up to ~30 % RE	**Stage 3** Up to ~50 % RE	**Stage 4** Up to ~70 % RE	**Stage 5** Near-100% RE
Real power	All provided by diesel generation	Diesels, Renewables	Diesels, Renewables	Renewables	Renewables
Reactive power		Diesels	Diesels	Enabling technologies	Enabling technologies
Frequency control		Diesels	Diesels	Enabling technologies	Enabling technologies
Voltage control		Diesels	Diesels	Enabling technologies	Enabling technologies
Inertia provision		Diesels	Diesels	Enabling technologies	Enabling technologies
Fault Currents		Diesels	Diesels	Enabling technologies	Enabling technologies
Spinning reserve		Diesels	Diesels, Enabling technologies	Enabling technologies	Enabling technologies

3 Techno-Economic Analysis Methodology

The aim of this techno-economic analysis is to identify high-level technology pathways for the RMI electricity sector to contribute to reductions in economy-wide national greenhouse gas emissions from 2010 levels by 32% by 2025, 45% by 2030, and 100% by 2050.

Electricity sector emissions reduction targets depend on a few variables, such as:

- the proportion of national emissions attributed to the electricity sector in 2010;
- the contribution of other sectors to emissions reductions; and
- the future demand for electricity.

Assumptions underpinning these variables are detailed in the RMI Roadmap technical note *RMI GHG inventory and electricity sector targets [7] .* The assumptions listed do include significant uncertainties around accounting for GHG and what other RMI sectors might be able to achieve in terms of GHG reductions. Applying these assumptions enabled maximum allowable diesel consumption constraints to be calculated, which were then applied to simulations of future scenarios. This excluded results which would not meet the targets.

As the targets are national targets, this maximum allowable diesel consumption applies as an aggregate across all electricity generating activities on all atolls and islands of RMI (excluding the operations of USAGKA).

3.1 Methodology for individual household power systems

A techno-economic analysis of small island systems is not included. Considering the costs involved in delivering liquid fuel to these islands, there are real benefits to having renewable energy generation on these islands from household-scale solar home systems. As it was assumed that these islands are principally already using 100% renewable energy systems, the contribution to national emissions reduction is presumed to be negligible. Also, the fuel for electricity to these islands has not been disaggregated from transport and industry fuel within the 2010 GHG inventory used. As a result, this contribution was ignored within the main techno-economic analysis.

3.2 Methodology for medium island power systems

Techno-economic analyses of island mini-grid power systems (described in Section 0) have previously been carried out by others. These analyses were not repeated. The solutions proposed by IT Power for Wotje, Jaluit, Rongrong and three other mini-grids were assumed to be implemented by 2025, and it was assumed that the load on these atolls will not change significantly from what it was in 2017.

As these mini-grid solutions are expected to result in a 90% reduction in diesel fuel use on these islands, the maximum allowable diesel consumptions for electricity in RMI in 2025 and 2030 included the use of 10% of all identified diesel used for electricity in 2017 outside of Majuro or Ebeye.

3.3 Methodology for large island power systems

The remaining allowable diesel consumption in 2025 and 2030 was then applied to Majuro and Ebeye combined. To optimise how much of this quota should be attributed to Majuro vs Ebeye would have significantly increased computation requirements. Instead, it was assumed that similar diesel fuel reductions (from 2010 levels) in percentage terms were required on both Majuro and Ebeye.

Techno-economic analyses of both the Majuro and Ebeye grids were performed, to identify at a high level the most cost-effective combinations of major electrical plant required to achieve these targets.

3.4 Computer modelling

Techno-economic analyses for large island power systems of Majuro and Ebeye were performed using HOMER 3.11 software. HOMER [9] is a computer software model that simplifies the task of designing hybrid renewable energy micro-grids, whether remote or attached to a larger grid. HOMER performs energy modelling that shows which system configuration provides highest economic returns and the lowest cost of energy, based on the input information and constraints.

Energy modelling in HOMER software is done in three steps:

1. Simulation - where the new system components and energy resources are modelled to best reflect the real world.
2. Optimisation – where different sizes and numbers of generating equipment are varied with a goal of finding the best solution - typically the system with the lowest cost of energy e.g. the amount of solar PV, number of wind turbines, number of diesel generators,
3. Sensitivity analysis – where sensitivity of the previously found solution is estimated on multiple parameters such as diesel fuel price, project costs, renewable energy penetration and diesel generator efficiency.

HOMER Energy software is widely accepted by engineers and decisions makers involved with hybrid microgrids - including the Pacific region, where most of the studies and roadmaps are based on this useful tool.

4 Modelling inputs and assumptions

Modelling inputs and assumptions are presented in detail in the technical note *Techno-economic modelling inputs and assumptions* [6] .

A review of viable technologies for use in the RMI Roadmap is presented in the technical note *Renewable energy generation and enabling technologies review* [1]

To meet RMI economy-wide emissions targets, diesel consumption for electricity generation on Majuro and Ebeye will have to reduce by 48% from 2010 consumption by 2025, 64% by 2030, and reach 100% renewable operation by 2050. For an explanation of how these reductions were derived, refer to *TN04 GHG Inventory and Electricity Target* [7], and *TN03 Techno-economic Modelling Inputs and Assumptions* [6]. Each of the above targets were modelled in a separate scenario and compared against the 2010 and near-present-day baseline.

5 Modelling Results

5.1 Majuro

A pre-requisite for the Majuro energy modelling scenarios was an assumed replacement of its existing diesel generation with new high-speed diesel generation, and refurbishment of Majuro's diesel tank fuel farm.

From there, two key options for technology pathways were considered for Majuro:

1. No wind development; only solar PV and batteries are used for reaching GHG targets,
2. Unconstrained wind development, along with solar PV and batteries.

In addition to the two approaches above, biodiesel technology was considered as a last-mile technology between 2030 and 2050 years (Figure 5.1).

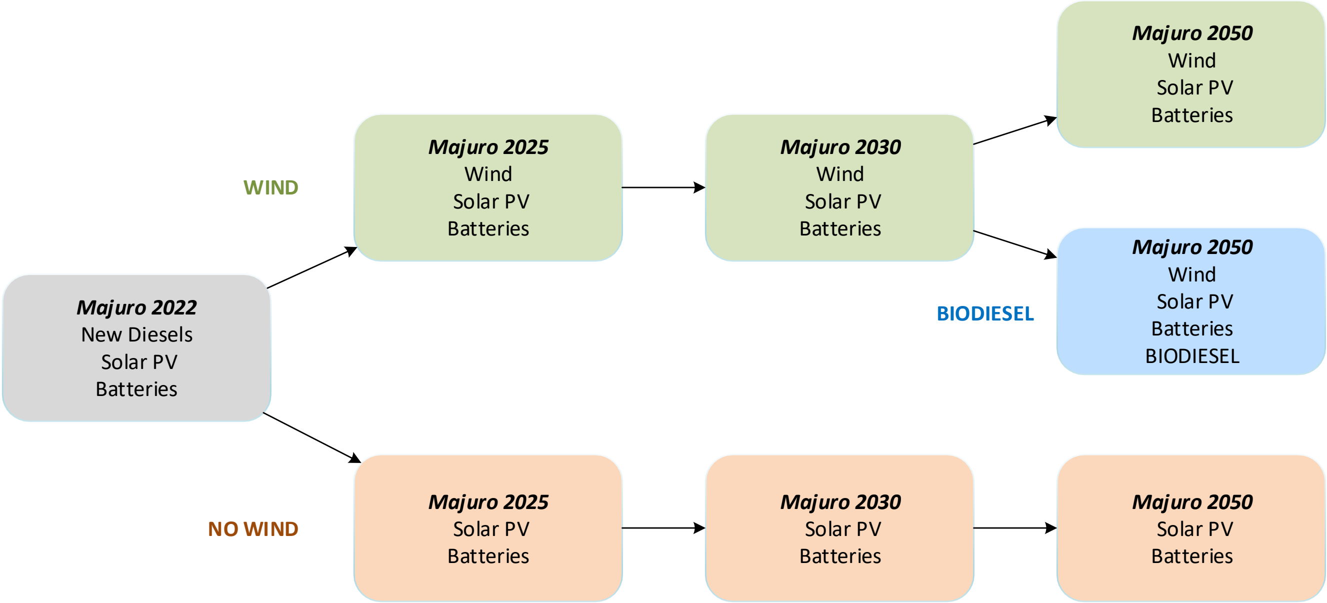

Figure 5.1 - Majuro Technology Pathway Approach

5.1.1 Majuro baseline 2010

Fuel used for electricity generation by MEC in 2010 was **4,486,747 gallons** [11] of diesel. This value presents a baseline against which diesel fuel savings were benchmarked through all scenarios in this section.

5.1.2 Majuro Scenario 2022

There are presently a number of planned projects which will be finalised before Majuro's first 2025 milestone, and their contribution is captured in this scenario, with an estimated finish date of 2022.

Inputs for the Majuro 2022 Homer model are:

- Total fixed capital cost of **$17.09M**, which considers:
    - $15.3M of distribution/system network upgrades [6] ,
    - $1.5M for new power house 1, and
    - $0.34M of wind resource assessment costs,
- Total fixed OPEX cost of **$5.26M**, which considers:
    - Present OPEX (from 2016) of $5.16M [6] , and
    - Additional $0.095M yearly OPEX for newly installed distribution/system equipment,
- New diesel generators (**6 x 2 MW**) are installed for a price of **$0.75/W**, for a total cost of **$9M**
- Total annual load is **65 GWh**, with a calculated average load of 7.42 MW consisting of both an increase in demand and a reduction in supply side losses [6]
- Diesel fuel price assumed at **$2.45** per gallon.
- Pre-existing solar PV generation up to a combined capacity of **920 kW**
- Under the current New Zealand Ministry for Foreign Affairs and Trade project, **137 kW** of solar PV is installed for a total cost of **$0.57M**, and
- Under the current World Bank project, **3 MW** of solar PV and **1.5 MWh** of battery energy storage[13] are installed in Majuro for a total cost of **$22.6M**

Scenario results are presented in Table 5.1 below.

Table 5.1 - Majuro Scenario 2022 - Results

Additional Solar PV size (MW)	Additional Battery size (MWh)	Total Annual Operating Cost ($M)	Total Capital investment from 2018 ($M)	COE ($/kWh)	Diesel Fuel Consumed (Mgal/yr)	Diesel Fuel reduction from 2010 (%)
3	1.5	17.1	49.5	0.294	4.30	4.8

Conclusions from the 2022 scenario are:

- Total fuel consumed is **4,304,000 USG per annum**, which represents **4.1%** of diesel fuel usage reduction (compared to 2010 baseline – noting decreases in demand prior to 2016).
- Total renewable energy infrastructure under Majuro 2022 scenario will be **4 MW** of solar PV and possibly ~**1.5 MWh** of battery energy storage,
- Total **capital investment** from 2018 is **$49.5M**

Although there are some investments in renewable energy, an increase in Majuro load since 2016 results in increase of diesel fuel use, and consequently, GHG emissions.

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[13] The battery size, if included at all, is still under consideration by the World Bank

5.1.3 Majuro Scenario 2025

Building on the Majuro baseline 2022 scenario, the 2025 scenario considers reaching the 48% diesel fuel usage reduction target in Majuro by either using 1) solar PV, wind and battery technologies, or 2) just solar PV and battery technologies.

Inputs into the Majuro Scenario 2025 Homer model are:

- The adopted methodology for 2025 is that the system will be capable of operating in diesel-off mode (Stage 4), when renewable generation conditions allow[14]. This implies additional capital cost of $6M for enabling technologies (10 MVA synchronous condensers and some resistive load banks) which support diesel-off operation.
- Total annual load is **63.8 GWh**, with a calculated average load of 7.28 MW consisting of both an increase in demand and a reduction in supply side losses
- Total fixed capital cost now is **$38.35M**, which includes:
    - Previous capital cost of $17.09M,
    - Additional capital cost spent on distribution/system projects of $15.26M
    - $6M spent on enabling technologies,
    - $0.2M for 2012 solar inverter replacement [6] ,
- Total fixed OPEX is now **$5.36M**, which considers:
    - OPEX from 2022 of $5.26M, and
    - Additional $0.10M yearly OPEX for newly installed distribution/system equipment,
- Renewable energy generation capacity installed by 2022
- Equipment costs for control system, additional solar PV, battery, diesel generators are as defined in [6] .

The Scenario 2025 modelling searched for the lowest technology mix capital cost which pushed the Majuro system over the 48% diesel fuel reduction hurdle. The modelling search space was limited to:

- Solar PV between 0 and 30 MW,
- Wind generation capacity between 0 and 12 MW, and
- Battery energy storage between 0 and 45 MWh.

Modelling results are presented in Figure 5.2 and selected solutions in Table 5.2. The mix of capacities which resulted in just more than 48% diesel fuel reduction and the lowest capital cost is 12 MW of wind capacity, 0 MW of additional solar PV capacity and an additional 18 MWh battery energy storage. This is presented as the larger green dot in Figure 5.2.

The most cost effective solution without wind resulting in just more than 48% diesel fuel reduction consists of 25 MW of additional solar PV capacity and an additional 36 MWh battery energy storage (presented as the larger red dot in Figure 5.2).

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[14] Previous iterations of the modelling suggested that the least-cost configuration on Majuro to reach the 2025 target, while not diesel off capable, had a similar whole-of-life cost to a diesel-off configuration.

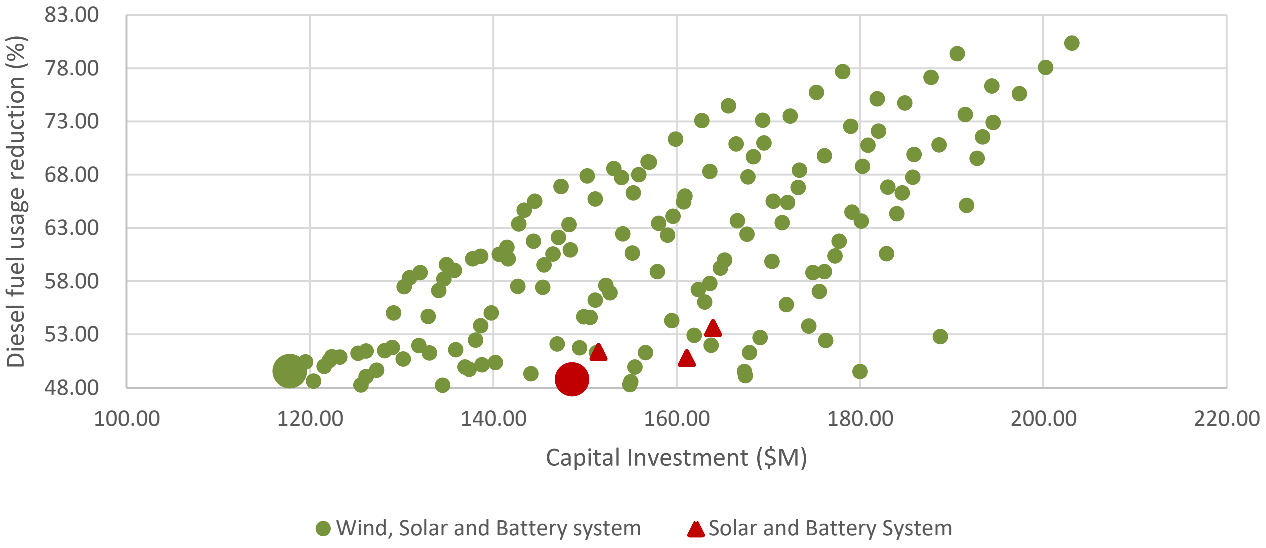

Figure 5.2 – Majuro 2025 scenario modelling results

Table 5.2- Majuro 2025 scenario modelling results

Additional Solar PV (MW)	Wind (MW)	Additional Battery Energy (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX (from 2022) ($M)	Diesel fuel consumed (Mgal/yr)	Diesel Fuel reduction from 2010 (%)
-	12	18	0.285	13.49	117.80	68.3	2.26	49.5
25	-	36	0.321	14.52	148.61	99.11	2.30	48.8

Conclusions from Majuro Scenario 2025 modelling are:

- For no-wind solutions:
  - Cost of energy is **increased** compared to 2022 scenario, reaching $0.32/kWh
  - Annual operating cost is reduced due to lower diesel fuel consumption,
  - Total renewable energy infrastructure under Majuro 2025 no-wind scenario will be **29 MW** of solar PV and **38 MWh** of battery energy storage,
  - Total capital investment is **$149M**, which represents an **additional $99.11M** from 2022 scenario.
- For solutions with wind:
  - Cost of energy is **reduced** compared to 2022 scenario, reaching $0.285/kWh
  - Operating cost is reduced due to lower diesel fuel consumption, and
  - Total renewable energy infrastructure under Majuro 2025 wind scenario will be **4 MW** of solar PV, **12 MW** of wind generation and **20 MWh** of battery energy storage,
  - Capital investment is additional **$68.3M** from 2022 scenario.

5.1.4 Majuro Scenario 2030

Modelling for the year 2030 follows the approach of Scenario 2025 – more solar PV and batteries (for a no-wind approach) or solar PV, wind and batteries are added to the system to achieve higher renewable energy contribution. Inputs for Scenario 2030 model are similar to inputs for Scenario 2025 Homer model:

- Adopted methodology for 2030 follows methodology in 2025, that the system will be capable operating as diesel-off system, when renewable generation conditions allow. As previous scenario added all necessary enabling technologies, no additional capital cost will be added in 2030.
- Renewable energy generation capacity installed by 2025
- Equipment costs for additional solar PV, battery, diesel generators are as defined in [6] and are somewhat lower due to expected reduction of cost of renewable components and battery technologies,
- Load has reduced from 2025 due to increase in energy efficiency programmes; it is now **62.3 GWh**, with an average of **7.1 MW,**
- Total fixed capital cost is now **$58.89M**, which includes:
  - Previous capital cost of $38.35M,
  - Additional capital cost spent on distribution/system projects of $20.34M
- Total fixed O&M cost is **$5.48M**, which considers:
  - OPEX from 2025 of $5.36M, and
  - Additional $0.13M yearly OPEX for newly installed distribution/system equipment.

Results in this Scenario build on outputs of Scenario 2025.

Scenario 2030 with no wind

Scenario 2030 without wind generation modelling results are presented in Figure 5.3 and the selected result in Table 5.3. Modelling search space for 2030 scenario with no wind included:

- Additional solar PV size from 1 to 30 MW of installed capacity, and
- Additional battery size from 0 to 52.5 MWh of storage capacity.

The result with over 64% diesel fuel usage reduction and lowest capital cost consists of an additional 5MW of solar PV capacity and an additional 37 MWh battery energy storage (presented as the larger red triangle in Figure 5.3).

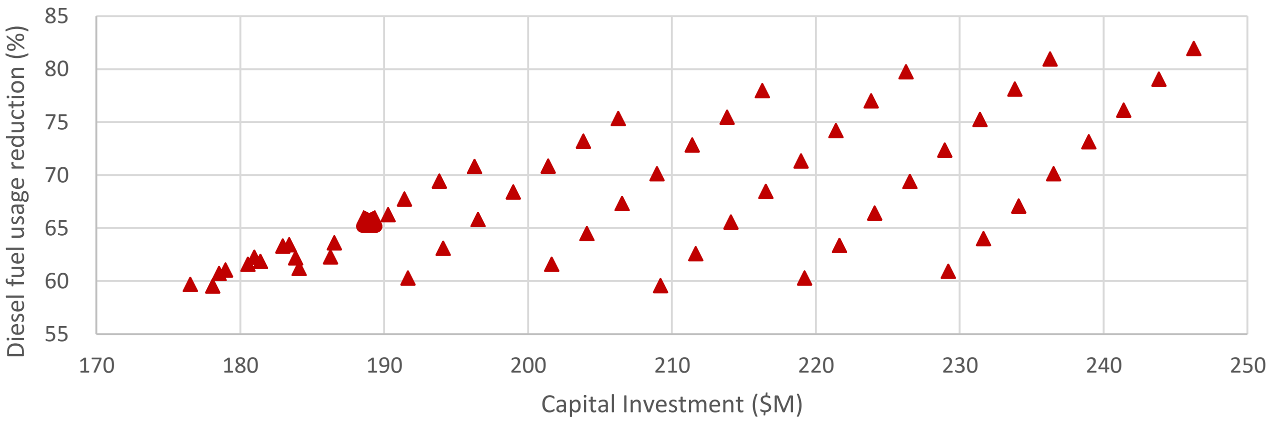

Figure 5.3 - Scenario 2030-no wind modelling results

Table 5.3- Scenario 2030-no wind modelling results

Additional Solar PV (MW)	Additional Battery Energy (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX (from 2025) ($M)	Diesel fuel consumed (Mgal/yr)	Diesel fuel usage reduction from 2010 (%)
5	37	$0.344	13.9	190	41.39	1.53	65.8

Conclusions from Majuro Scenario 2030 no-wind (solar and battery only) are:

- Cost of electricity rises further to $0.344/kWh,
- Battery needed to reach at least 64% of diesel fuel use reduction is almost double the size of battery needed to reach 50% diesel fuel use reduction,
- Additional solar PV needed to reach 65% diesel fuel reduction target was **5 MW**, and additional battery was **37 MWh**,
- Total renewable energy infrastructure under Majuro 2030 no-wind scenario will be **34 MW** of solar PV and **75 MWh** of battery energy storage,
- Capital investment is **additional $41.39** from 2025 no-wind scenario.

Scenario 2030 with wind

Scenario 2030 modelling results including wind generation are presented in Figure 5.4 with the selected result in Table 5.4. Modelling search space for 2030 scenario with wind included:

- Additional wind generation from 0 to 20 MW of installed capacity,
- Additional solar PV from 0 to 15 MW of installed capacity, and
- Additional battery size from 0 to 30 MWh of storage capacity.

The result with over 64% diesel fuel usage reduction and lowest capital cost is the one with additional 0 MW of wind capacity, 9 MW of solar PV capacity and no additional battery energy storage (presented as larger red triangle in Figure 5.4).

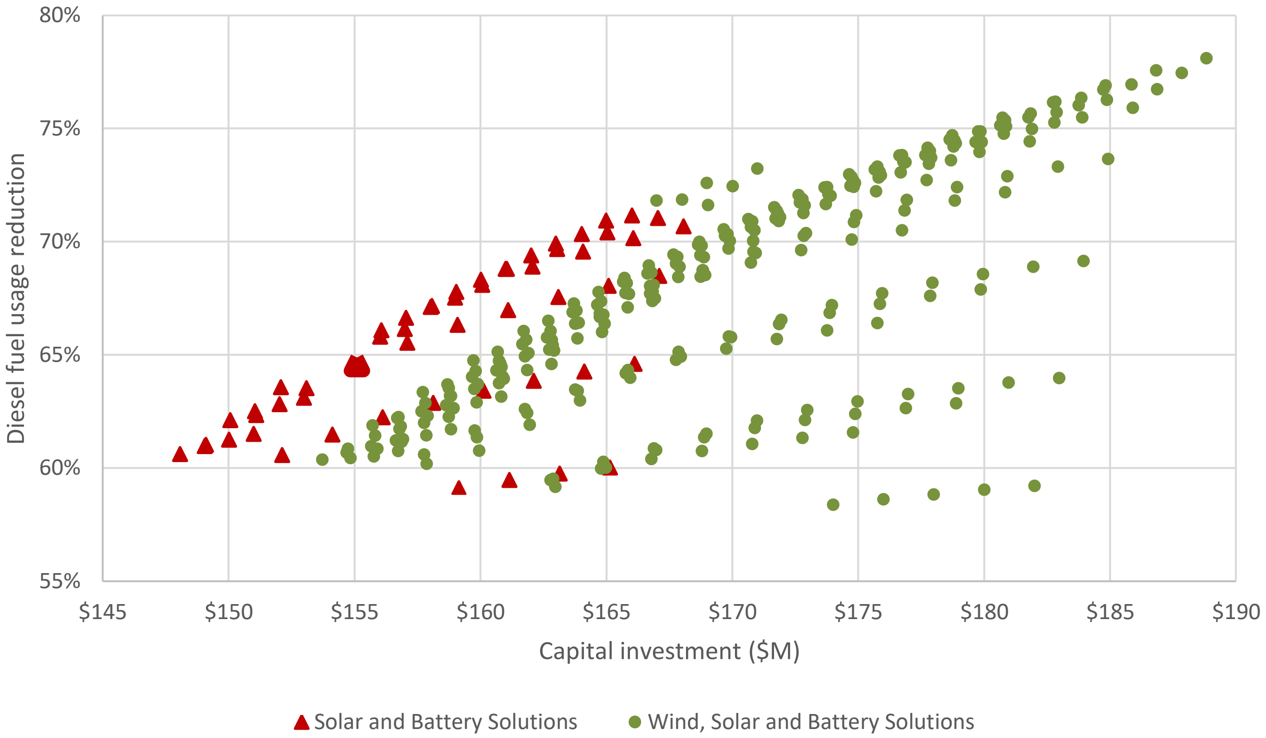

Figure 5.4 - Scenario 2030 modelling results

Table 5.4- Scenario 2030 modelling results

Additional Solar PV (MW)	Additional Wind (MW)	Additional Battery Energy (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX (from 2025) ($M)	Diesel fuel consumed (Mgal/yr)	Diesel fuel usage reduction from 2010 (%)
9	0	0	0.294	12.1	156.0	38.2	1.59	64.6

Conclusions from Majuro Scenario 2030 (wind, solar and battery) are:

- Cost of electricity dropped further to $0.294/kWh,
- The battery capacity needed to reach 64% diesel fuel use reduction is the same as the battery capacity needed to reach 50% diesel fuel use reduction,
- Additional solar PV needed to reach 65% diesel fuel reduction target was **9 MW**, additional wind was **0 MW**, and additional battery was **0 MWh**,
- Total renewable energy infrastructure under Majuro 2030 wind scenario will be **13 MW** of solar PV, **12 MW** of wind generation and **20 MWh** of battery energy storage.
- Capital Investment is an **additional $38.2M** from 2025 wind scenario.

5.1.5 Majuro Scenario 2050

Modelling for the year 2050 follows the approach of Scenarios 2025 and 2030 – either more solar PV and batteries (for a no-wind approach) or solar PV, wind and batteries are added to the system to achieve higher renewable energy contribution. As a last-mile technology, 100% biodiesel is also considered in this scenario.

Inputs for Scenario 2050 model are similar to inputs for Scenario 2030 Homer model:

- Adopted methodology for 2050 follows methodology in 2030, that the system will always be capable operating as diesel off system, when renewable generation conditions allow (Stage 5). As previous scenarios added all necessary enabling technologies, no additional capital cost will be added in 2050.
- Renewable energy generation capacity installed by 2030
- Equipment costs for additional solar PV, battery, diesel generators are as defined in [6] ,
- Load has increased from 2030 due to population increase and is now **76.0 GWh**, with an average of **8.7 MW,**
- For solar and battery scenarios, total fixed capital cost is now **$104.837M**, where:
  - Fixed capital cost of $58.88M as in 2030 Scenario,
  - 1 MW of solar installed in 2012 needs to be completely replaced in 2037, which is additional $2M,
  - 3 MW of solar installed in 2022 needs to have its inverters replaced in 2035, for additional cost of $0.6M,
  - 3 MW of solar installed in 2022 needs to be completely replaced by 2047, which is additional $6M,
  - 1.5 MWh battery installed in 2022 needs to be completely replaced by 2035, for additional cost of $0.45M,
  - 12 MW of diesel generators installed in 2022 need to be completely replaced in 2032, for additional cost of $9M,
  - 36 MWh battery installed in 2025 needs to be completely replaced by 2040, for additional cost of $10.8M
  - 25 MW of solar PV installed in 2025 needs to have its inverters replaced by 2038, for additional cost of $5M
  - 5 MW of solar PV installed in 2030 needs to have its inverters replaced by 2045, for additional cost of $1M,
  - 37 MWh battery installed in 2030 needs to be completely replaced by 2045, for additional cost of $11.1M.
- For wind, solar and battery scenarios, total fixed capital cost is now **$84.74M**, where:
  - Fixed capital cost of $58.89M as in 2030 Scenario,
  - 1 MW of solar installed in 2012 needs to be completely replaced in 2037, which is additional $2M,
  - 3 MW of solar installed in 2022 needs to have its inverters replaced in 2035, for additional cost of $0.6M,
  - 3 MW of solar installed in 2022 needs to be completely replaced by 2047, which is additional $6M,
  - 1.5 MWh battery installed in 2022 needs to be completely replaced by 2035, for additional cost of $0.45M,
  - 12 MW of diesel generators installed in 2022 need to be completely replaced in 2032, for additional cost of $9M,
  - 18 MWh battery installed in 2025 needs to be completely replaced by 2040, for additional cost of $5.4M

  - 12 MW of solar PV installed in 2025 needs to have its inverters replaced by 2045, for additional cost of $2.4M
- Total fixed O&M cost is **$5.48M**, as in 2030 scenario.

Results in this Scenario build on outputs of Scenario 2030, with and without wind generation.

Scenario 2050 with no wind

Scenario 2050 without wind generation modelling results are presented in Figure 5.5, and selected scenario is presented in Table 5.5. Modelling search space for this scenario case included considering:

- Additional solar PV size from 0 to 100 MW,
- Additional battery size from 37.5 to 1500 MWh of total storage capacity.

The result with 100% diesel fuel usage reduction and lowest capital cost consists of an additional 60 MW of solar PV capacity and additional 975 MWh battery energy storage (presented as larger red triangle in Figure 5.5).

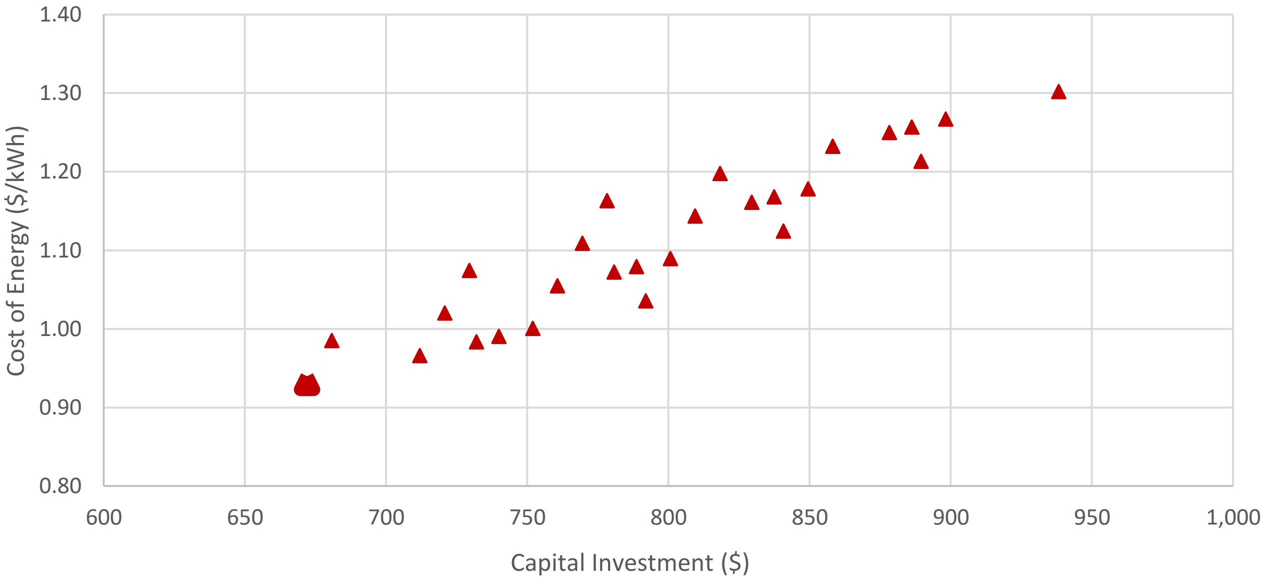

Figure 5.5 - Scenario 2050 no-wind modelling results

Table 5.5- Scenario 2050-no wind modelling results

Additional Solar PV (MW)	Additional Battery Energy (MWh)	COE ($/kWh)	Operating Cost ($M)	Total Capital investment from 2018 ($M)	Additional CAPEX (from 2025) ($M)	Diesel fuel consumed (Mgal/yr)	Diesel fuel usage reduction from 2010 (%)
60	975	0.931	43.95	672	482	0	100

Conclusions from Majuro Scenario 2050 no-wind (solar and battery only) are:

- Cost of electricity rises further to $0.961/kWh,
- Battery needed to reach 100% diesel fuel use reduction is about 15 times larger than the size of battery needed to reach 64% diesel fuel use reduction,
- Additional solar PV needed to reach 100% diesel fuel reduction target was **60 MW**, and additional battery was **975 MWh**.
- Total renewable energy infrastructure under Majuro 2050 no-wind scenario will be **94 MW** of solar PV and **1,050 MWh** of battery energy storage,
- Capital investment is **$672M**, which represents **additional $482M** from 2030 no-wind scenario.

Scenario 2050 with wind

Scenario 2050 with wind generation modelling results are presented in Figure 5.6, and selected scenario is presented in

Table 5.6. Modelling search space for this scenario included considering:

- Additional solar PV size from 0 to 100 MW,
- Additional wind generation of 0 to 50 MW, and
- Additional battery size from 0 to 500 MWh of storage capacity.

The result with 100% diesel fuel usage reduction and lowest capital cost consists of an additional 60 MW of solar PV capacity, additional 30 MW of wind power and additional 280 MWh battery energy storage (presented as larger green dot in Figure 5.6).

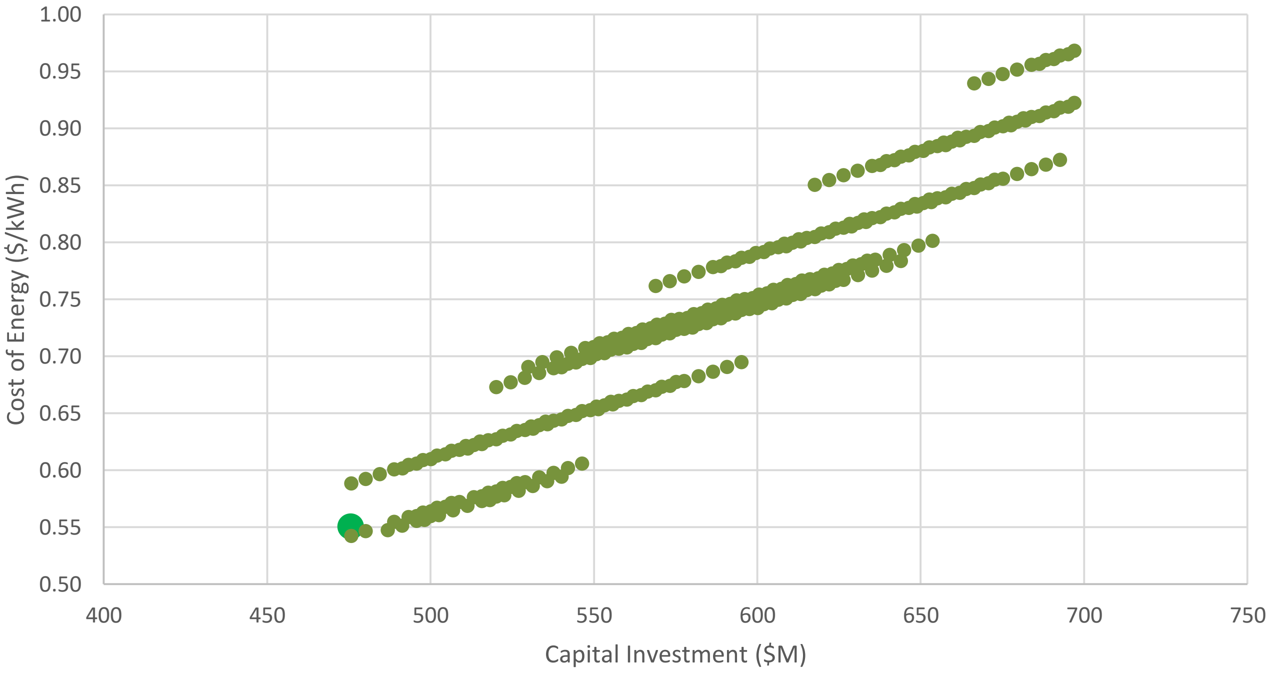

Figure 5.6 - Scenario 2050 modelling results

Table 5.6- Scenario 2050 modelling results

Additional Solar PV (MW)	Additional Wind (MW)	Additional Battery Energy (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX (from 2030) ($M)	Diesel fuel consumed (Mgal/yr)	Diesel fuel usage reduction from 2010 (%)
60	30	280	0.551	22.5	475.5	319.5	0	100

Conclusions from Majuro Scenario 2050 (wind, solar and battery) are:

- Cost of electricity increased to $0.551/kWh,
- Battery needed to reach 100% diesel fuel use reduction is almost 13 times larger than battery needed to reach 65% diesel fuel use reduction,
- Additional solar PV needed to reach 100% diesel fuel reduction target was **60 MW**, additional wind was 3**0 MW**, and additional battery was **280 MWh**.
- Total renewable energy infrastructure under Majuro 2030 wind scenario will be **73 MW** of solar PV, **42 MW** of wind generation and **300 MWh** of battery energy storage (wind and storage size will not change)
- Capital investment is **additional $319.5** from 2030 wind scenario.

Scenario 2050 with wind, solar, battery and biodiesel

This variation of the 2050 scenario investigates biodiesel as a technology which could cap cost of energy as the cost starts to rise approaching 100% renewable operation. Modelling results are presented in Figure 5.7 and selected solution is presented in Table 5.7. Modelling search space for this scenario included:

- Additional solar PV size from 0 to 30 MW of installed capacity,
- Additional wind from 0 to 15MW, and
- Additional battery size from 0 to 300 MWh of total storage capacity.

The result with 100% mineral diesel fuel usage reduction and lowest capital cost is the one with no additional wind, no additional solar PV capacity, and no additional battery, but with two new diesel generators (due to the increased peak loads) which join the existing generators in providing electricity using biodiesel.

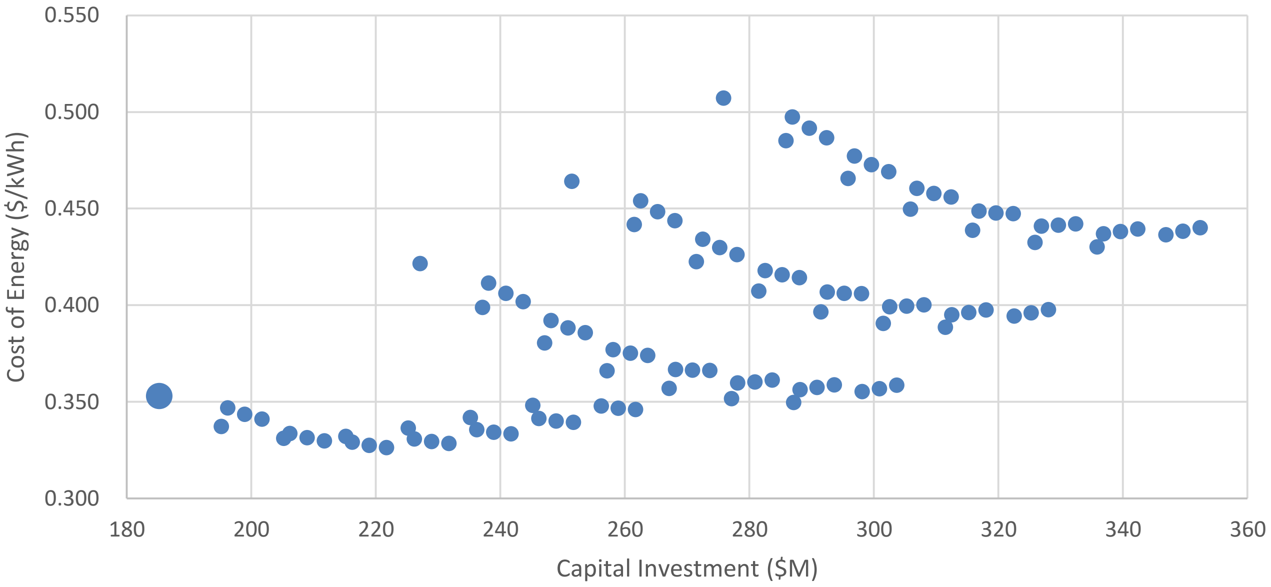

Figure 5.7 - Scenario 2050 modelling results

Table 5.7- Scenario 2050 modelling results

Add. Solar PV (MW)	Add. Wind (MW)	Add. Battery Energy (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX (from 2030) ($M)	Biodiesel fuel consumed (Mgal/yr)	Diesel fuel usage reduction from 2010 (%)
-	-	-	0.353	19.4	185.2	29.2	1.00	100

Conclusions from Majuro Scenario 2050 (wind, solar, battery and biodiesel) are:

- Cost of electricity increased to $0.353/kWh,
- Battery, solar and wind capacity stays the same, as in 2030 scenario,
- Total renewable energy infrastructure under Majuro 2050 biodiesel scenario will be **13 MW** of solar PV, **12 MW** of wind generation, **20 MWh** of battery energy storage (wind, solar and storage size will not change), and all previous diesel generation switches over to biodiesel.
- Capital investment is **additional $29.2M** from 2030 wind scenario.

5.2 Ebeye results

A pre-requisite for the Ebeye energy modelling scenarios is replacement of its existing diesel generation with new high-speed diesel generation, and refurbishment of its diesel power house.

From there, two main approaches are considered for Ebeye:

1. No wind development, only solar PV and batteries are used for reaching GHG targets,
2. Unconstrained wind development, with solar PV and batteries.

In addition to two approaches above, biodiesel technology is considered as a last-mile technology between 2030 and 2050 years (Figure 5.8).

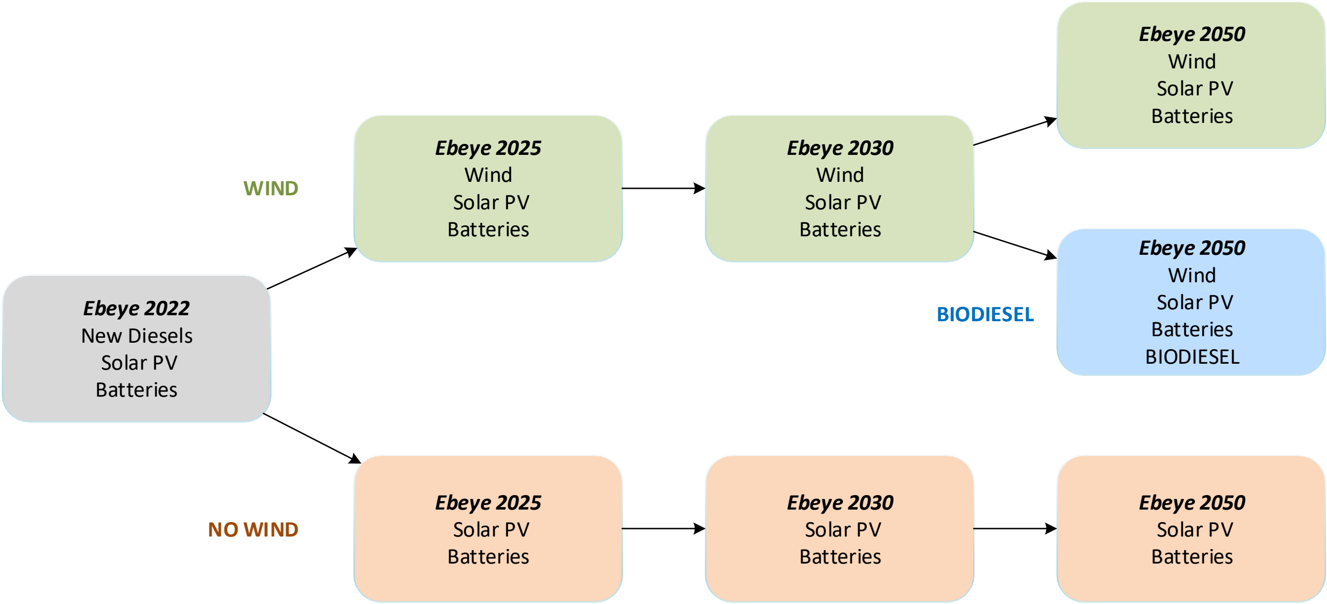

Figure 5.8 - Ebeye Technology Pathway Approach

5.2.1 Ebeye baseline 2010

Ebeye 2010 baseline is used to establish the baseline value for amount of diesel fuel used for electricity generation in Ebeye.

Fuel used for electricity generation by MEC in 2010 was **1,070,000 gallons** [11] . This value presents a baseline against which diesel fuel savings were benchmarked through all scenarios in this section.

5.2.2 Scenario 2022

There are presently a few planned projects which will be finalised before Ebeye's first 2025 milestone, and their contribution is captured in this scenario, with an estimated finish date of 2022.

Inputs for Ebeye 2022 scenario are:

- Fixed capital cost of **$4.04M**, which considers:
    - $3.54M for renovating existing power plant building and its fuel system, and
    - $0.504M for projects identified by electrical masterplan [6] ,
- Fixed OPEX cost of **$2.6M**, which considers utility operating costs (excluding depreciation and amortisation, fuel and lubes, operations and maintenance)
- New diesel generators (**2 x 1.3 MW**) are installed for a price of **$0.75/W**, for a total cost of **$1.9M**
- Total annual load is **17 GWh**, with a calculated average load of 1.94 MW,
- Diesel fuel price is **$2.45** per gallon,
- Under the current JICA financed project, **600 kW** of solar PV and **600 kWh** of batteries are installed for a total cost of **$9.75M**.

Scenario results are presented in Table 5.8 below.

Table 5.8 - Ebeye Scenario 2022 - Results

Solar PV size (MW)	Battery size (MWh)	Total Annual Operating Cost ($M)	Total Capital investment from 2018 ($M)	COE ($/kWh)	Diesel Fuel Consumed (Mgal/yr)	Diesel Fuel reduction from 2010(%)
0.6	0.6	5.63	15.7	0.368	1.11	-3.5

Conclusions from the Ebeye 2022 baseline scenario modelling are:

- Total fuel consumed is 1,107,000 gallons per annum, which is an increase from the 2010 baseline and presents an increase of **3.5%** of diesel fuel usage,
- Total renewable energy infrastructure under Ebeye 2022 scenario will be **0.6 MW** of solar PV and **0.6 MWh** of battery energy storage,
- **Capital investment** up to this point is **$15.7M**

Although there are some investments in renewable energy, Ebeye increases its diesel fuel use compared to 2010 baseline, and consequently, its GHG emissions.

5.2.3 Ebeye Scenario 2025

Building on Ebeye baseline 2022 scenario, Scenario 2025 considers reaching 48% diesel fuel usage reduction target in Ebeye by using solar PV, wind and battery technologies, or just solar PV and battery technologies.

Inputs into the Ebeye Scenario 2025 are:

- Adopted methodology for 2025 is that the system will be capable of operating in diesel-off mode (Stage 3), when renewable generation conditions allow[15]. This implies additional capital cost of $1.8M for enabling technologies (3 MVA synchronous condensers and some resistive load banks) which support diesel off operation.
- Total fixed capital cost now is **$6.35M**, which includes:
    - Previous capital cost of $4.04M,
    - Additional $0.504M for projects identified by the Electrical Masterplan [6] ,
    - Enabling technologies $1.8M.
- Total fixed O&M cost is **$2.6M**, as in 2022 scenario.
- Renewable energy generation capacity installed by 2022
- Equipment costs for additional solar PV, battery, diesel generators, control system are as defined in [6] .

Scenario results are presented in Figure 5.9 and

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[15] Previous iterations of modelling found this configuration to be least-cost

Table 5.9 below.

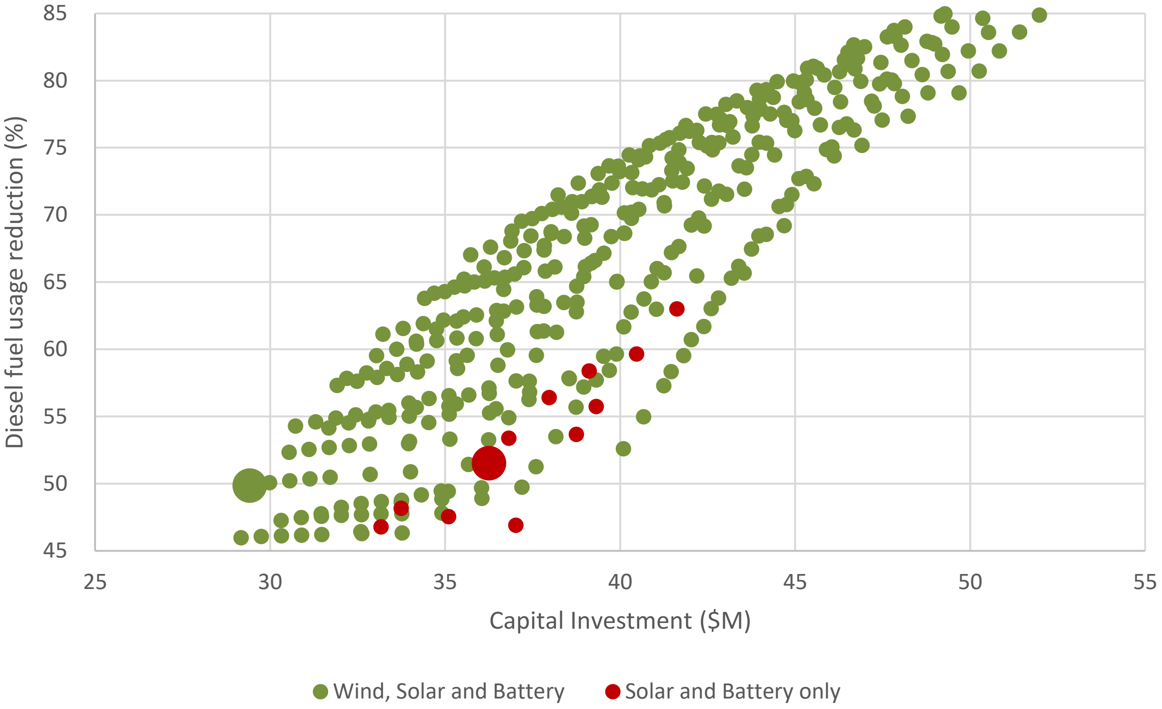

Figure 5.9 - Ebeye Scenario 2025 – Results

Table 5.9 - Ebeye Scenario 2025 - Results

Add. Solar PV (MW)	Add. Wind Capacity (MW)	Add. Battery (MWh)	COE ($/kWh)	Total Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX from 2022 ($M)	Diesel Fuel Consumed (kgal/yr)	Diesel Fuel reduction from 2010 (%)
-	3	5.4	0.359	4.5	29.4	13.7	537	49.9
6	-	9.9	0.386	4.7	36.3	20.6	519	51.5

Conclusions from Ebeye 2025 scenario modelling are:

- For no-wind solutions:
  - Cost of energy is **increased** compared to 2022 scenario, reaching $0.386/kWh
  - Operating cost is reduced due to lower diesel fuel consumption,
  - Total renewable energy infrastructure under Ebeye 2025 no-wind scenario will be **6.6 MW** of solar PV and **10.5 MWh** of battery energy storage,
  - Capital investment is **additional $20.6M** from 2022 scenario.
- For solutions with wind:
  - Cost of energy **decreased** compared to 2022 scenario, to $0.359/kWh
  - Operating cost is reduced due to lower diesel fuel consumption, and
  - Total renewable energy infrastructure under Ebeye 2025 scenario will be **0.6 MW** of solar PV, **3 MW** of wind and **6 MWh** of battery energy storage,
  - Capital investment is **additional $13.7M** from 2022 scenario.

5.2.4 Ebeye Scenario 2030

Modelling for the year 2030 follows the approach of Scenario 2025 – either more solar PV and batteries (for a no-wind approach) or solar PV, wind and batteries are added to the system to achieve higher renewable energy contribution. Inputs for Scenario 2030 model are similar to inputs for Scenario 2025:

- Adopted methodology for 2030 follows methodology in 2025, that the system will be capable operating as diesel-off system, when renewable generation conditions allow. As previous scenario added all necessary enabling technologies, no additional capital cost for enabling technologies will be added in 2030.
- Renewable energy generation capacity installed by 2025
- Equipment costs for additional solar PV, battery, diesel generators are as defined in [6] and are somewhat lower due to expected reduction of cost of renewable components and battery technologies,
- Load has reduced from 2025 due to increase in energy efficiency programmes; it is now **16 GWh**, with an average of **1.63 MW,**
- Total fixed capital cost is now **$5.22M**, which includes:
    - Previous capital cost of $4.55M, and
    - Additional $0.672M for projects identified by electrical masterplan [6] ,
- Total fixed O&M cost is **$2.6M**, as in 2025 scenario.

Results in this Scenario build on outputs of Scenario 2025.

Ebeye Scenario 2030 with no wind

Scenario 2030 without wind generation modelling results are presented in Figure 5.10 and selected result is presented in

Table 5.10. Modelling search space for 2030 scenario with no wind included:

- Additional solar PV size from 0 to 10 MW of installed capacity, and
- Additional battery size from 0 to 10 MWh of storage capacity.

The result with over 64% diesel fuel usage reduction and lowest capital cost is the one with no additional solar PV capacity and additional 6.5 MWh battery energy storage (presented as larger red triangle in Figure 5.10).

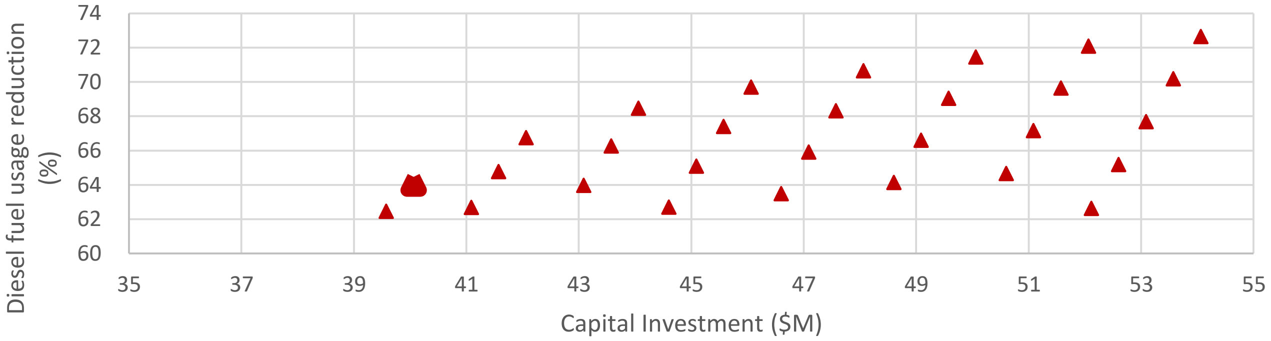

Figure 5.10 - Scenario 2030-no wind modelling results

Table 5.10- Scenario 2030-no wind modelling results

Add. Solar PV (MW)	Add. Battery (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX from 2022 ($M)	Diesel fuel consumed (kgal/yr)	Diesel fuel usage reduction from 2010 (%)
-	6.5	0.427	4.5	40.1	3.8	384	64.1

Conclusions from Ebeye Scenario 2030 no-wind (solar and battery only) are:

- Cost of electricity rises further to $0.427/kWh,
- Battery needed to reach 64% of diesel fuel use reduction is about 50% the size of battery needed to reach 48% diesel fuel use reduction,
- Additional solar PV needed to reach 64% diesel fuel reduction target was **0 MW**, and additional battery was **6.5 MWh**,
- Total renewable energy infrastructure under Majuro 2030 no-wind scenario will be **6.6 MW** of solar PV and **17 MWh** of battery energy storage,
- Capital investment is **additional $3.8M** from 2025 no-wind scenario.

Ebeye Scenario 2030 with wind

Scenario 2030 modelling results including wind generation are presented in Figure 5.11 and selected result is presented in Table 5.11. Modelling search space for 2030 scenario with wind included:

- Additional wind generation from 0 to 5 MW of installed capacity,
- Additional solar PV from 0 to 10 MW of installed capacity, and
- Additional battery size from 0 to 10 MWh of storage capacity.

The result with over 64% diesel fuel usage reduction and lowest capital cost is the one with no additional wind capacity, 2 MW of additional solar PV capacity and no additional battery energy storage (presented as larger green dot in Figure 5.11).

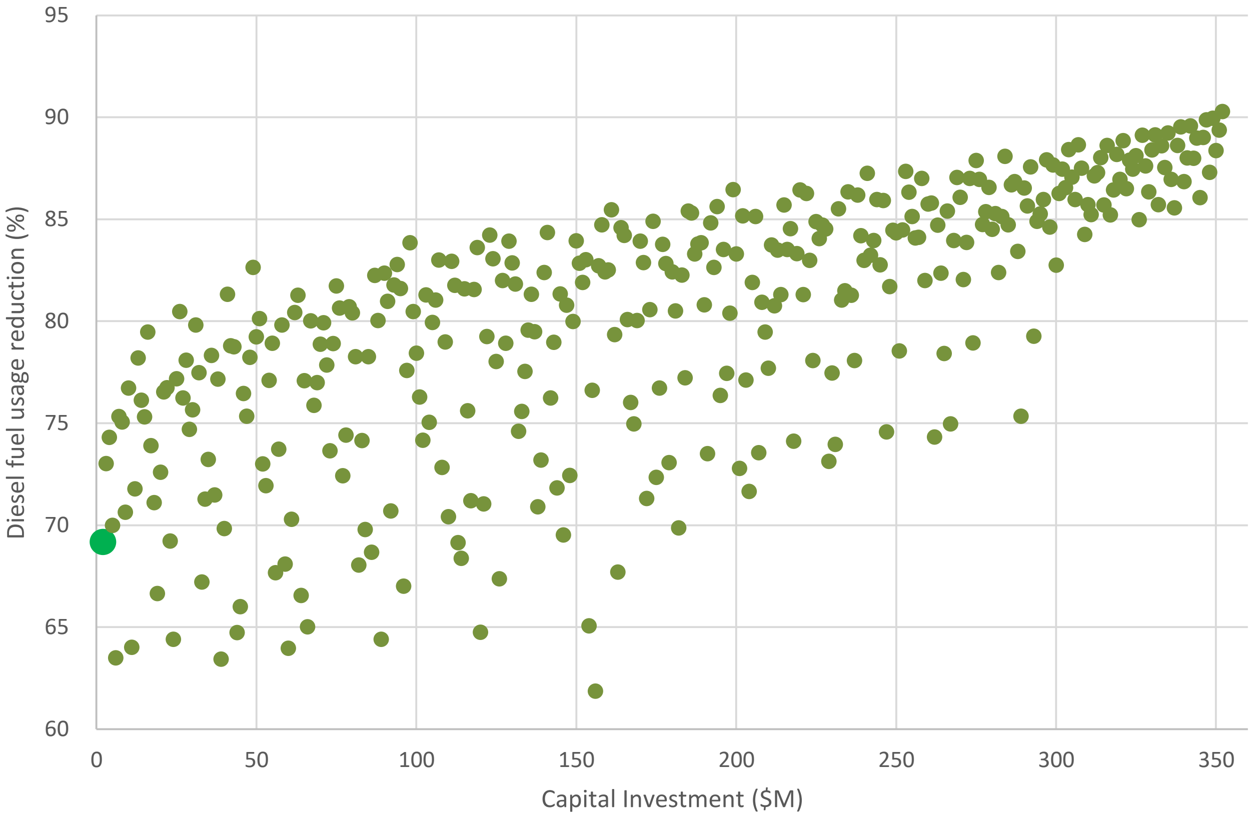

Figure 5.11 - Scenario 2030 modelling results

Table 5.11- Scenario 2030 modelling results

Add. Solar PV (MW)	Add. Wind (MW)	Add. Battery (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX from 2022 ($M)	Diesel fuel consumed (kgal/yr)	Diesel fuel usage reduction from 2010 (%)
2	-	-	0.384	$4.1	$35.5	6.1	330	69.2

Conclusions from Ebeye Scenario 2030 (wind, solar and battery) are:

- Cost of electricity climbed to $0.384/kWh,
- The battery capacity needed to reach 64% diesel fuel use reduction is the same as the battery capacity needed to reach 50% diesel fuel use reduction,
- Additional solar PV needed to reach 64% diesel fuel reduction target was **2 MW** - no additional wind or additional battery are required,
- Total renewable energy infrastructure under Majuro 2030 wind scenario will be **2.6 MW** of solar PV, **3 MW** of wind generation and **6 MWh** of battery energy storage.
- Capital investment is **additional $6.1M** from 2025 wind scenario.

5.2.5 Ebeye Scenario 2050

Modelling for the year 2050 follows the approach of Scenarios 2025 and 2030 – more solar PV and batteries (for a no-wind approach) or solar PV, wind and batteries are added to the system to achieve higher renewable energy contribution. As a last-mile technology, 100% biodiesel is also considered in this scenario.

Inputs for Scenario 2050 model are similar to inputs for Scenario 2030:

- Adopted methodology for 2050 follows methodology in 2030, that the system will always be capable operating as diesel off system (Stage 5), when renewable generation conditions allow. As previous scenarios added all necessary enabling technologies, no additional capital cost will be added in 2050.
- Renewable energy generation capacity installed by 2030
- Equipment costs for additional solar PV, battery, diesel generators are as defined in [6] ,
- Load has decreased further from 2030 due to energy efficiency programs and is now **14 GWh**, with an average of **1.67 MW,**
- For solar and battery scenarios, total fixed capital cost is now **$18.72M**, where:
    - Fixed capital cost of $7M is a roll-over from 2030,
    - 0.6 MW of solar installed in 2022 needs to have its inverters replaced in 2035, for additional cost of $0.12M,
    - 0.6 MW of solar installed in 2022 needs to be completely replaced by 2047, which is additional $1.2M,
    - 0.6 MWh battery installed in 2022 needs to be completely replaced by 2037, for additional cost of $0.27M,
    - 2.5 MW of diesel generators installed in 2022 need to be completely replaced in 2032, for additional cost of $1.5M,
    - 9.9 MWh battery installed in 2025 needs to be completely replaced by 2040, for additional cost of $4.5M
    - 6 MW of solar PV installed in 2025 needs to have its inverters replaced by 2038, for additional cost of $1.2M
    - 6.5 MWh battery installed in 2030 needs to be completely replaced by 2045, for additional cost of $2.93M.
- For wind, solar and battery scenarios, total fixed capital cost is now **$13.35M**, where:
    - Fixed capital cost of $7M is a roll-over from 2030,
    - 0.6 MW of solar installed in 2022 needs to have its inverters replaced in 2035, for additional cost of $0.12M,
    - 0.6 MW of solar installed in 2022 needs to be completely replaced by 2047, which is additional $1.2M,
    - 0.6 MWh battery installed in 2022 needs to be completely replaced by 2037, for additional cost of $0.27M,
    - 2.5 MW of diesel generators installed in 2022 need to be completely replaced in 2032, for additional cost of $1.5M,
    - 5.4 MWh battery installed in 2025 needs to be completely replaced by 2040, for additional cost of $2.43M
    - 2 MW solar PV installed in 2030 needs to have its inverters replaced 2045, for additional cost of $0.4M.
- Total fixed O&M annual cost is **$2.6M**, as in 2030 scenario.

Results in this Scenario build on outputs of Scenario 2030, with and without wind generation.

Scenario 2050 with no wind

Scenario 2050 without wind generation modelling results are presented in Figure 5.12, and selected scenario is presented in Table 5.12. Modelling search space for this scenario case included considering:

- Additional solar PV size from 0 to 100 MW,
- Additional battery size from 37.5 to 1500 MWh of total storage capacity.

The result with 100% diesel fuel usage reduction and lowest capital cost is the one with additional 10 MW of solar PV capacity and additional 208 MWh battery energy storage (presented as larger green dot in Figure 5.12).

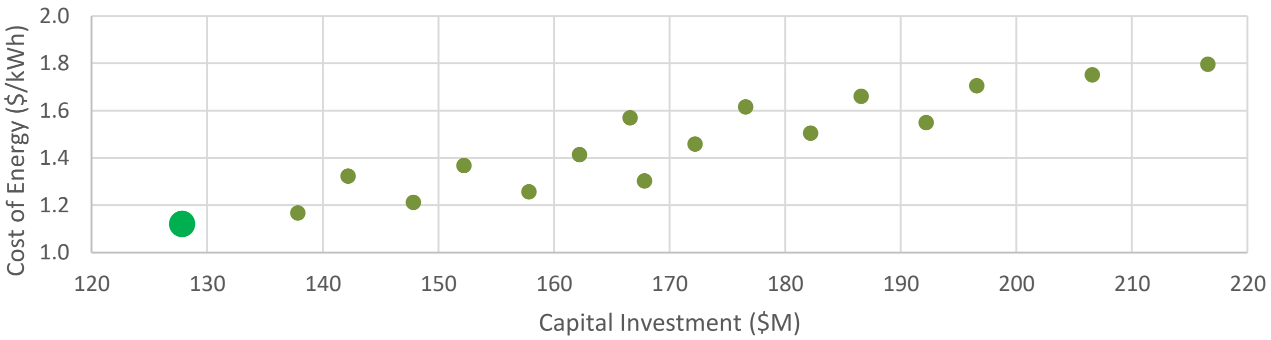

Figure 5.12 - Scenario 2050 no-wind modelling results

Table 5.12- Scenario 2050-no wind modelling results

Add. Solar PV (MW)	Add. Battery (MWh)	COE ($/kWh)	Annual Operating Cost ($M)	Total Capital investment from 2018 ($M)	Additional CAPEX from 2030 ($M)	Diesel fuel consumed (kgal/annum)	Diesel fuel usage reduction from 2010(%)
10	208	1.122	11.3	139.5	99.4	0	100

Conclusions from Ebeye Scenario 2050 no-wind (solar and battery only) are:

- Cost of electricity rises further to $1.122/kWh,
- Additional solar PV needed to reach 100% diesel fuel reduction target was **10 MW**, and additional battery was **208 MWh**.
- Total renewable energy infrastructure under Ebeye 2050 no-wind scenario will be **17 MW** of solar PV and **225 MWh** of battery energy storage,
- Capital investment is **additional $99.4M** from 2030 no-wind scenario.

Scenario 2050 with wind

Scenario 2050 with wind generation modelling results are presented in Figure 5.13, and selected scenario is presented in Table 5.13. Modelling search space for this scenario included considering:

- Additional solar PV size from 0 to 5 MW,
- Additional wind generation of 0 to 20 MW, and
- Additional battery size from 0 to 100 MWh of storage capacity.

The result with 100% diesel fuel usage reduction and lowest capital cost is the one with additional 5 MW of solar PV capacity, additional 4.5 MW of wind power and additional 144 MWh battery energy storage (presented as larger green dot in Figure 5.13).

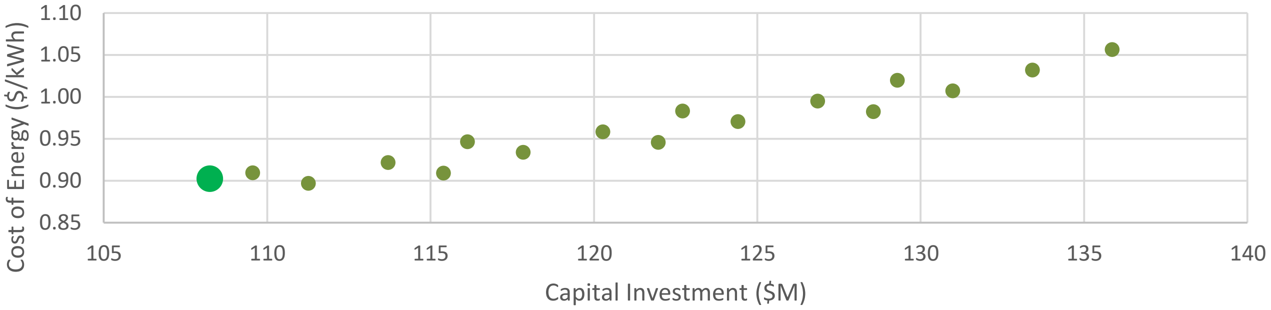

Figure 5.13 - Scenario 2050 modelling results

Table 5.13- Scenario 2050 modelling results

Add. Solar PV (MW)	Add. Wind (MW)	Add. Battery (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX from 2030 ($M)	Diesel fuel consumed (kgal/yr)	Diesel fuel usage reduction from 2010 (%)
5	4.5	144	0.902	8.8	114.55	79.05	-	100

Conclusions from Ebeye Scenario 2050 (wind, solar and battery) are:

- Cost of electricity increased to $0.902/kWh,
- Additional solar PV needed to reach 65% diesel fuel reduction target was **5 MW**, additional wind was **4.5 MW**, and additional battery was **144 MWh**.
- Total renewable energy infrastructure under Majuro 2050 wind scenario will be **7.6 MW** of solar PV, **7.5 MW** of wind generation and **150 MWh** of battery energy storage
- Capital investment is **additional $79.05** from the 2030 wind scenario.

Scenario 2050 with wind, solar, battery and biodiesel

This variation of the 2050 scenario investigates biodiesel as a technology which could cap cost of energy once it starts to rise as it approaches 100% renewable operation. Modelling results are presented in Figure 5.14 and selected solution is presented in Table 5.14. Modelling search space for this scenario included:

- Additional solar PV size from 0 to 5 MW of installed capacity,
- Additional wind from 0 to 20 MW, and
- Additional battery size from 0 to 30 MWh of storage capacity.

Result with 100% diesel fuel usage reduction and lowest capital cost is the one with no additional wind, no additional solar PV capacity, and no additional battery, but with diesel generators which consume biodiesel, shown as the large red dot in Figure 5.14.

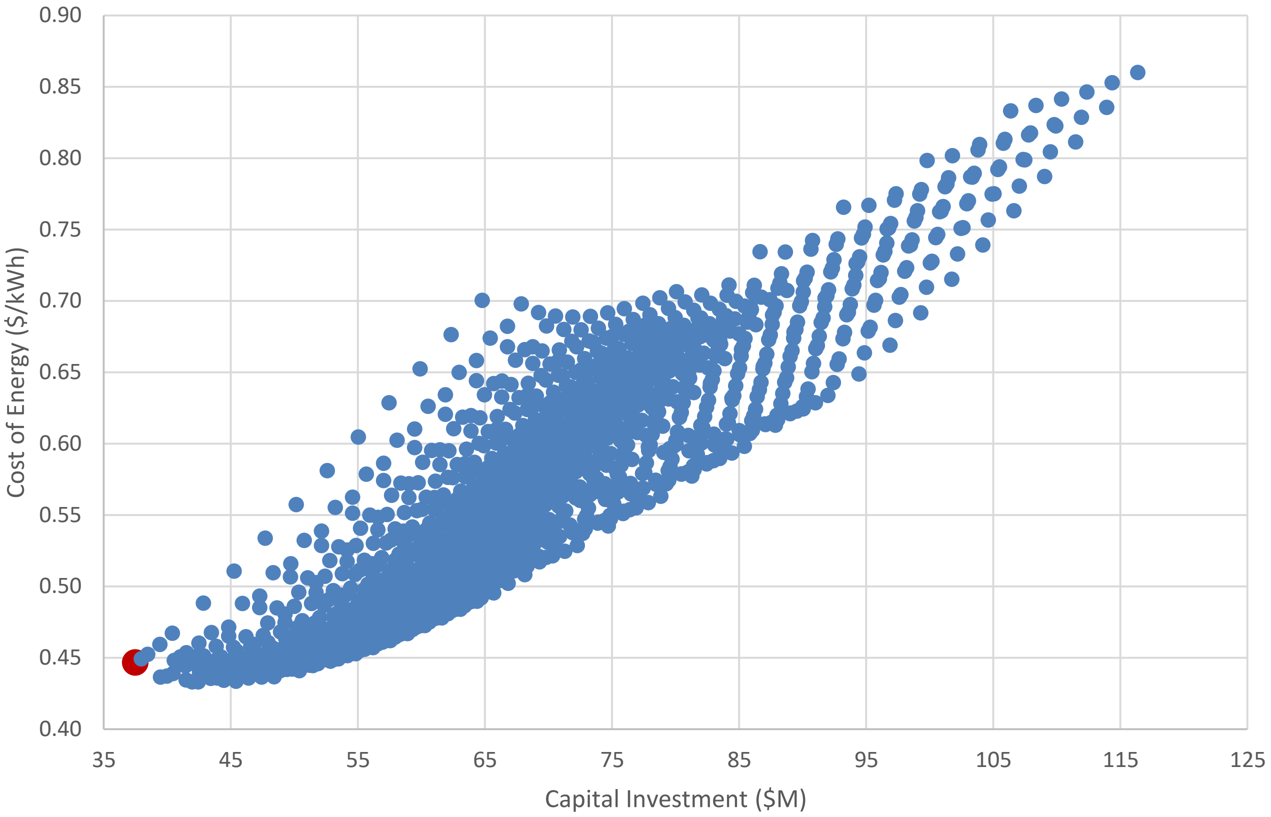

Figure 5.14 - Scenario 2050 biodiesel modelling results

Table 5.14- Scenario 2050 biodiesel modelling results

Add. Solar PV (MW)	Add. Wind (MW)	Add. Battery (MWh)	COE ($/kWh)	Annual OPEX ($M)	Total CAPEX from 2018 ($M)	Additional CAPEX from 2030 ($M)	Biodiesel fuel consumed (kgal/yr)	Diesel fuel usage reduction from 2010 (%)
-	-	-	0.447	5.0	43.85	8.35	183	100

Conclusions from Ebeye Scenario 2050 (wind, solar, battery and biodiesel) are:

- Cost of electricity increased to $0.447/kWh,
- Battery, solar and wind capacity stays the same, as in 2030 scenario,
- Total renewable energy infrastructure under Ebeye 2050 biodiesel scenario will be **2.6 MW** of solar PV, **3 MW** of wind generation, **6 MWh** of battery energy storage, and all previous diesel generation switches over to biodiesel.
- Capital investment is **additional $8.35M** from 2030 wind scenario.

5.3 Modelling results Summary

After modelling results for Majuro and Ebeye, and medium island systems modelling results done by others, summary table for Technology Pathways for entire RMI Energy Sector can now be presented (Table 5.15).

Table 5.15 - Technology Pathways for RMI Energy Sector - Modelling Results

		Baseline	**Solar and Battery only Pathway**			**Wind, Solar and Battery Pathway**			**Biodiesel, Wind, Solar and Battery Pathway**		
		2022	**2025**	**2030**	**2050**	**2025**	**2030**	**2050**	**2025**	**2030**	**2050**
Majuro	Diesel generation (MW)	12	-	-	12	-	-	12	-	-	12
	Solar PV (MW)	4	29	34	94	4	13	73	4	13	13
	Wind (MW)	-	-	-	-	12	12	42	12	12	12
	Battery (MWh)	1.5	38	75	1050	20	20	300	20	20	20
	Annual OPEX ($M)[16]	17.1	14.5	13.9	44.0	13.5	12.1	22.5	13.5	12.1	19.4
	Total CAPEX from 2018 ($M)	49.5	148	190	672	118	156	476	118	156	185
	Incremental CAPEX ($M)	49.5	99.1	41.4	482	68.3	38.2	320	68.3	38.2	29.2
	- Diesel Generation ($M)	9.0	-	-	9.0	-	-	9.0	-	-	9.0
	- Solar PV ($M)	21.6	62.5	10.0	120	-	18.0	120	-	18.0	-
	- Wind ($M)	-	-	-	-	39.2	-	165	39.9	-	-
	- Battery ($M)	1.0	14.0	11.1	307	6.9	-	-	6.9	-	-
	- Network and system ($M)	17.9	15.3	20.3	-	15.3	20.3	-	15.3	20.3	-
	- Asset Replacements ($M)	-	0.2	-	46.0	0.2	-	25.9	0.2	-	20.9
	- Enabling Technologies ($M)	-	6.0	-	-	6.0	-	-	6.0	-	-
	Simple LCOE ($/kWh)	0.29	0.32	0.34	0.93	0.29	0.29	0.55	0.29	0.29	0.35
	Renewable energy fraction (%)	9	51	67	100	54	68	100	54	68	100

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[16] This is "Operating Cost" from HOMER and includes fixed overheads, fuel, maintenance, and annualised periodic costs

		Baseline	Solar and Battery only Pathway			Wind, Solar and Battery Pathway			Biodiesel, Wind, Solar and Battery Pathway		
		2022	2025	2030	2050	2025	2030	2050	2025	2030	2050
Ebeye	Diesel generation (MW)	2.6			2.5			2.5			2.5
	Installed solar PV (MW)	0.6	6.6	6.6	17.0	0.6	2.6	7.6	0.6	2.6	2.6
	Wind (MW)	-	-	-	-	3	3	7.5	3	3	3
	Battery (MWh)	0.6	10.5	17.0	225	6	6	150	6	6	6
	Annual OPEX ($M)	5.6	4.7	4.5	11.3	4.5	4.1	8.8	4.5	4.1	5.0
	Total CAPEX from 2018 ($M)	15.7	36.2	40.1	139	29.4	35.5	115	29.4	35.5	43.9
	Incremental CAPEX ($M)	-	20.6	3.8	99.4	13.7	6.1	79.1	13.7	6.1	8.4
	- Diesel Generation ($M)	1.9	-	-	1.5	-	-	1.5	-	-	1.5
	- Solar PV ($M)	8.8	15.0	-	20.8	-	5.4	10.0	-	5.4	-
	- Wind ($M)	-	-	-	-	9.4	-	13.4	9.4	-	-
	- Battery ($M)	1.0	3.3	3.1	65.4	2.0	-	47.8	3.3	-	-
	- Network and system ($M)	4.0	0.5	0.7	-	0.5	0.7	-	0.5	0.7	-
	- Asset Replacements ($M)	-	-	-	11.7	-	-	6.4	-	-	6.4
	- Enabling Technologies ($M)	-	1.8	-	-	1.8	-	-	0.5	-	-
	Simple LCOE ($/kWh)	0.37	0.39	0.43	1.12	0.36	0.38	0.90	0.36	0.38	0.44
	Renewable energy fraction (%)	5	51	62	100	51	68	100	51	68	100
Wotje Jaluit Rongrong Santos Rongelap and Kili[17]	Total CAPEX from 2018 ($M)	0	22	22	22	na	na	na	0	22	22
	Annual OPEX[18] ($M)	3.3	2.4	2.4		na	na	na	3.3	2.4	2.5
Small island stand-alone power systems	Installed systems	3000 SHS		Schools, health clinics, fish bases, telecoms			Schools, health clinics, fish bases, telecoms			Schools, health clinics, fish bases, telecoms	
	Capital investment to increase services			3.7			3.7			3.7	
	- Annualised Asset Replacements ($M)	1	1	1.8	1.8	1	1.8	1.8	1	1.8	1.8

In addition to modelling results presented in this Section, sensitivity analysis modelling results are presented in Appendix 1, given the uncertainty in real world technology costs and wind resource, and to account for revisions to the GHG targets

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[17] Santos and Kili capacities and costs are indicative only, lacking firm data, see Section 2.4.4

[18] Including annual contribution to replacement reserve fund, and RepMar subsidy applied to baseline only

6 Discussion and Recommendations

6.1 Wind energy

Results from energy modelling in Homer for 'wind' scenarios suggest that the largest contribution to national electricity sector emissions reduction to 2030 could be wind energy (Figure 6.1). This finding relies on several assumptions, such as that the price of energy storage will decrease over time, the cost of diesel does not change over time, the estimated prices of new equipment used is sufficient to cover all necessary logistic and installation costs, the turbines modelled are appropriate and viable for the location and maintaining grid stability with no diesel generators running is feasible.

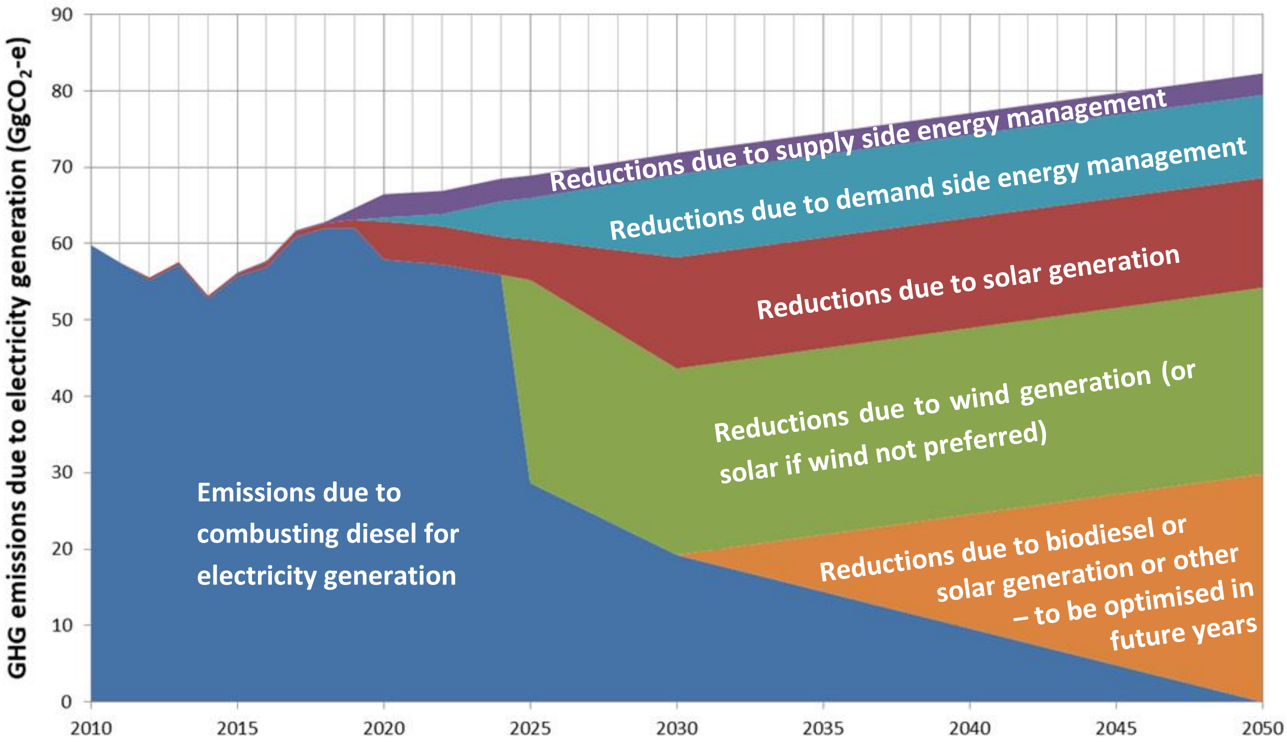

Figure 6.1: Wedge diagram of recommended RMI electricity sector solution to contribute to national emissions targets

Further consideration of wind energy on Majuro will require a detailed resource assessment, in order to more accurately predict expected production and also to better understand extreme wind speeds to aid selection and pricing of suitable machines. It is understood that Ebeye wind resource has been assessed, and that resource may be better than that of Majuro[19]. Assessments of available space, social acceptance (including visual and noise impacts) and logistical barriers and costs (for example, a crane would need to be barged to Ebeye) will also be required. Results suggest as many as twenty four 500 kW turbines powering Majuro and six 500 kW turbines

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[19] Subsequent to this analysis a summary of two years of wind monitoring on Carlos Island, Kwajalein Atoll was provided, suggesting a mean wind speed of 7.81 m/s and mean power density of 401 W/m^2 at 50m over that period – compared with the 7.05 m/s and 317 W/m^2 modelled.

powering Ebeye could potentially be a suitable option to help meet the 2025 and 2030 targets if no impediments to this much capacity existed.

6.2 Waste to Energy

Viability of adequate waste to energy (WTE) technology for use in Majuro is currently (July 2018) under assessment. This technology was not presented in this energy modelling exercise as the GHG implications of the technology are very dependent on the composition of the waste and the identification of a feasible technology. However, previous modelling [10] showed that, if found viable, WTE could benefit energy generation by providing up to around 1MW of "baseload" power.

A WTE plant has potential to reduce waste emissions as well as electricity emissions, depending on the waste composition (see technical note [8]). While the net reduction in electricity emissions (diesel savings minus WTE feedstock emissions) is minor, the required total electricity sector emissions reduction is less severe, due to the possibility of extra reductions made in the waste sector.

However, this reduction in emissions assumes a high proportion of organic material in the feedstock. If much of this organic material is removed from the feedstock then a WTE plant may instead increase electricity sector emissions and have less effect on waste emissions. This suggests that a feasibility study into the viability of WTE on Majuro - including a techno-economic and GHG emissions analyses - would be worthwhile. Only after that would WTE be fully integrated into energy modelling.

6.3 Solar energy

If wind energy and WTE are excluded, the only RE generating technology considered is solar PV, along with the associated battery storage required to allow large amounts of solar energy into the generation mix. In scenarios where wind energy is excluded, the LCOE (including capital expenditure) is likely to be several cents per kWh higher than continuing to generate electricity almost entirely using diesel fuel (dependent on fuel price assumed), which the results suggest is in turn higher than a wind/diesel/battery hybrid. This assumes that the price of PV and energy storage will decrease over time, the cost of diesel does not change over time, the price of new equipment used is sufficient to cover all necessary logistic and installation costs, there is sufficient space to install PV, and maintaining grid stability with no diesel generators running is feasible.

The capacities of PV and batteries required to meet the targets without complementary wind production are quite significant and would result in large areas being covered by solar panels; an obvious challenge for the limited land space and existing building structures of Majuro. As we look towards 100% renewables in 2050, the size of batteries is so large as to be unwieldy and too expensive.

For scenarios where wind energy is considered, solar PV has value in increasing renewable beyond 50% renewable energy contribution. Solar PV can complement wind energy and provide increased renewable energy contribution during months of low seasonal wind resource.

6.4 Enabling technologies

All scenarios feature a transition from stage 1 or 2 systems on Ebeye and Majuro to a stage 4 type systems by 2025. Stage 4 type systems experience very high instantaneous penetrations of variable renewable energy sources, which are likely to cause significant technical challenges to manage while maintaining minimum service levels [2] . Part of the next step of a design study for Majuro and Ebeye grids will include detailed power systems modelling to detail the enabling technologies required and the cost. These measures have not been addressed in detail as part of this high level techno-economic analysis. In particular, substituting rotating power production (alternators) with electronic power production (inverters) will require enabling technologies to provide inertia, fault current, load imbalance provision etc. These may take the form of synchronous condensers, flywheels, diesel-UPS or other as identified by the power systems modelling.

In all scenarios energy storage is required. Based on current technology trends, this is most likely to be in the form of batteries. The critical requirement for this energy storage is initially a power requirement, which substitutes diesel spinning reserve for battery operating reserve, and allows diesel generators to be dispatched in an optimal manner. Sufficient energy capacity is also required to limit excessive generator start/stop cycles. To meet 2030 targets with restrictions on wind capacity, enough battery capacity will also be required to perform some time shifting (fundamentally day to night time) of variable renewable energy.

Optimising diesel generator dispatch, curtailment of PV and wind where required, and managing battery charging/discharging will require supervisory control systems (programmable logic controllers and SCADA) on Majuro and Ebeye far more sophisticated than currently installed.

6.5 Sensitivity analyses

Modelling results demonstrate that even with a significant degree of uncertainty around the capital costs of installing wind and solar within RMI in the future, the decision whether to include or exclude wind or solar in the generation mix on Majuro and Ebeye to meet the emissions targets does not change – the optimum capacities of each does however change (see Appendix 1). Identifying the optimum capacity of wind energy will require more detailed analysis in the future once wind resource and installation/site options are better understood.

6.6 2050 results

Performing HOMER modelling at year 2050 is highly speculative. Under a set of working assumptions, indicative HOMER results were generated to give indicative outcomes.

These results suggest that systems with enough solar, wind, and energy storage to meet 100% of demand may approximately double the cost of generation (including capital expenditure). Similarly, meeting demand by importing biodiesel instead of mineral diesel may approximately double the cost of diesel generation. However, combining significant quantities of solar, wind, and energy storage as a hybrid system with biodiesel generators significantly limits this cost increase for the last level of Stage 5.

6.7 Majuro pathway

It is assumed that prior to 2025, the existing diesel generators will be replaced, and some upgrades to the distribution network and to the powerhouse will be implemented, to facilitate the required increases in renewable energy.

To determine the optimum technology mix to achieve the targets on Majuro will require a feasibility study of waste to energy technology, a full assessment of the appropriateness of wind energy, and grid stability analyses. In lieu of these studies, the high-level techno-economic analysis suggests that by 2025 this mix is likely to need to be a “stage 4” type system and might include between 4 and 29 MW PV, between 0 and 12 MW of wind energy, and between 20 and 38 MWh battery storage. The wide ranges are indicative of the remaining uncertainty around wind capacity. This would require a sophisticated control system, capable of automating generator dispatch and curtailing solar and wind production, and optimising battery charging decisions and enabling diesel-off operation. Running with low or no diesel generation will likely require some form of rotating equipment for inertia and fault current, such as a synchronous condenser, as well as a grid-forming battery inverter capable of setting grid voltage and frequency. The capital cost to implement this mix along with network strengthening projects might be $118M - $149M (at expected 2025 prices and including existing and planned projects)

To achieve the 2030 targets will likely require between 13 and 34 MW PV, between 0 and 12 MW of wind energy, and between 20 and 75 MWh battery storage. The capital cost required to upgrade from the 2025 systems might be $38M - $41M (at expected 2030 RT prices), in addition to previous investments.

If “zero-emission” biodiesel is used to achieve the 2050 targets, the optimum technology mix might be in the order of 13 MW PV, 12 MW of wind energy, and 20MWh battery storage. The capital cost required to upgrade from the 2030 systems might be around $29M (at expected 2050 RT prices) in addition to previous investments.

If biodiesel is not used, the mix will likely require at least 73 MW PV, 42 MW wind, and 300 MWh battery storage. The capital cost required might be around $320M (at expected 2050 RT prices) in addition to previous investments. However, this does not account for the fact that new technology such as large capacity flow batteries may be available at low cost by then.

In all scenarios to 2030, and a hybrid biodiesel/renewables system in 2050, moving to a lower emissions generation mix is also expected to save utility annual operating costs. This however depends in part on the price of diesel fuel - which is highly volatile - and assumes that the operating and maintenance costs of the renewable systems modelled here adequately reflects operation in a Pacific island environment.

6.8 Ebeye pathway

Like Majuro, Ebeye would require repairs to its generation fleet, power house, and distribution grid.

To determine the optimum technology mix to achieve the targets on Ebeye will require a full assessment of the appropriateness of wind energy and grid stability analyses. In lieu of these studies, the high-level techno-economic analysis suggests that by 2025 this mix is likely to need to be a “stage 4” type system, and might include between 600 kW and 6.6 MW PV, between 0 and 3 MW of wind energy, and between 6 and 10 MWh battery storage. This would require a sophisticated control system, capable of automating generator dispatch, curtailing solar and wind production, optimising battery charging decisions and enabling diesel-off operation. Running with no diesel generation will likely require some form of rotating equipment for inertia and fault current, such as a synchronous condenser, as well as a grid-forming battery inverter capable of setting grid voltage and frequency. The capital cost to implement this mix along with network strengthening projects might be $29M - $36M (at expected 2025 RT prices).

To achieve the 2030 targets will likely require between 2.6 and 6.6 MW PV, between 0 and 3 MW of wind energy, and between 6 and 17 MWh battery storage. The control systems and enabling technologies will need to allow diesel-off operation. The capital cost required to upgrade from the 2025 systems might be $4M - $6M (at expected 2030 RT prices) in addition to previous investments.

If “zero-emission” biodiesel is to achieve the 2050 targets, the optimum technology mix might be in the order of 2.6 MW PV, 3 MW of wind energy, and 6 MWh battery storage, with additional energy provided by biodiesel generators. The control systems and enabling technologies will need to allow diesel-off operation. The capital cost required to upgrade from the 2030 systems might be around $8M (at expected 2050 RT prices) in addition to previous investments.

However, if biodiesel is not used, the mix will likely require at least 7.6 MW PV, 7.5 MW wind, and 150 MWh battery storage. The capital cost required to upgrade from the 2030 systems might be around $80M (at expected 2050 RT prices) in addition to previous investments. However, this does not account for the fact that new technology such as large capacity flow batteries may be available at low cost by then.

6.9 Recommendations

The recommended technology pathway for electricity generation on small outer islands without electricity distribution is to transition directly to 100% renewable solar/battery household scale systems (solar home systems). A detailed techno-economic analysis is not performed for this transition, given the lack of available data on energy needs and social factors, and because the effect on national greenhouse gas emissions is considered minor. Previous experience in the RMI suggests that a challenging barrier to this transition to address may be to develop an economically sustainable solution to maintaining such systems. Prior to further widespread installation of solar home systems, a workable solution should be designed.

The recommended technology pathway for electricity generation on medium sized islands with existing distribution networks, such as Wotje and Jaluit, is the installation of centralised PV/battery systems. These should be sized such that almost all electricity is supplied from these solar/battery systems, with diesel generators and fuel supplies retained for periods of extended bad weather or periods of unusual demand. This represents a direct near-term transition to systems with very low emissions. A gradual, staged approach is not recommended for several provided reasons. Previous techno-economic analyses by others have provided indicative sizing and costs for these systems, and so similar techno-economic analyses have not been repeated here. Even though a PV/battery system sized to meet most loads is costly at current-day prices, so is transporting relatively small quantities of diesel fuel to remote islands.

The recommended technology pathway for electricity generation on Majuro and Ebeye is a staged approach. Increasing contributions from variable renewable energy need to be accompanied by supporting enabling technologies which counter the destabilising influence of these variable sources. Techno-economic analyses of Majuro and Ebeye electricity generation were performed under multiple hypothetical future scenarios.

These analyses identified that very significant changes to electricity generation will be required by 2025 – a move from manually dispatched aged diesel generators to an automated system which allows stable operation with little or no diesel generation running during periods of high renewable energy resource, along with other enabling technologies such as battery storage to provide operating reserve.

For both Majuro and Ebeye, from a techno-economic perspective wind energy in RMI is potentially an attractive form of generation and could provide a significant portion of the energy generation in Majuro and Ebeye, reducing emissions as well as the cost of generation. There is confidence in this assessment for Ebeye based on summary wind data provided by the US Army on Kwajalein Atoll. A robust wind resource assessment and a full assessment of technical, social, environmental and economic factors are, of course, pre-requisites to successful wind projects. Given the imminence of the GHG targets and the typical lead time of wind projects, it is recommended that a wind resource assessment commences as soon as practicable on Majuro. Presuming that these will further highlight the benefits of wind generation: local social acceptance, environmental impacts, logistical construction challenges and long-term maintenance requirements and capability should all sought to be better understood.

A waste to energy plant was also identified as potentially of benefit to reducing national greenhouse gas emissions (TN02). However, this depends on the composition of the waste feedstock stock extracted from the waste stream, and the technical feasibility of WTE on Majuro. It is recommended that a feasibility study of the potential for WTE on Majuro is undertaken, including consideration of the effect on greenhouse gases.

In all scenarios, solar PV also featured. Many of the capacities suggested by the modelling (e.g. 29 MW powering Majuro in some scenarios) would require a significant footprint, for example 70 acres. This may require considering the use of floating arrays in the lagoons.

Meeting 2025 targets may require prior investment of around $170M in physical assets alone, highlighting the need for large and rapid investment in the RMI electricity sector. Ongoing investment would be required to continue to meet the targets, potentially increasing to total capital investment of $210M by 2030 and increasing to $320M to $620M by 2050 (depending on whether liquid biofuels are used and depending on how the transport sector is powered).

7 References

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APPENDIX 1: Majuro key parameters sensitivity analysis

2025 GHG target Sensitivity modelling results

Fuel reduction from 2010 levels by 2025	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)	Total capital cost ($m)
48%	4	12	20	139
55%	6	13	20	147
60%	9	13	20	154

2030 GHG target Sensitivity modelling results

Fuel reduction from 2010 levels by 2030	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)	Total capital cost ($m)
63%	13.1	12	19.5	156
70%	19.1	12	19.5	168
80%	19.1	20	30.0	197

Solar PV technology price Sensitivity modelling results for Scenario 2025

PV cost ($/W)	Wind cost ($/W @ 2.5MW scale)	BESS cost ($/kWh)	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)
1.2	6.38	230	29	0	38
1.6	4.47	306	9	9	20
2	3.19	383	4	12	20
2.6	3.19	500	4	12	20

Wind speed Sensitivity modelling results for Scenario 2025

Average wind speed	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)
6.34	14	9	20
7.05	4	12	20
7.75	4	9	20

APPENDIX 2: Ebeye key parameters sensitivity analysis

2025 GHG target Sensitivity modelling results

Fuel reduction from 2010 levels by 2025	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)	Total capital ($m)
48%	0.6	3.0	6.0	32
55%	1.6	3.5	6.0	36
60%	2.6	3.5	6.0	38

2030 GHG target Sensitivity modelling results

Fuel reduction from 2010 levels by 2030	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)	Total capital ($m)
63%	2.6	3	6.0	36
70%	3.6	3	6.0	38
80%	4.6	3	12.0	41

Solar PV technology price Sensitivity modelling results for Scenario 2025

PV cost ($/W)	Wind cost ($/W @ 2.5MW scale)	BESS cost ($/kWh)	Total PV installed (MW)	Total wind installed (MW)	PV cost ($/W)
1.2	6.38	230	6.6	0	1.2
1.6	4.47	306	2.6	2	1.6
2	3.19	383	0.6	3	2
2.6	3.19	500	0.6	3	2.6

Wind speed Sensitivity modelling results for Scenario 2025

Average wind speed	Total PV installed (MW)	Total wind installed (MW)	Total BESS installed (MWh)
6.34	2.6	2.5	6
7.05	0.6	3	6
7.75	0.6	2.5	4