Republic of the Marshall Islands Energy Future

Electricity Roadmap

Technical Note 07: Renewable Energy Generation and Enabling Technologies Review

Final version, December 2018

Prepared by: Dusan Nikolic

Reviewed by: Nicole Baker

Approved by: Andrew Revfeim, December 2017

NEW ZEALAND
FOREIGN AFFAIRS & TRADE
Aid Programme

The development of the Marshall Islands Electricity Roadmap and related analysis was supported by the New Zealand Ministry of Foreign Affairs and Trade.

Summary

This technical note investigates renewable energy conversion technologies along with complementary technologies with potential for use in the RMI. Technologies assessed as viable in this note were then used in HOMER energy modelling for determining suitable roadmap pathways for RMI islands. The technical note also provides a framework to assist decision-makers in determining the suitability of proposals for renewable energy projects in the RMI.

Technologies have been assessed for suitability for use in the Marshall Islands against a range of criteria including indigenous resource, technology availability (maturity), environmental impacts, power system stability impact, economics (cost of energy), and local know-how, operation and maintenance.

A summary of recommended technologies is given in the table below.

	Recommended to be used in:		
	Short-term (<10 yrs)	*Medium-term (10-20 yrs)*	*Long-term (>20 years)*
RENEWABLE ENERGY			
Solar PV - ground mount	Y	Y	Y
Solar PV - roof-top mount	Y	Y	Y
Solar PV – floating (reservoir)	Y	Y	Y
Solar PV – floating (marine)	Assess	Y	Y
Solar thermal	N	N	N
Wind	Y	Y	Y
Ocean thermal energy conversion	N	N	Assess
Ocean current, waves and tidal energy	N	N	Assess
Biodiesel	N	Assess	Y
ENABLING TECHNOLOGIES			
Resistive load banks	Y	Y	Y
Synchronous condensers	N	Y	Y
Battery energy storage	Y	Y	Y
Distributed battery energy storage	N	N	Assess
Vehicle to grid	N	N	Assess
Power inverter	Y	Y	Y
Automatic control system	Y	Y	Y
Smart Grids	N	Assess	Y
Thermal energy storage	Assess	Y	Y
ADDITIONAL BENEFICIAL TECHNOLOGIES			
Solar hot water heaters	Y	Y	Y
Carbon capture storage	N	N	N
Waste to energy	Assess	Assess	N

1 Renewable energy technologies

This section considers renewable energy technologies for electricity generation which have a potential resource in the RMI - solar energy, wind energy, ocean energy technologies and biomass/biofuels (locally manufactured or imported).

1.1 Solar Photovoltaic

Solar photovoltaic (PV) generators are well-proven technology and RMI has plentiful solar resource at its disposal. Although this technology has its short-comings, such as generation during daylight only and limited power system support, it is one of the prime candidates for future renewable energy generators in RMI.

This section investigates solar PV technology only; concentrated solar or similar technologies are not considered. Solar hot-water panels are discussed in Section 4 of this technical note.

1.1.1 Resource availability

The entire RMI stretches across the North Pacific Ocean, on latitudes close to the Equator. The solar resource given by Meteonorm software [1] shows average annual daily radiation of 5.03 kWh/m2/day for Majuro. This solar resource is consistent across all RMI islands.

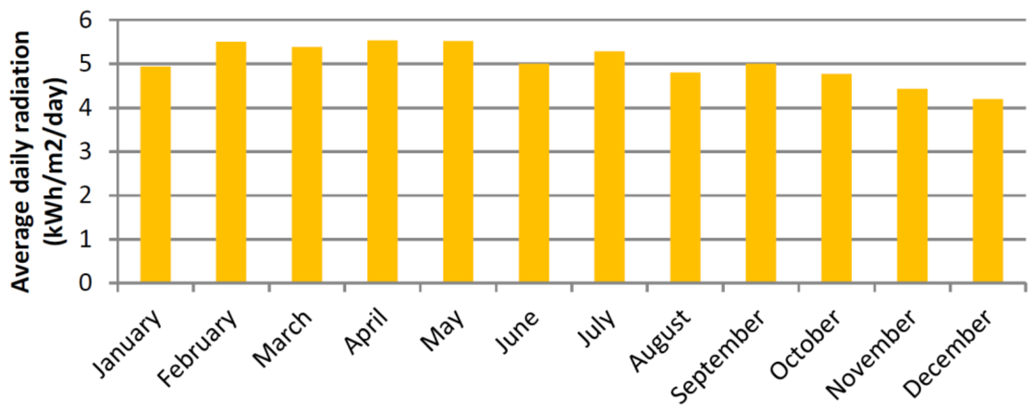

Figure 1.1 - Majuro solar resource, given by the Meteonorm software [1]

A rule-of-the-thumb application of the above data gives a rough annual averaged value of about 4 MWh of energy per day from each 1 MW of solar PV installed, when all losses and inefficiencies are accounted for.

On the other hand, solar PV technology requires large land areas – a megawatt of solar PV requires around 1 hectare of land area. Land area is scarce in RMI, so alternative solutions such as floating lagoon solar should be considered.

1.1.2 Technology availability

Solar PV is well established, widely accepted and utilised technology. There are numerous examples of solar PV technology in the Pacific region, including RMI.

Solar PV technology is based on an array of solar photovoltaic modules, connected to an AC power system via one or more power inverters. In RMI context, there are three potential types of installations for solar PV panels.

The first one is ground-mount solar PV, where solar panels are installed above ground using mounting beams. Advantages of this type is easy installation and easy access for maintenance.

This type of installation however requires land, which is scarce in RMI. While there are some examples where this type of installation is a perfect fit, such as around water reservoirs in Majuro (Figure 1.2), it is likely that available land areas are not enough for all necessary solar PV installations after considering the dispersed ownership.

Figure 1.2 – Solar ground mounted PV panels installed around a water reservoir in Majuro atoll

The second type of solar PV installation is roof-top mounted, and it offers a clear advantage of not requiring additional land space. There are roof tops in both Majuro and Ebeye which could be utilised for solar PV generators, however as there is limited suitable roof-top space, there isn't enough space for all necessary solar PV capacity on roof-tops alone.

This type of solar PV is harder to install and maintain, as it requires work on heights and special equipment. Roof-top solar PV requires solid roof structures for installation, which is a challenge in a tropical humid environment such as the RMI.

Figure 1.3 - Solar Roof-top mounted PV panels on roof top of College of RMI, Majuro atoll

Finally, the third type of solar PV installations is floating solar, where solar panels are placed on floating modules and bundled together (Figure 1.4). The lagoon in both Majuro and Ebeye offers relatively calm waters for a floating structure, and easy access to distribution grids around both atolls.

Floating solar technology is still young relative to the other two installation types, and there might be unresolved technological challenges. There are now many successful international examples on fresh-water reservoirs, but utility scale marine systems are only now going into trial. Proximity to seawater, wave motion and salt sprays during high winds pose a challenge for future integrity and maintenance.

On the other hand, installed floating solar PV cost per watt seems to be becoming very competitive, compared to other installation types. Both Majuro and Ebeye have large water surfaces inside their lagoons, and this approach could potentially provide all the necessary space for a future large solar PV capacity.

Figure 1.4 - Solar PV - Lagoon floating trial installation in Baa Atoll, Maldives (Source: Swimsol company)

1.1.3 Environmental impacts

The environmental impacts of ground, roof-top and floating solar installations were assessed at high level in [2] . No significant threats to the environment were identified, although larger solar installations, and especially floating solar installations, should be additionally assessed.

1.1.4 Social Impact

Roof-top solar PV installations have relatively little social effect, while ground-mount installations require land. In RMI, land is scarce and ground-mount solar could cause more disturbance to island society.

Lagoon-positioned floating solar does not require land, but it is highly visible in the lagoon and due to its size, may disrupt lagoon transport, vessel anchoring, lagoon fishing and beach access.

1.1.5 Power system stability impact

Power system stability is affected by both renewable energy resource variation and inertia of the technology harvesting it. Solar PV technology unfortunately has a less than desirable effect on power system stability, given the fluctuating nature of solar irradiance and the lack of inertia in electronic power conditioning.

Solar resource is known to experience sharp falls during the passing of ‘fast clouds’. This in turn affects total output of a solar PV plant and requires that amount of power to be quickly compensated by other generating sources. There are three ways for reducing negative effects of solar resource variability. The first one is building distributed solar, so passing clouds affect only a small portion of total solar PV generation at any one time. The second is by using solar cameras which constantly look at the sky and raise alarms if sun is to be covered by passing clouds, signalling other generation sources to respond in a timely fashion. The third is to use energy storage to buffer and smooth out the output fluctuations.

Solar energy is delivered to a power system by solar inverters, a technology which is capable of providing limited fault current and does have ability with reactive power control for voltage support (according to IEEE1547:2018 category B inverters). That said, solar PV generators do need to be complemented by additional technologies, if they are to operate reliably in an island power system.

1.1.6 Cost of Energy (LCOE)

Based on available solar resource and estimated capital and maintenance costs over the service life of the solar plant, the approximate levelized cost of energy can be calculated within the 0.11–0.15 $/kWh range if the scale is large enough and enabling technologies required are limited. This makes PV technology economically attractive for use in RMI.

1.1.7 Local know-how, operation and maintenance

Solar PV farms are usually automatically operated in island power systems, so there is no need for manual local workforce input.

Compared to other generation technologies, solar PV panels require very little maintenance per installed watt. They generally only require occasional cleaning, grass cutting (if applicable), periodic inspection and 10+ year inverter replacement.

In the last few years, almost a megawatt of solar PV systems was installed in Majuro and around a half a megawatt will soon be installed in Ebeye. Therefore, local crews do have some exposure to this technology and how it operates. Future training and more experience will be necessary, especially with arrival of larger, more complex, and potentially floating solar PV systems.

1.2 Solar thermal

Solar thermal technology is a well-proven large-scale solar technology which utilises sunlight to produce steam which is then used by steam turbines for electricity generation. This technology has several advantages over photovoltaic technology; at the same time, its main downside is that it is not economic at scales less than 10MW and can only be ground mounted. Furthermore, it is not suited to tropical environments where humidity and aerosols disperse much of the direct solar irradiation needed to create heat. As such, it is not recommended for use in the RMI.

1.2.1 Resource availability

Similar to solar photovoltaic, solar thermal uses sunlight to produce electricity, however it only utilises direct solar irradiation, unlike solar PV which uses both direct and indirect solar irradiation.

1.2.2 Technology availability

Solar thermal technology is readily available, and in use in several countries. Solar thermal plants are usually built in flat, desert regions with plenty of sunshine and clear skies. They are usually large in size with typical installations surpassing 100 MW of installed capacity. Large-scale plant is needed to generate the economies of scale needed to be economic; smaller scale solar thermal plants are not common.

Figure 1.5 - Mojave Solar Project [25] has a capacity of 280 MW.

Solar thermal technology utilises large mirrors to concentrate sunlight onto a single tube carrying a heating medium or onto a single focal point at the top of a tower where salt is melted.

1.2.3 Environmental impacts

Environmental impacts are similar to those of large-scale ground-mount solar farms.

1.2.4 Social Impact

Social impact of a large-scale thermal is potentially high, as this installation would require a significant amount of land in a single location. In RMI, land is a scarce resource and quite possibly the first showstopper to this technology.

1.2.5 Power system stability impact

Solar thermal uses steam turbines to generate electricity. As such, it brings more benefits to a power system than typical solar photovoltaic; rotating turbine is capable of providing inertia to the system, fault currents and regulation of voltage and reactive power.

In addition, thermal inertia of the working fluid ensures there is no sudden drop of generation, even with a sudden heavy cloud coverage. Further, solar thermal plants are able to generate power after sunset when the heating medium is stored in a tank for later use. Solar thermal has been commercially operated for 24 hours using molten salt storage, whereas achieving the same with solar PV and batteries is currently economically prohibitive.

1.2.6 Cost of Energy (LCOE)

Solar thermal installations are large-scale, and as such have competitive cost of energy, very similar to standard solar PV large-scale plants.

1.2.7 Local know-how, operation and maintenance

There is no know-how in operation and maintenance of this technology in the RMI. To be able to effectively convert sunlight to thermal energy, solar thermal plant needs to move its mirrors the whole day, which implies many moving parts which might not operate in highly saline environments.

1.3 Wind Turbines

Wind turbine technology is a well-proven technology and RMI does appear to have sufficient wind energy resources to make this technology very attractive. While there are challenges associated with the potential for extreme wind events, siting of wind turbines and increased maintenance due to saline environment, wind energy could be beneficial to RMI power systems.

Wind energy in Marshall Islands is discussed in detail in the Technical Note 'Wind in the RMI'. The summary of its main findings is presented here.

1.3.1 Resource availability

The analysis presented in [3] [1] found that a sufficient wind potential (roughly 7.0 m/s average) exists for wind energy to be used cost effectively in the two more populated islands, Ebeye and Majuro. RMI lies in the north Pacific Ocean outside the main typhoon belt but is potentially exposed to extreme weather events. However, those events prove to be rare and wind turbines which are not completely cyclone-proof might be used.

1.3.2 Technology availability

Wind turbine technology is well established, and there are numerous examples of its successful operation. The wind Technical Note [3] investigated wind turbine models from manufacturers such as Vergnet, Xant, Komai Haltec, Windflow and Enercon, in a range between 275 kW and 900 kW. Smaller wind turbines, Vergnet (275 kW) and Xant (330 kW) are tilt-up and therefore considered "cyclone-proof", while larger wind turbines from Windflow and Enercon are traditional wind turbines but are more efficient and cost-effective.

Wind turbines have a small area footprint and could be installed in RMI on-shore (on the atolls of Majuro and Ebeye), or on the reef-flats, where adequate foundations could be manufactured to support wind turbines. The wind Technical Note [3] presents a case for both of those approaches.

Figure 1.6 - Vergnet wind turbines on the island of Upolu, Samoa

As presented in Figure 1.6, wind turbines have been successfully used in Pacific for a number of years. This Figure shows two Vergnet wind turbines integrated into the Samoan large island power system.

1.3.3 Environmental impacts

Environmental impacts of wind turbines have not been assessed in the Marshall Islands context. Negative impacts could be disturbance of the land or a reef flat, where a platform would need to be created. Wind turbines could have negative impacts to local wildlife particularly migratory birds, and if poorly sited could produce noise disturbance at nearby receptors.

The positive impact of wind turbines is a potentially huge reduction of fossil fuels usage, and high reduction of GHGs.

1.3.4 Social impact

The highest social impact wind turbines have is visual amenity, due to their size. People living in proximity of a wind farm may have impacted views, although most will not find this significantly detrimental.

Additionally, when operational, wind turbines produce noise which quickly degrades with distance. As a guide, they should not be placed within 300 meters of human residences [3] . This ensures any noise is below that of a working air-conditioning unit level. In the Marshall Islands, noise produced by wind turbines could also be masked by the constant breaking of waves.

Wind turbines require small footprint for their masts, but the size of the turbine and blades requires clearance space within which no domestic or commercial developments should be placed. Wind turbines at scale of 500 kW yield approximately 200 W of installed capacity per every m^2. Wind turbines could however be placed offshore where they disturb no arable or residential land.

1.3.5 Power system stability impact

Wind turbines affect power systems depending on the variability of the wind resource and technology of wind turbines used. In general, wind turbines do tend to degrade the stability of a power system although all modern wind implementations use power electronics and control systems to mitigate this.

Due to its proximity of the Equator, the RMI enjoys steady trade winds during the windy season, and wind gusts are not common. Consequently, wind turbine outputs in such locations tend to be smooth, predictable and fairly constant for long periods of time. Notably there appears to be no correlation between the intensity of the wind resource and the intensity of the solar resource in RMI. Therefore, the two technologies complement each other well in the RMI environment.

There are several wind turbine technologies and while some tend to provide greater power system support than others, in general, wind turbines do increase instability of a system, reduce its inertia and fault current levels. In an island power system context, wind turbines should be considered in conjunction with some form of enabling technologies which would reduce its negative effects.

1.3.6 Cost of Energy (LCOE)

Based on preliminary wind resource monitoring data and estimated capital and maintenance costs for suitable wind turbines, the approximate levelized cost of energy can be calculated within the 0.09–0.13 $/kWh range, which makes this technology economically attractive.

1.3.7 Local know-how, operation and maintenance

Wind turbines need regular minor maintenance works, occasional major maintenance and constant operational oversight (performed remotely). While major maintenance will always be performed by a manufacturer or authorised servicing crews, minor maintenance and operations would fall onto local workforce.

There are currently no wind turbines in the RMI and no skilled maintenance/operation crews. The environment is corrosive and as such would probably increase maintenance needs. However, the recent growth in international offshore wind business has greatly reduced maintenance needs for wind turbines designed for marine environments. If wind turbine technology is implemented in the RMI, it would require adequate upskilling of the local workforce and establishment of proper maintenance routines.

1.3.8 Conclusion

The RMI has a good wind resource [3] which could supplement present and future solar generation. Adequate technologies exist and are suitable for RMI islands. Suitable wind turbine sites were identified (but not enquired on) through the process of considering wind energy in the RMI [3] . Wind turbine technology would impose technical power system integration challenges and would require upskilled labour. At the same time, wind energy has a potential to support RMI's renewable energy journey and highly contribute to the reduction of fossil fuels, GHGs and cost of energy where used.

Undoubtedly, wind turbine technology will impose challenges to RMI's utility, but its benefits outweigh its shortcomings.

1.4 Ocean thermal energy conversion (OTEC)

OTEC uses the temperature difference between the ocean surface and water temperature at ~1 km depth. This thermal gradient is used to drive a turbine which in turn generates electric energy. OTEC technology promises base-load electric energy generation and RMI has one of the World's best OTEC resources in its waters. At the same time, OTEC is an emerging technology, with operation, maintenance, economics and environmental impacts not yet understood. This technology is a long way from being technically proven but could be revisited in 10-20 years as a potential future renewable technology.

1.4.1 Resource availability

For OTEC system to be efficient, it needs sufficient thermal gradient between the ocean surface and temperature at 1 km depth. Northern Pacific and specifically Majuro and Ebeye seem to enjoy one of the best thermal gradient resources in the world, reaching about 24°C.

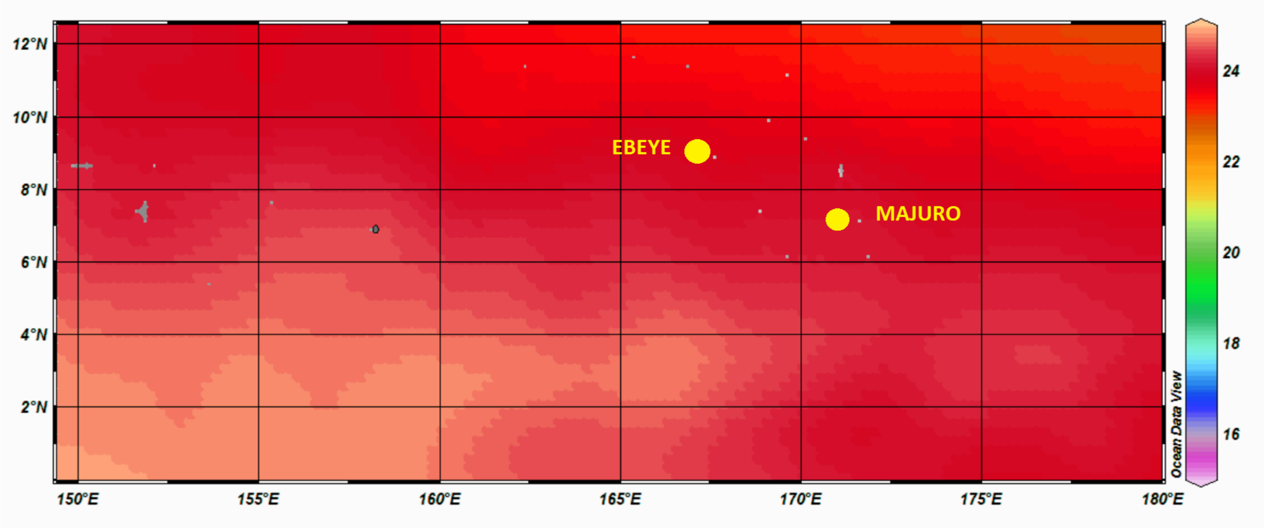

Figure 1.7 - Ocean thermal gradient resource in RMI [4]

In addition to an excellent thermal gradient resource, water depth increases very quickly off the coast of both Majuro and Ebeye atolls. Figure 1.8 demonstrates this on an example of Majuro atoll; water depth greater than 1 km is shaded in green, and only between 2 and 10 km off the costs of Majuro.

Figure 1.8 - Water depth greater than 1 km (in green) surrounding Majuro atoll. All water depths were taken from Google Earth software.

1.4.2 Technology availability

OTEC technology utilises temperature difference between the ocean surface and ocean floor (at about 1 km water depth). It requires large infrastructure, most of which is submerged and exposed to the ocean, for its proper operation. Thermal efficiency of OTEC installations is still less than 5%, however large quantities of warm seawater could potentially provide large quantities of electric energy.

OTEC technology is an emerging technology, still in its infancy. Currently, facilities around the world [5] , [6] are researching the prospects of this technology. The largest operating OTEC plant has capacity of only 0.1 MW and is located in Okinawa, Japan. No information on economics is yet available.

While there are several demonstration projects around the globe, there are no prominent companies offering OTEC technology as economically viable. Therefore, it can be concluded that OTEC technology is not a pathway for RMI in the next 10-20 years.

1.4.3 Environmental impacts

OTEC technology environmental impacts are not yet understood. [7] states that environmental impact studies from the 1980s concluded that the risks of OTEC would likely be acceptable, however; further environmental assessments and research are needed to address the potential issues around treatment and discharges of large quantities of cold, nutrient rich water at surface.

1.4.4 Social impact

OTEC technology is located deep underwater, it has on-shore installations for control of the generation and connection to the island's power system. While underwater installation would impose little social disturbance, on-shore installations would require land acquisition/resettlement.

1.4.5 Power system stability impact

OTEC facility would provide a power system with a base-load generation, which would be sufficient to completely supplement or entirely replace diesel generation on an island like Majuro or Ebeye. Similar to diesel generation, it would provide both the electric energy and all necessary power system stability services.

1.4.6 Cost of Energy (LCOE)

Reference [5] states the cost of energy from OTEC system is around US 0.18 $/kWh from a theoretical system of 10 MW scale. If scaled up to 100 MW, the cost of energy could potentially be halved. To date, there are no OTEC installations larger than 1 MW, and no base on which cost of energy calculations could be formed. Consequently, these preliminary cost of energy estimates are taken as completely speculative and therefore given no credibility. Parallels may be drawn to wave technology that has made huge advances in recent years but remains an order of magnitude below being economic at this time.

1.4.7 Local know-how, operation and maintenance

OTEC technology is little understood and no real large-scale know-how exists anywhere in the world, including RMI. Considering other emerging technologies which entered the mainstream such as solar PV and wind, it is likely that decades might pass before sound operation and maintenance routines are established for OTEC.

Additionally, large parts of OTEC infrastructure lies at great depths making it virtually unserviceable. It seems evident the OTEC technology needs much more time to mature before it is installed in remote power systems.

1.5 Wave Energy

Wave energy is present in the entire RMI, and its gross potential is higher than entire RMI's energy needs. However, this young technology does not provide base-load power, and as such, an island power system would still need additional renewable energy capacity. A recommendation is for RMI not to use this technology in the next 10-20 years, and then to re-assess it.

1.5.1 Resource availability

Wave Energy Resource can be estimated at a high level, while every specific installation would need consideration of its local factors. One of the most illustrative wave energy potential maps is shown in Figure 1.9. According to this model, RMI enjoys a potential of about 15 – 20 kW/m.

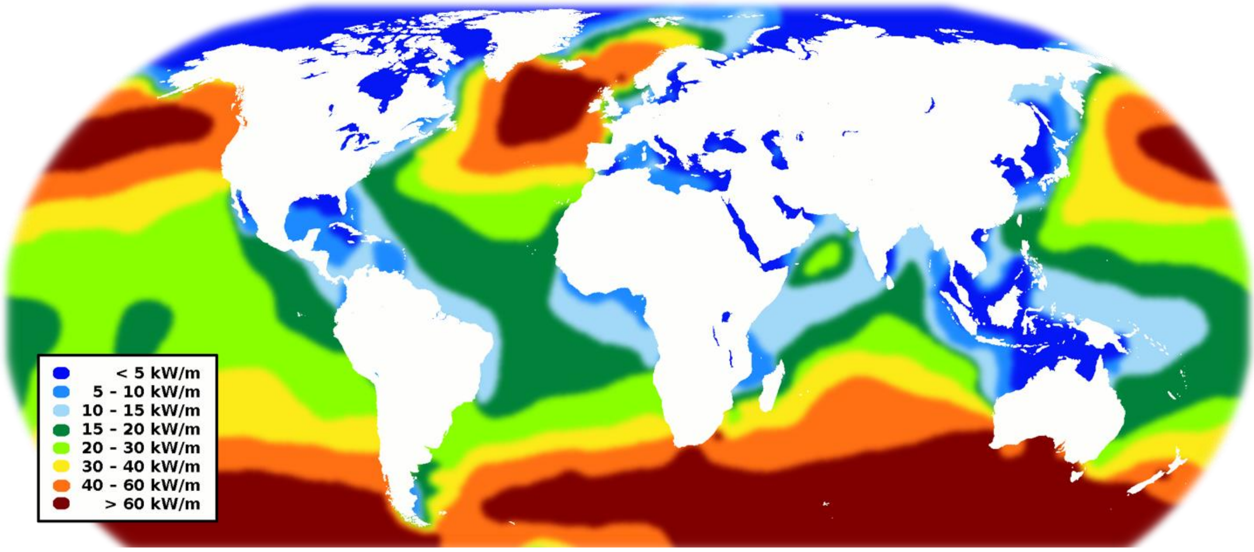

Figure 1.9 - World map showing wave energy flux in kW per meter wave front [14] .

Additional source of wave energy was considered (Figure 1.10); although it is a short-term prediction tool, it demonstrates good correlation with the Figure 1.10 Australia-Pacific region wave map.

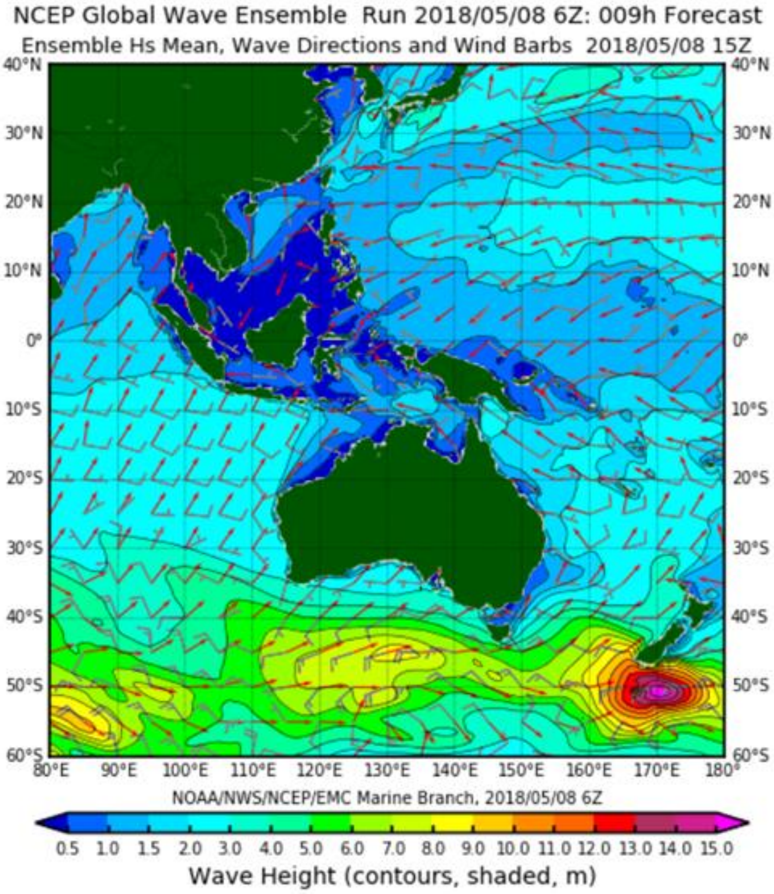

Figure 1.10 - Short-term prediction of wave intensity in Australia - Pacific Region [13]

An estimate of the wave energy potential in waters around RMI islands is hard to estimate, however it is highly likely this potential is higher than total RMI energy needs. As an example, in US territorial waters around the state of Hawaii, total wave power potential is around 34 GW (averaged annual power) [15] , which is far more than what entire state of Hawaii consumes.

1.5.2 Technology availability

There are three main types of wave energy technologies. One type uses floats, buoys, or pitching devices to generate electricity using the rise and fall of ocean swells to drive hydraulic pumps. A second type uses oscillating water column (OWC) devices to generate electricity at the shore using the rise and fall of water within a cylindrical shaft. The rising water drives air out of the top of the shaft, powering an air-driven turbine. Third, a tapered channel, or overtopping device can be located either on or offshore. They concentrate waves and drive them into an elevated reservoir, where power is then generated using hydropower turbines as the water is released. The majority of recently proposed wave energy projects would use offshore floats, buoys or pitching devices.

The technology considered in this technical note is wave floats (Figure 1.11). This technology was selected as utilisation of wave power through other technologies would mean disturbing an island's reef.

Figure 1.11 - Pelamis type wave power turbine. Water inside the 'tube' flows from one side to the other, thereby rotating small turbines inside the 'tube', which in turn generate electricity.

Any wave technology is exposed to extreme ocean events and the consequences of that are higher risk of failure and higher maintenance costs.

It is also important to note the wave energy is not a base-load, constant resource, but it changes from day to day, which implies RMI would still need to complement such a technology with other renewable energy technologies.

1.5.3 Environmental impacts

As the wave power technology is not yet fully researched and understood, environmental impacts are not fully understood; thereby, common environmental concerns associated with marine energy developments are: marine mammals and fish risk being struck by any moving parts of wave power generators, EMF and underwater noise generated by wave power technology, and physical presence of marine technology has a potential to alter the behaviour of marine mammals, fish, and seabirds.

1.5.4 Social impact

Wave energy generators are usually installed in high seas, outside of lagoons and would cause disturbance to marine transport and fishing activities only, although that disturbance might be limited. This technology also requires on-shore installations which would imply land acquisition.

1.5.5 Power system stability impact

Wave energy is a variable resource, but it is not highly variable, on a minute to minute basis, and a wave generator would not impose high stress on an island power system.

However, generators used for generating electric energy from waves are light, do not carry an adequate amount of inertia and cannot provide power system support to an island power system.

1.5.6 Cost of Energy (LCOE)

Reference [16] states wave energy power cost of energy is down to US 0.3 $/kWh. It also predicts, if this technology sees massive uptake and technology advancements, that the cost of energy could fall to reach up to US 0.1 $/kWh. That said, there are no commercially operating wave farms in the world, so numbers such as this remain highly speculative.

1.5.7 Local know-how, operation and maintenance

There is very little knowledge on this technology's operation and maintenance routines in the world, including the RMI. Most of wave power generation technologies resides underwater or surrounded by seawater, and as such they might prove extremely challenging for any maintenance.

1.6 Biodiesel

Biodiesel fuels are consumed in standard diesel generators, and as such, contribute to both green energy generation and good power system stability. Downside to this resource is its cost, which is up to two times higher than mineral diesel generation. Furthermore, biodiesels often require significant usage of fossil fuels in their production. Regardless, it is likely this technology will be used in later stages of RMI's renewable energy journey and should be covered in present-day analyses.

1.6.1 Resource availability

Various reports have proposed the RMI develop indigenous biofuel from coconuts as a potential resource. One of the reasons for the lack of development of coconut oil as a biofuel is the recent high world price of coconut oil based on its value in other uses for food and cosmetics. Which means that in general, it is more cost effective for the RMI to export coconut oil and to import cheaper biodiesel manufactured elsewhere. However, the current world price of biodiesel and coconut oil are both currently around $1,000 per metric tonne, so the option of manufacturing biodiesel from coconut oil could be further considered in the future to replace imported biodiesel.

In terms of resource availability, the RMI may not be able to consistently produce quantities required for significant energy generation.

Biofuels are nowadays readily available in world markets and RMI could supply itself from either US or Asia.

1.6.2 Technology availability

Biodiesel fuels are consumed by diesel generators, and as such, they are an established and well-known technology. That said, it is expected that there will be some increased operations and maintenance costs in using biodiesels in engines designed for mineral diesels.

1.6.3 Environmental impacts

Biodiesel generation would re-use diesel generation assets and would not require any additional land areas. While biodiesel does emit certain GHG emissions (other than CO_2) during combustion in an engine, for the purposes of this report it is considered to be carbon neutral.

1.6.4 Social impact

Biodiesel is consumed by standard diesel generators, and biodiesel fuel could be stored in existing diesel fuel tanks; as such, this technology has a relatively low incremental social impact.

1.6.5 Power system stability impact

Biodiesel fuel is consumed by standard diesel generators, and as such, they provide all necessary power system services, and have a positive impact on power system stability. However, as noted above, it is expected that there will be increased operations and maintenance costs while biodiesels are burned in engines designed for mineral diesel, but in time new technology will resolve this.

1.6.6 Cost of Energy (LCOE)

The cost of biodiesel fuels varies but a general price of US 3 $/gal could be adopted as a median value [17] . This is about two times higher than the current price of mineral diesel in RMI. In addition, biodiesel has a lower calorific value than mineral diesel fuel (so more of it is needed for the same amount of energy), and diesel generators usually require higher service costs when consuming biodiesel.

The cost of biodiesel generation could therefore be estimated at between US 0.3-0.4 $/kWh in RMI. While this cost is higher than current diesel generation, and immediate renewable energy alternatives, biodiesel generation could be utilised as a 'last mile' technology – for bridging the gap between 70 and 100% renewable generation in larger islands.

1.6.7 Local know-how, operation and maintenance

As the technology which utilises biodiesel fuels is standard diesel generation, there already is local know-how. Biofuels do require some special skills, and some upskilling will be necessary.

2 Review of Enabling Technologies

Conventional generators used in island power systems were effective at providing both necessary electric energy and stability to an island power system. Renewable energy sources have started replacing some of that generation by providing emission-free energy fuelled by local renewable resources, at a lower cost. However, renewable generation is not capable of providing power system stability to an island system. Additional technologies then need to be coupled with renewable generation to mimic the high level of service once provided by conventional generation. Since those additional technologies enable renewable energy sources to replace conventional generation, they are called enabling technologies.

2.1 Resistive Load Banks

Resistive load banks are well-proven technology which play a role of providing limited amount of quick spinning reserve in island power systems. They dissipate renewable energy surplus, which they can increase or decrease in very short time periods.

2.1.1 Technology

Resistive load banks are an old, well-understood and very well-developed technology. There are many manufacturers available across all continents, offering load banks as a standard, off-the-shelf product. There are many service centres and companies who would know how to integrate them into a power system and maintain them.

This technology is very simple, easy to operate and of low maintenance ([14] Figure 2.1) [20] . Consequently, it is very reliable and can play a useful role in high-renewable energy power systems.

Figure 2.1 - Resistive load banks (ASCO power technologies) of 0.5 MW, with horizontal hot air discharge [20] . The unit shown above is about 1 meter in height.

2.1.2 Environmental impacts

Load banks have a low direct environmental impact. They do not consume fossil or other fuels, do not hold any dangerous materials or corrosive liquids. If handled properly, and disposed of responsibly, resistive load banks would have next to no negative environmental effect.

As an enabling technology, resistive load banks support renewable technologies and by doing so, contribute to reduction of GHGs in island power systems.

2.1.3 Power system stability impact

One of the power system services a large island power system needs to have is provision of quick spinning reserve. Resistive load banks consume real power usually produced by renewable energy generation, thereby increasing the island's load.

Power consumed by resistive load bank can very quickly be diverted from the load bank to the system, in a time frame as short as couple of cycles. By doing so, it can provide access to almost instantaneous spinning reserve of real power in a case of rapid renewable energy generation drop. Alternatively, access to spinning reserve could be provided by renewable energy generators in some cases by increasing set points, however this process takes several seconds. It is the speed of provision of spinning reserve that differentiates resistive load banks from other sources.

2.1.4 Economics

Resistive load banks do not generate any energy but use energy from other sources to provide necessary power system services. This technology is very basic, and consequently of low cost, with installed cost of below 0.2 $/W [20] . Ongoing maintenance costs are also relatively low. However, the greater the spinning reserve required the greater the constant power consumption required. For example: for 100kW of spinning reserve required the load banks consumes 100kW of energy in "reserve" mode.

2.1.5 Local know-how, operation and maintenance

Load banks are automatically operated, when a system needs them, and require very little maintenance. The technology uses fans to dissipate heat from its resistors, so the maintenance is mostly focused on maintaining fans, as the only moving part of this technology. Cooling air used in RMI is of high salinity and will cause increased maintenance and cleaning of resistors. Even when taking all the above into account, maintenance needs remain low for this technology.

Local workforce does not have experience working with load banks; even though the technology is basic and has low maintenance needs, a certain amount of upskilling will be necessary.

2.2 Synchronous condensers

Synchronous condensers are a well-proven technology which can provide reactive power support, voltage regulation, necessary fault currents and inertia to an island power system. As such, it provides tremendous support to a high renewable energy large island power system and should be considered for islands of Majuro and Ebeye.

2.2.1 Technology

Synchronous condensers are a well-established technology for providing reactive power and correcting power factor in industrial settings. In hybrid renewable power systems, they can be paralleled with diesel generators, where they assist the diesels in regulating voltage. During high wind and/or solar periods, and when diesel generators are turned off, the Synchronous Condenser is capable of regulating the voltage control of the entire island system.

Technically, a synchronous condenser is a diesel generator without a prime mover (diesel engine). Instead of the engine, it has a small pony motor which starts it from standstill and synchronises it to the grid (small black motor in Figure 2.2).

Figure 2.2 - Synchronous condenser, product of Sustainable Power Systems company [21] .

All parts comprising a synchronous condenser are well-proven technologies, present in energy markets for decades. The result is a low-cost, reliable and powerful device, requiring very little operation and maintenance.

2.2.2 Environmental impacts

Synchronous condensers have a low direct environmental impact. They do not consume fossil or other fuels, do not hold any dangerous materials or corrosive liquids. If handled properly, and disposed of responsibly, synchronous condensers would have next to no negative environmental effect.

As an enabling technology, synchronous condensers support renewable technologies and by doing so, contribute to reduction of GHGs in island power systems.

2.2.3 Power system stability impact

The main component of a synchronous condenser is an alternator, which is the same component used by diesel generators. Therefore, synchronous condensers are capable of providing support to an island power system by regulating voltage, generating reactive power, providing inertia, and providing necessary fault currents necessary for the island protection schemes. Overall, synchronous condensers could provide a tremendous support to stability of an island power system and match a service level usually provided by diesel generators.

2.2.4 Economics

Synchronous condensers do not generate any real power but can generate reactive power, without consuming any fuel (although they do have some losses which are covered by other generating sources in a system).

Installed cost of a synchronous condenser is around 0.3 $/VA [21] .   Ongoing maintenance costs are very low.

2.2.5 Local know-how, operation and maintenance

Synchronous condensers are automatically operated, dispatched by a control system when needed. Being made from very simple and well-understood components, they require very little maintenance.

The local workforce does not have experience working with synchronous condensers, however they do have experience maintaining diesel generator alternators, and small motor loads in the power station yard, which are very similar to synchronous condenser components. Therefore, only a small amount of local workforce upskilling will be necessary, mostly focused on operation and maintenance of its control system.

2.3 Battery Energy Storage

Battery energy storage technology benefits island power systems on their renewable energy journey. At the same time, the economic cost of producing energy and storing it in batteries is still high, so their involvement is set for later stages of renewable energy penetration.

2.3.1 Technology

Battery energy storage is a very old and known technical concept which won't be further discussed in this Section. There are many different battery energy storage technologies available. Some of the basic types and their pros and cons are presented in Table 2.1.

Table 2.1 - Comparison of major battery energy storage technologies [18]

Technology	Advantages	Disadvantages
Lead-acid battery	▪ Mature technology with established recycling infrastructure ▪ Advanced lead-acid technologies leverage existing technologies	▪ Poor ability to operate in a partially charged state ▪ Relatively poor depth of discharge and short lifespan
Lithium Ion battery	▪ Multiple chemistries available ▪ Rapidly expanding manufacturing base leading to cost reductions ▪ Efficient power and energy density	▪ Remains relatively high cost ▪ Safety issues from overheating ▪ Requires advanced manufacturing capabilities to achieve high performance
Sodium	▪ High temperature technology: Relatively mature technology (commercially available); high energy capacity and long duration ▪ Low temperature technology: Smaller scale design; emerging technology and low-cost potential; safe	▪ Although mature, inherently higher costs - low temperature batteries currently have a higher cost with lower efficiency ▪ Potential flammability issues for high - temperature batteries
Zinc	▪ Currently quoted as low cost ▪ Deep discharge capability	▪ Currently unproven commercially ▪ Lower efficiency
Flow battery	▪ Power and energy profiles highly and independently scalable (for technologies other than zinc - bromine) ▪ Designed in fixed modular blocks for system design (for zinc - bromine technology) ▪ No degradation in “energy storage capacity”	▪ Power and energy rating scaled in a fixed manner for zinc-bromine technology ▪ Relatively high balance of system costs ▪ Reduced efficiency due to rapid charge/discharge

Battery energy storage can be used in two ways – to provide short-term power, or spinning reserve, to a power system; or to serve as a long-term energy storage, where it is used to provide energy during times of longer period of renewable energy output deficiency. Batteries are used in conjunction with power inverter/chargers which connect batteries to a power system, and which are discussed in the following Sections.

Most of the battery energy storage technologies are commercially viable, with lead-acid and lithium ion batteries leading the way. Other technologies such as Zinc, Sodium and Flow-batteries are less present in the market, less known, and have less support. For the purposes of the RMI roadmap, analysis will be based on Lead-Acid and Lithium Ion batteries.

2.3.2 Environmental impacts

Batteries contain hazardous and often very corrosive substances and have a limited life, and need to be properly managed, operated, and maintained. Today, there are multiple centres around the world which are willing to accept used battery systems and recycle them, so if a battery is properly disposed of, it will have minimal impact on an island’s environment.

In addition, battery energy systems are used in conjunction with renewable energy generators to increase renewable generation and reduce GHGs; in this regard, battery energy systems have a positive effect on the environment.

2.3.3 Power system stability impact

Energy storage is connected to a power system through an inverter, therefore this paragraph will be commented in Power Inverter – Power system and stability impact paragraph below.

2.3.4 Economics

According to [18] , the levelized cost of storage (LCOS) for a Lithium Ion battery energy system is in the range of US $0.37 – 0.51 per kWh throughput, if installed in a microgrid system. However, costs are rapidly falling, which will increase the economic application of batteries in the coming years.

The energy stored in a battery needs to be produced by another resource, so the total cost of energy provided to a power system from a battery is a sum of the two (energy production and energy storage). Furthermore, some energy is lost in the storage and release process – up to 20%. Due to their capabilities, batteries do benefit renewable power systems, however due to the combined economic cost of both produced energy and cost of storage, batteries usually play a role in later stages of a power system's renewable energy journey.

2.3.5 Local know-how, operation and maintenance

Modern battery energy storage systems have sophisticated electronic battery control systems and new battery technologies are very different from typical lead-acid (car) and lithium ion (computer) batteries. As such, there is very little know-how in RMI for operating and maintaining these technologies and upskilling of local workforce will be essential if those technologies are to be used.

2.4 Power Inverters

Power inverters are a technology used to connect energy storage with the grid. Regardless of whether energy storage is battery-based or not, power inverters will undoubtedly be a part of medium to long term renewable energy journey for larger islands in RMI.

2.4.1 Technology

With the rise of modern semiconductor elements in the last few decades, new control systems and improved algorithms, inverters become capable of providing both real and reactive power to power systems, in all four quadrants [22] , which is more flexible than conventional generators.

Nowadays, inverters have become common and off-the-shelf technology, for both small, medium (Figure 2.3), and large island power systems (Figure 2.4).

Figure 2.3 - Small and Medium Island power system inverter. This inverter can form a grid and providing customers with frequency and voltage control. It has very limited overload capabilities.

Figure 2.4 - Dynapower CPS-2000 utility scale inverter is capable of full four-quadrant operation, provision of virtual inertia, limited overload currents and spinning reserve. It is a type of inverter larger islands of Majuro and Ebeye would utilise.

2.4.2 Environmental impacts

Inverter technology requires little space but needs to be cooled. It does not have any significant direct effects on the environment.

Indirectly, through support of higher renewable energy penetration, inverters positively affect the environment.

2.4.3 Power system stability impact

Modern power inverters are capable of controlling frequency and voltage, which is of great use to renewable power systems which turn off diesel generators for short of long periods of time.

Power inverters are also capable of providing operating reserve utilising battery energy storage. They can also provide limited fault currents due to their short-time overload capabilities.

On the other hand, inverters alone cannot provide sufficient fault currents or system inertia for system stability, which is why they are often supplemented by a synchronous source.

2.4.4 Economics

The cost of power inverters varies depending on their capabilities; the cost of power inverters which would be used in larger island systems is around US $1/W. For storage systems the inverter cost is usually included in battery energy system cost of energy, and therefore is hard to explicitly state. However, in general, the cost of inverters is a relatively small cost in renewable energy systems (<10%).

2.4.5 Local know-how, operation and maintenance

There is very little know-how in RMI for operating and maintaining these technologies and upskilling of local workforce will be essential if inverter technologies are to be used.

2.5 Thermal Energy Storage for excess electrical energy

In contrast to molten salt storage (above) which is used with Solar Thermal power generation to store the suns energy until it is needed to be converted to electricity, thermal energy storage is converting excess electricity (from PV or wind) into either heat or coolth, such that that heat or coolth can be used at a later time (e.g. hot water for bathing or cool air for A/C).

2.5.1 Technology

The technology for producing and storing thermal energy for later use is very simple and proven. In the case of heat it would most likely be large insulated hot water tanks, with that hot water later being used for bathing (e.g. hotel) or wash down (fish processing plant). In the case of chilling, it would involve chillers producing chilled water (fresh or saline) or an ice-bank. The stored cool energy would later be used for air conditioning, refrigeration (e.g. super market) or processing (fish plant).

It is further noted, that electricity used in heating or cooling application can also often be deferred from times of energy shortfall to time of energy excess. For example, the approximately 2MW of proposed refrigerated container load in Majuro could be run hard during solar hours and run on minimal load at other times. In this way thermal energy storage can act like resistive load banks in the grid.

The use of thermal energy storage as a means of effectively storing electricity is both highly inefficient and complex. To achieve this excess electricity would be used to e.g. melt salt, with that heat being later used to produce electricity through a steam turbine and some later time when the electricity is need. However the round-trip efficiency of this is less than 30%, and requires the installation steam production and steam turbine equipment, which is typically large and complex to operate. This is not considered economic nor feasible in an RMI context.

2.5.2 Environmental impacts

In most expected applications, thermal energy would be stored as hot, chilled or frozen water, in large insulated tanks. Environmental foot print and impact are therefore expected to be low. If another medium were to be used, e.g. saline or heating oil, then an environmental impact investigation would be required.

2.5.3 Power system stability impact

As noted above, the ability for thermal energy storage to ramp up or down dependent on power supply and demand, and grid stability, enable this type of technology to not only to act as a storage medium, but also as an enabling technology like resistive load banks. So long as control is fully integrated into the grid management system, this ability can provide considerable benefit.

2.5.4 Economics

The economics of thermal energy storage are well proven in locations where time of use electricity pricing exists. For example, in New Zealand the majority of electric hot water cylinders can be controlled by the Utilities to manage grid constraints. Further, the use of industrial ice-banks is common.

The storage of hot or cold water in tanks for later use will be far cheaper than storing that energy as chemical potential energy in batteries, for example. However, as noted above, it will not be economic or feasible to convert the thermal energy back to electrical energy.

2.5.5 Local know-how, operation and maintenance

The skill sets required for this type of energy storage are those found in industrial HVAC systems and process engineering. These skills sets may not be prevalent in MEC or KAJUR, but will exist in some of their end-users – who will be the hosts of thermal energy storage systems.

2.6 Distributed energy storage including Vehicle-to-grid storage

Distributed energy storage is used to locally store excess of locally produced renewable energy; in some instances, to provide backup power supply, or to support the larger grid when properly coordinated.

With the rise of electric vehicles in the modern transportation industry, households in the future are increasingly likely to have energy storage in the form of electric vehicle battery. Therefore, electric vehicles are a special case of distributed energy storage technology.

2.6.1 Technology

Battery energy storage is a technology which predates modern petrol engines, and as such is an old and well-understood technology. However, the application of battery energy storage in energy power systems on a local, distributed level is relatively new. Each battery needs suitable inverter devices to connect it to the grid and manage its power flows. This aspect and its impacts on the power systems are still being tested on large scale.

The premises behind distributed energy storage are:

- To provide energy storage when too much local renewable energy (mostly from residential solar PV panels) is generated. In this way, energy storage prevents renewable energy spill, and helps power system better manage usual evening load peak.
- Take the stress off the distribution grid, postpones maintenance costs and potentially, capital investment in network infrastructure.
- Enabling customers in the electricity market to become *'pro-sumers'* and invite private investment into renewable energy technologies, thereby reducing economic stress on government and local utilities.
- Provide customers with emergency power supply in times of power outage.

Electric vehicles are a special case of distributed energy storage technology. Their primary purpose is transport of goods and passengers, but in most cases, they are only used a small percentage of time during a day. The rest of the time, vehicles are parked in public places or private garages. If electric vehicles are connected to a power system, they can act as bi-directional energy storage, consuming power from the grid (charging their batteries) during times of excess renewable energy generation, stopping charging at times of grid demand increase (i.e. act as a load bank) or exporting power to the grid (or discharging) during times of low renewable generation.

In a broad sense, distributed energy storage and electric vehicles are very similar. However, distributed storage is present at only one location and built for only one purpose, while electric vehicles need larger infrastructure (present at more locations), and optimisation of their energy storage needs to take into account the fact that the vehicle might be used for transport purposes at any time.

2.6.2 Environmental impacts

The positive side to using distributed (or local) energy storage is that it may reduce losses in a distribution grid, and consequently reduce GHG emissions.

However, the use of distributed energy storage is usually less efficient than use of a centralised energy storage, especially when smaller distribution grids are considered. Less efficient operation of a battery would lead to a shorter service life, earlier replacement and decommissioning.

Using vehicle batteries for energy storage utilises vehicle batteries more than they would be used if a vehicle was used for transport only, therefore is more suited to emergency application than day to day grid storage. If a community does not have proper vehicle recycling plans in place, then using this technology could be disastrous to the RMI. However, this is not different to ICE vehicles. Best case scenario, with proper plans put in place, is that this technology might have a neutral environmental effect.

2.6.3 Power system stability impact

Both distributed energy storage and vehicle-to-grid technologies offer a benefit of local energy storage and in some sense, relieving stress from the local distribution network.

At the same time, if that energy is further distributed to be used outside of the local network, this technology causes more strain to the distribution network, as it causes bi-directional power flows and local voltage rises. If this technology is utilised on a large-scale, then distribution networks should be upgraded to support its rollout.

2.6.4 Economics

Economics of the distributed energy storage and vehicle to grid technologies are still not fully researched. It is however possible to compare economics of distributed energy storage and centralised battery storage on a high level. The former would need many domestic batteries or electric vehicles (whose primary purpose is to provide transport), upgraded distribution network infrastructure capable of supporting bi-directional power flows and a communications network (smart grid) capable of managing large number of small distributed energy storages in real time. As a contrast, centralised battery energy storage would be built for renewable energy storage, it would not require large-scale upgrades to the distribution network and complex communications infrastructure.

From here, it may be concluded that the cost of distributed energy storage or vehicle to grid storage would be significantly higher than cost of centralised energy battery. However, that is partly dependent on how the battery is utilised, being time-shifting vs grid stabilising, export to the grid or simply load shedding/scheduling.

2.6.5 Local know-how, operation and maintenance

There is no local know-how on energy storage technologies, electric vehicles or supporting smart grid infrastructure technologies in the RMI.

2.7 Automatic control systems and ‘smart grids’

Automatic control systems are comprised of computers, communications networks (hardware) and control algorithms (software) and are designed to communicate between and optimise the operation of multiple generation sources within a power system. Automatic control systems will play a crucial role in any large-island high renewable penetration power system and will be an integral part of the systems on Majuro and Ebeye.

When these systems are extended into controllable loads, distributed storage (e.g. using EV charging and storage as above) and 'smart' appliances (consumers), this is often referred to as a 'smart grid'. It is highly unlikely, given the complex and emerging technical nature of this type of application, that smart grids controlling small loads and appliances would be used in the RMI before 2030.

2.7.1 Technology

Traditionally, island power systems were supplied from a singe power station involving several diesel generators which supplied slowly varying load.

With the introduction of renewable energy generators in island power systems, the number of generating sources has increased, as renewable generators are usually installed across larger distances and near renewable resources. In addition, renewable generation is variable, and the load the traditional diesel generators serve has become highly variable. Therefore, generation across a power system must be closely coordinated in real time.

2.7.2 Environmental impacts

The footprint of all communication technologies is relatively small. As these technologies have beneficial effect to high renewable penetration, their overall environmental impact can be considered to be positive.

2.7.3 Power system stability impact

Automatic control system technologies are used to coordinate all generation sources across the entire power systems manage distribution network power flows and sometimes, control dispatchable loads. In high renewable penetration power systems, they are essential to enabling renewable energy while maintaining power system stability. Therefore, they have a positive impact on power system stability and reliability of power supply.

2.7.4 Economics

Due to the boom of telecommunications devices, computing and mobile telephony in the last few decades of twentieth century, the cost of communication technologies has decreased dramatically. They are also well understood and easily maintainable or replaceable.

Control algorithms and programming are relatively new, highly specialised and somewhat expensive. However, in the scheme of high renewable energy investment, the control systems component will be relatively small and investment in these technologies is estimated to prove itself over a short period of time.

2.7.5 Local know-how, operation and maintenance

The RMI has a local telecommunications network which is maintained and operated by internal resources, therefore the hardware aspect of future control systems infrastructure can be maintained by local crews, with modest upskilling.

The software aspect is very specialised and most probably will not be able to be handled by local crews; luckily this is the only aspect which can be maintained by remote crews, either by remote computer access (over the internet) or casual site inspections and maintenance.

3 Review of additional beneficial technologies

Listed here are technologies which do not directly increase renewable energy participation in an electric power system but try to reduce RMI GHG emissions through other avenues.

3.1 Solar hot-water heaters

Solar hot-water heater technology removes heating of water from the electric energy sector to direct heating via sunlight and by doing so, it reduces RMI's electric energy load and its emissions. It is recommended that RMI adopts and incentivises use of this technology in both short and long term. However, many households in the RMI do not have hot water systems as traditionally people do not wash in warm water.

3.1.1 Technology availability

Solar hot water heaters are readily available, off-the-shelf technology. From "old-days" black barrels in the sun, to modern evacuated tubes, this technology is easily implementable and can be rolled out by small trades shops.

3.1.2 Environmental impacts

Solar hot water heaters are replacing hot water boilers which use electric energy to produce hot water. As such, solar heaters are reducing an island power system's load and consequently, reducing its emissions.

Solar hot water heaters do not hold dangerous substances, and if managed and disposed of properly they have a positive environmental effect.

3.1.3 Economics

Solar hot water heaters are more efficient than electric or gas water heaters and have a potential to halve a household's energy bills [23] if that household uses large amounts of hot water. However, as noted, in this climate heating water often forms a small proportion of household energy use. Solar hot water heaters are a sound, old technology which should be fully implemented in RMI.

That said, where households are installing home solar PV systems, there is a trend towards using excess PV power to produce hot water rather the dispatching it to the grid at low prices.

3.1.4 Local know-how, operation and maintenance

Although it was not investigated, it was assumed that there is some local know-how on solar hot water heaters. This technology will most probably be installed and managed by a private sector, so accepting this technology would have positive impacts for both RMI knowledge capacity and its economy.

3.2 Carbon Capture Storage

Carbon Capture Storage technology carries direct positive environmental benefits. However, this technology is still in its infancy, and has not been tested in island power systems. Additionally, RMI might not have storage capacity which would imply carbon shipping, and consequential increase in emissions. It is recommended that RMI does not utilise this technology in the short run, but to revisit it in 20 to 30-year timeframe.

3.2.1 Resource

Carbon dioxide resource can be captured at the source of its production either pre or post combustion. In the first case, RMI could capture emissions from large emitters in the RMI, such as diesel generators in it energy sector, or larger industries. Emissions from power generation and other sectors in the RMI will be decreasing over the next few decades, so capturing carbon from the source might not be a long-term solution for RMI.

There hasn't been a study or resource investigation on how much carbon can RMI capture from the atmosphere, so this resource remains unknown.

3.2.2 Technology availability

Carbon capture and sequestration (CCS) is a three-stage process [19] . The first stage in the CCS process is the capture of CO2 released during the burning of fossil fuels, or as a result of industrial processes such as making cement, steel or in the chemical industry. Once captured, carbon dioxide (CO2) must then be transported by pipeline or ship for storage at a suitable site. The technologies involved in pipeline transportation are the same as those used extensively for transporting natural gas, oil and many other fluids around the world. Once the carbon dioxide (CO2) has been transported, it can be sequestered in range of ways, including porous geological formations, saline aquifers or the deep ocean sea bed.

CCS technologies are relatively new and although being supported by large companies such as B P and Shell, cost challenges still exist while there are no penalties on carbon emissions.

3.2.3 Environmental impacts

CCS technology was designed with a focus on direct positive environmental impact [24] . During its operation, carbon emissions are being captured and returned to the ground, without negative influence to the atmosphere. As such, it has a clear environmental benefit.

3.2.4 Economics

On large scale, CCS technology adds to the cost of generation of electricity by around US $0.05-0.20 per kWh, depending on how the carbon is sequestered. Data for application of CCS technology in island power systems is not available but will be orders of magnitude higher due to the tiny scale.

3.2.5 Local know-how, operation and maintenance

There is very little knowledge on this technology's operation and maintenance routines in the world, including the RMI. Therefore, local workforce does not have experience working with CCS, and if this technology is feasible, significant amount of upskilling will be necessary.

3.3 Waste to Energy / Waste Incineration

Waste to Energy technologies could provide power generation in Majuro while solving one of the island's biggest problems – what to do with its waste. In short to medium term, these technologies could be used to incinerate general household waste or waste oil from power generation diesel generators, and waste oil from international fishing ships coming through Majuro lagoon.

Future feasibility studies should establish whether municipal waste could be used for power generation. Waste oil from diesel generation or fishing fleet could be used as a cheap source of generation in Majuro.

By 2050 (or to achieve net zero emissions), any waste incineration or generation of power from waste or waste oil should be halted as this technology does produce GHG.

3.3.1 Resource

According to [2], Majuro produced about 6,700 tonnes of municipal solid waste in 2017, which includes everything from green waste to plastics, cans, metal, cardboard, etc.

Additionally, MEC diesel engines produce about 1,000 tonnes of waste oil per year, which could be burned to generate electricity, or mixed with municipal waste to increase its calorific value. There is also an unknown resource of waste oil produced by RMI and international fishing boats which could also be used in electricity generation.

3.3.2 Environmental impacts

Household and commercial/industrial waste is currently deposited at the Jable waste tip, which is operating at above its capacity, and has a negative environmental effect both in overflowing waste which ends in the ocean and methane generation. There is no solution for Majuro island waste at present.

If feasibility studies show that a waste to energy technology is feasible in Majuro, this could mean reduction of waste on the island as well as reduction of methane emissions, while that waste could provide some power to Majuro households.

While operating, diesel generators produce waste lubricating oil which is currently stored at Majuro's tank farm. There is no environmental plan for this waste oil, and the tanks are slowly filling up. At the same time, RMI and international fishing boats are run by diesel engines which also produce waste oil. It is unknown what fishing boats do with their waste oil, but there are some indications that waste could be dumped in the ocean. Instead of dumping or storing waste oil indefinitely, a small generator run on waste oil could be commissioned in Majuro which could reduce environmental impacts of this waste in RMI by burning it. By doing so, it would generate some GHG (and other toxic emissions due to its non-refined origins), but it would generate electricity in Majuro, which would otherwise be generated by Majuro's power plant.

Regardless of which waste technology selected for Majuro, it should be de-commissioned by 2050, as any technology produces GHG in some form. Therefore, waste technologies are a temporary solution which, if feasible, could be used in the RMI for the next three decades only.

3.3.3 Economics

Economics seems to be in favour of either using waste for energy production, or incinerating waste. In the first case, waste (which is free or has very low cost) is burned to produce electric energy, saving some of the diesel used in Majuro's power house. In the second way, incinerating waste does make economic sense, as the alternative implies building another waste dump in Majuro and paying landowners for its use over years which is capital intensive in both installation and operation. Further, waste dumps produce large amounts of methane, a high impact GHG.

3.3.4 Local know-how, operation and maintenance

There is very little knowledge on this technology's operation and maintenance in the RMI. Local workforce does not have experience working with waste technologies, and if this technology is shown to be feasible, significant amount of upskilling will be necessary.

4 Recommendations

Technologies needed for the successful transition of RMI to zero GHG emissions and 100% renewable exist today and are technically proven. Standard technologies such as solar, wind and batteries will undoubtedly play a key role in RMI's future.

As global interest in renewable energy expands in the future, other technologies might gain technical confidence and become a part of the RMI's strategy.

For now, the following technologies are recommended to be used in the RMI:

Renewable technologies:

- Solar PV
- Wind turbines
- Biodiesel

Enabling technologies:

- Resistive Load Banks
- Synchronous Condensers
- Battery Energy Storage (including power inverters)
- Automatic control systems

Additional technologies:

- Solar Hot Water heaters
- Waste incineration / waste oil to energy

A summary of all technologies considered in this tech note is given in Table 4.1.

Table 4.1 - Reviewed technologies - summary of advantages and disadvantages

					Economics		***Power system impact***		***Local Operation and Maintenance know-how***	***Recommended use***		
Technology	***Resource Availability***	***Technology availability***	***Environmental Impacts***	***Social Impact***	***CAPEX***	***Cost of Energy***	***Power generation***	***Stability Services***		***Short-term (<10 yrs)***	***Medium-term (10-20 yrs)***	***Long-term (>20 years)***
Renewables												
Solar PV - ground mount	Medium	High	Neutral	High	Medium	Low	Intermittent	Low	Medium	Y	Y	Y
Solar PV - roof-top mount	Medium	High	Neutral	Low	Medium	Low	Intermittent	Low	Medium	Y	Y	Y
Solar PV - floating	High	Low	Neutral	Medium	Medium	Medium	Intermittent	Low	Medium	Assess	Y	Y
Solar Thermal	Low	High	Neutral	High	High	Medium	Firm	High	Low	N	N	N
Wind	High	High	Neutral	High	High	Low	Intermittent	Medium	Low	Y	Y	Y
Ocean thermal energy Conversion	High	-	Negative	Low	High	High	Firm	Low	Low	N	N	Investigate
Wave Energy	Medium	Low	Neutral	Low	High	High	Intermittent	Low	Low	N	N	Investigate
Biodiesel	High	High	Neutral	Low	Low	Medium	Firm	Full services	Low	N	N	Y
Enabling Technologies												
Resistive Load Banks	-	High	Neutral	Low	Low	-	-	Medium	Low	Y	Y	Y
Synchronous Condensers	-	High	Neutral	Low	Low	-	-	High	Low	N	Y	Y
Battery Energy Storage	-	High	Neutral	Low	High	High	-	Medium	Low	Y	Y	Y
Power Inverter	-	High	Neutral	Low	Medium	-	-	Medium	Low	Y	Y	Y
Thermal Energy Storage (heat and cooling)		High	Neutral	Low	Medium			-	Medium	Investigate	Y	Y
Distributed energy storage	-	High	Neutral	Low	High	High	-	Medium	Low	N	N	Investigate
Vehicle to grid	-	Low	Neutral	Low	High	High	-	Medium	Low	N	N	Investigate
Automatic control systems	-	Medium	Positive	Low	Low	-	-	High	Low	Y	Y	Y
'Smart grid'		Low	Positive	Medium	Low			High	Low	N	Investigate	Y
Additional beneficial technologies												
Solar Hot Water heaters	Medium	High	Neutral	Low	Low	Low	-	-	Medium	Y	Y	Y
Carbon Capture Storage	Low	Low	Neutral	Low	High	High	-	-	Low	N	N	N
Waste to Energy	Medium	Low	Medium	Low	High	Medium	-	-	Low	Investigate	Investigate	N

5 References

[1] Meteonorm software, http://www.meteonorm.com/

[2] ADB, TA-9225 RMI: Majuro Power Network Strengthening Final Report, May 2018.

[3] Technical Note, '*Wind Energy in RMI*', William Thorp, May 2018.

[4] Temperature Difference between 20 m and 1000 m Depths (°C), Hawaii National Marine Renewable Energy Centre, http://hinmrec.hnei.hawaii.edu/hinmrecftp/area12/area12.html, Data from NOAA/NODC World Ocean Atlas 2005.

[5] Okinawa working 100 kW OTEC plant website, http://otecokinawa.com/en/OTEC/index.html

[6] OTEC technology, Hawaii National Marine Renewable Energy Centre, https://www.hnei.hawaii.edu/projects/ocean-thermal-energy-conversion-otec

[7] OTEC Environmental Impacts, NOAA's Office of Ocean & Coastal Resource Management, https://coast.noaa.gov/czm/media/environmentalfactsheet.pdf

[8] Tidal stream Energy, http://greenrhinoenergy.com/renewable/marine/tidal_stream.php

[9] Tidal Energy Technology Brief, International Renewable Energy Agency (IRENA), http://www.irena.org/DocumentDownloads/Publications/Tidal_Energy_V4_WEB.pdf

[10] Strangford Lough Tidal Turbine, Northern Ireland, United Kingdom, https://www.power-technology.com/projects/strangford-lough/

[11] Strangford tidal energy turbine to be removed, BBC News, http://www.bbc.com/news/uk-northern-ireland-35416282

[12] AR1500 tidal stream turbine, Atlantis Resources Ltd, https://www.atlantisresourcesltd.com/wp/wp-content/uploads/2016/08/AR1500-Brochure-Final-1.pdf

[13] Ocean Wave Energy, Bureau of Ocean Energy Management, https://www.boem.gov/Ocean-Wave-Energy/

[14] Ingvald Straume, World map showing wave energy flux in kW per meter wave front, https://commons.wikimedia.org/wiki/File:World_wave_energy_resource_map.png

[15] NOAA Wavewatch III Model, US National Weather Service Environmental Modelling Center, http://polar.ncep.noaa.gov/waves/viewer.shtml?-gwes-latest-hs-aus_ind_phi-

[16] Wave and Tidal Technology Fact Sheet, Renewable Northwest Project, https://renewablenw.org/sites/default/files/pdfs/Wave%20Tidal%20FactSheet%2007April4.pdf

[17] Biodiesel Economics - Costs, Tax Credits and Co-product, AgMRC Renewable Energy Newsletter, https://www.agmrc.org/renewable-energy/biodiesel/biodiesel-economics-costs-tax-credits-and-co-product/

[18] Lazard's Levelized Cost of Storage, Lazard, https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf, December 2016

[19] Carbon Capture and Storage Association website, http://www.ccsassociation.org/

[20] Resistive load banks, ASCO power technologies company, http://www.ascopower.com/en-us/products-catalog/products/load-banks/

[21] Synchronous condenser product, Sustainable power systems company, http://www.sustainablepowersystems.com/synchronous-condenser/

[22] 2000 kW Energy Storage Inverter for Utility Scale Applications, Dynapower Product, https://www.dynapower.com/products/energy-storage-inverter-solutions/utility-scale-energy-storage-inverters/cps-2000/

[23] Estimating the Cost and Energy Efficiency of a Solar Water Heater, https://www.energy.gov/energysaver/estimating-cost-and-energy-efficiency-solar-water-heater,

[24] Carbon Dioxide Capture and Storage, Intergovernmental Panel of Climate Change, http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

[25] Mojave Solar Thermal Project web-site, https://www.energy.gov/lpo/mojave.