Government of Tokelau

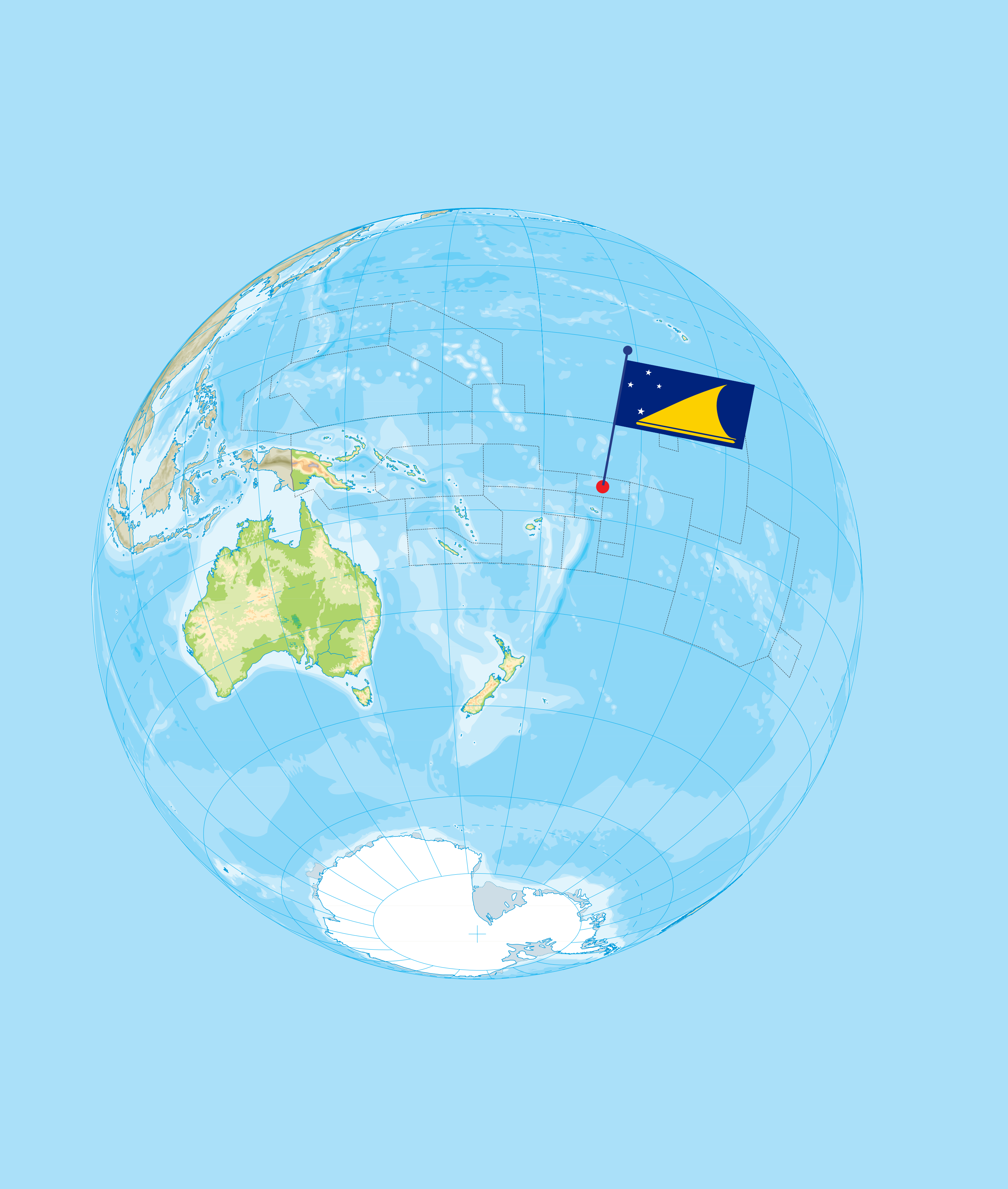
Tokelau

RENEWABLE ENERGY PROJECT CASE STUDY MARCH 2013




TOKELAU MO TE ATUA

NEW ZEALAND
FOREIGN AFFAIRS & TRADE
Aid Programme



About this report

This report was commissioned by the New Zealand Ministry of Foreign Affairs and Trade (MFAT) to showcase the Tokelau Renewable Energy Project, to share information on the project with partners, and to contribute to the pool of knowledge and information about the design and implementation of remote-area mini-grids in the Pacific.

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Executive Summary

The Tokelau Renewable Energy Project, launched in 2010 and due to be completed in 2013, has seen the construction of a PV/diesel hybrid system on each atoll in the Pacific island nation of Tokelau. Previously, the atolls used diesel generator sets to provide electricity on a centralized distribution network.

The new solar power systems were designed to provide at least 90% of the islands' electricity needs from solar power, and are expected to save roughly NZD 900,000 per year in diesel costs (for a capital cost of NZD 8.45 million). Training was provided to existing utility staff when the systems were installed, both during and after installation. The maintenance requirements on the new power systems are far less demanding than those of the previous diesel generators. In the four months since the project was officially commissioned (November 2012 to February 2013), the hybrid systems provided 88% of Tokelau's electricity needs from solar energy, and the remainder from diesel. This figure is expected to increase in the coming months, as the November to February months are generally quite cloudy.

This case study provides a technical description of the three PV systems, as well as a cost breakdown of the TREP project. Figure 1 provides a breakdown of the project's costs, and Table 1 provides the technical specifications of the systems on each atoll.

FIGURE 1: COST BREAKDOWN OF PROJECT, AS PERCENTAGES OF NZD 8.45 MILLION TOTAL PROJECT COST

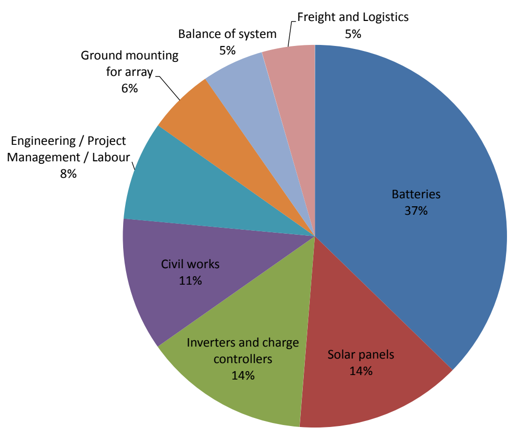


TABLE 1: TECHNICAL SPECIFICATIONS OF TOKELAU PV SYSTEMS

	Cluster	Fakaofo	Nukunonu	Atafu	Total
PV capacity	33.12 kWp	365 kWp	265 kWp	300 kWp	**930 kWp**
No. of 230W PV panels	144	1,584	1,152	1,296	**4,032**
Capacity of string inverters	21 kW	231 kW	168 kW	189 kW	**588 kW**
No. string inverters	7	77	56	63	**196**
Capacity of DC charge controllers	9.6 kW	106	77	86	**269**
No. of DC charge controllers	4	44	32	36	**112**
Capacity of battery inverters (at 35°C)	13.5 kW	150	110	120	**380**
No. of battery inverters	3	33	24	27	**84**
No. of batteries	48	428	384	432	**1,344**
Total battery storage (nominal)	288 kWh	3,168 kWh	2,304 kWh	2,592 kWh	**8,064 kWh**
No. of clusters	1	11	8	9	**28**
Peak load	-	75 kW	44 kW	51 kW	**-**
Daily demand	-	985 kWh	660 kWh	715 kWh	**2,360 kWh**
Solar fraction (Nov '12 – Feb '13)	-	86%	91%	89%	**88%**

1. Introduction

The Tokelau Renewable Energy Project (TREP) was a joint undertaking between the Government of Tokelau (GoT) and the New Zealand Ministry of Foreign Affairs and Trade (MFAT). Started in 2010, it culminated in the construction of three solar photovoltaic (PV) power systems, one for each atoll of the small island nation.

Construction of the last system was completed in late October 2012, after a 5-month construction phase for all three atolls: Fakaofo, Nukunonu, and Atafu. Each PV power system is composed of an array of PV panels, power conditioning equipment, batteries for night time energy delivery, and a diesel generator as backup for several days of cloud cover.

Prior to the TREP systems being installed, all three atolls had their power provided by diesel generator sets. Each island originally had three sets, although by the time the construction phase of the project began Fakaofo had only two working sets, and Nukunonu and Atafu one each. The rate of electrification was 100% on the permanently settled motus of each atoll, and the existing distribution network had recently been upgraded in 2004. The cost of the fuel for running these generator sets, including the cost of shipping the fuel to the atolls, was close to NZD 1 million per year.

With the price of fuel rising over the long term, and to increase its energy security while reducing the risk of damaging its fragile reef environment with accidental fuel spills, the GoT approached MFAT to secure a NZD 7 million advance on its aid allocation to fund the project. The systems that are installed have been designed to provide 90% of each island's electricity needs (on an annual basis) through solar power, with the balance of electricity being provided by the diesel generators when the batteries are at a low state of charge after several days of cloud cover.

The Tokelau National Energy Policy and Strategic Action Plan (NEPSAP) 2004 sets achieving energy independent through the development of indigenous energy resources, and eliminate the country's almost total dependence on imported diesel for electricity generation. This commitment is confirmed in the Tokelau National Strategic Plan 2010 to 2015 which includes the objectives of improving energy efficiency and of integrating Renewable energy into Tokelau's energy mix.

The PV systems were designed, supplied, and installed by Powersmart Solar NZ Ltd, with assistance from IT Power (Australia) Pty Ltd.

2. Technical configuration

2.1 General system overview

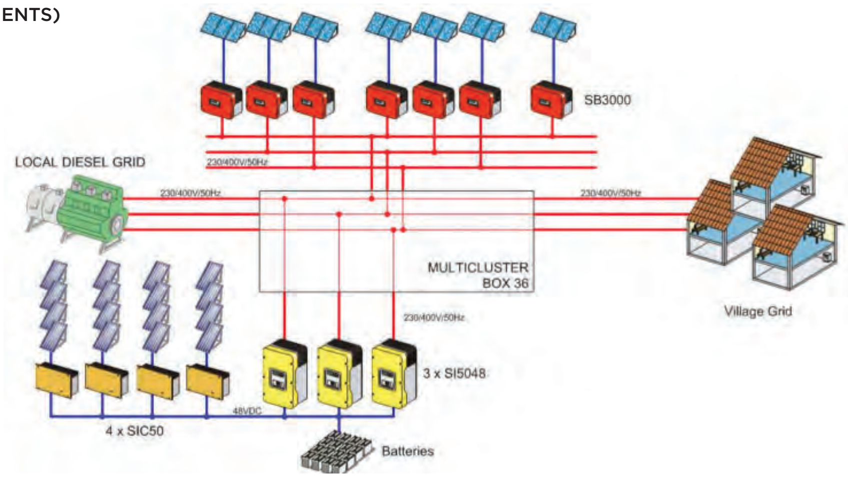
The PV power systems installed in Tokelau were designed in line with MFAT's Renewable Energy Mini-grid **Common Design Principles,** which set guidelines for the design of off-grid and hybrid PV systems in the Pacific. These guidelines were written to provide donor organizations and Pacific electrical utilities with a consistent approach to PV system design that is tailored to the remote tropical marine conditions of the Pacific Islands. They were drafted based on decades of in-field experience with off-grid PV systems in remote communities, so the key goal was to provide a design that is reliable in the long-run. The **Common Design Principles** specifies power conditioning equipment and components that have a proven track history of reliability and regional support in the Pacific region. At the core of the Tokelau PV systems' architecture is SMA's multi-cluster design. Each cluster is composed of a PV array, string inverters, DC charge controllers, battery inverters, and batteries. The entire PV system is then composed of several of these identical clusters. Having a uniformity of design and of components across several systems makes it easier for the utility to troubleshoot problems (as the same solution can be applied across all systems) and to order and stock spare parts (as the number of different components is low).

Figure 2 shows the basic design of a single cluster, and Figure 3 shows the design of several clusters connected together into one system.

PV array: The panels in the array convert sunlight[1] into DC electricity, which must be converted to 230 V, 50 Hz AC electricity to be injected into the utility grid, or 48 V DC electricity to be stored in the batteries. As sunlight and module temperature vary throughout the day, the voltage and current outputs of the panels will vary, so any power conditioning equipment that is used will need to adapt in order to extract the maximum

1 Note that PV panels convert sunlight, not heat, into electricity. High temperatures will result in a decrease in power output, so the lower the panels' temperature the better they will perform. Allowing enough space under the panels for proper ventilation is the easiest way to keep temperatures low.

FIGURE 2: SINGLE CLUSTER (FROM TREP TENDER DOCUMENTS)



power out of the panels. This feature is called Maximum Power Point Tracking (MPPT), and is used on all SMA string inverters and charge controllers.

String inverters: The string inverters convert the panels' DC electricity into usable 230 V, 50 Hz AC electricity that is injected into the grid.

DC charge controllers: These devices convert the panels' DC electricity into 48 V DC electricity that is used to recharge the batteries. They do not participate in directly powering the grid; the battery inverters need to convert the 48 V DC electricity first.

Battery inverters: The battery inverters are at the heart of the cluster design. They:

1. form the grid by setting its voltage and frequency;
2. regulate the batteries' state of charge[2];
3. throttle back the solar production from the DC charge controllers and the string inverters if the batteries are full and loads on the grid are low;
4. activate the backup generator when the battery state of charge is below a certain threshold;
5. convert the energy stored in the batteries to electrical energy used on the grid (e.g. at night or on cloudy days when solar production is below the load requirements of the grid);
6. convert any excess electricity from the string inverters into 48 V DC electricity to charge the batteries.

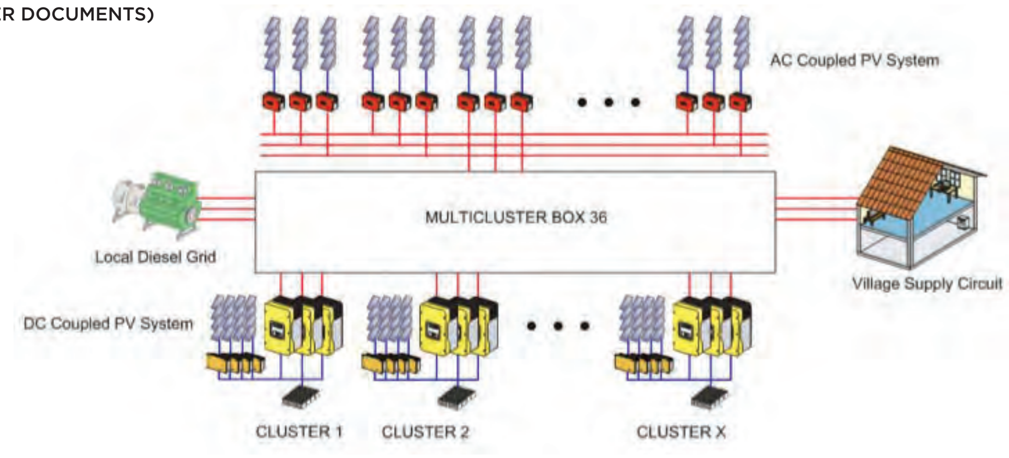
Batteries: The batteries are used to store any excess electricity produced by the solar panels and not used by the loads during the day. This energy is used to power loads at night or during periods of very low irradiance when the solar production cannot meet the loads (e.g. cloudy days, dawn and dusk). The batteries are sized to be capable of providing power for several days in a row.

Multicluster Box: The Multicluster Box (MC-Box) combines all the clusters into a single system. Whereas the battery inverters are at the heart of the cluster, the MC-Box is at the heart of the PV system. The entire system is controlled by a single master battery inverter, which communicates to the other inverters to coordinate power delivery via the MC-Box.

The backup generator also provides power |to the grid via the MC-Box.

2 i.e. how full a battery is.

FIGURE 3: MULTICLUSTER SYSTEM OVERVIEW (FROM TREP TENDER DOCUMENTS)



Backup generator: The generator is called upon to deliver power when the battery state of charge is below a given threshold and the PV modules cannot provide sufficient power to recharge them. The generator is typically sized to provide the entirety of the loads on the grid, in case of a malfunction of the PV system or for maintenance of the battery inverters. The dispatching strategy for the generator is such that it is either run at its optimum load factor, or not run at all. This improves the fuel efficiency of the generator, and reduces maintenance costs as maintenance is done on the number of hours a generator is run, regardless of the amount of electricity produced.

2.2 PV array foundations and battery building

2.2.1 Array foundations

The PV array foundations were built by each village's men's group under supervision by staff from Powersmart Solar between March and August 2012, before the arrival of the PV installation team. The foundations are designed specifically for the array mounting frame, and use a single unified grid of concrete for every row of panels. A unified grid was preferred over individually cast footings (i.e. one footing for every anchoring point of the mounting frame) as individually cast footings may shift over time, thereby warping the PV array and possibly damaging panels. However, building a unified grid requires more concrete and time, and is therefore more expensive than individual footings.

Concrete was mixed on-site using beach sand. As no testing samples for the concrete were provided during the construction phase, the mounting frame's design had to assume a very low concrete strength. The threaded rods that are used to bolt the mounting frame to the foundation are therefore set deeper than what would normally be expected for a 20 MPa concrete.

FIGURE 4: THE ARRAY FOUNDATIONS ON ATAFU.

2.2.2 Battery building

The inverters, charge controllers and batteries are housed in a battery building next to the PV array. On Nukunonu and Atafu, the building was designed to minimize heat gain through passive architectural design features. Reducing heat gain passively means that no energy is required to power air conditioning equipment or fans to blow air over equipment, so the entire system is more efficient (and reliable, as there is no cooling equipment to break down). The passive cooling design features are:

- Walls painted white and white roofs to reduce absorption of solar radiation;
- Foil insulation under roofs;
- Veranda all around the building to protect walls from direct sunlight;
- High window coverage to allow cooling breezes to pass through;
- Ceiling cavity kept separate from main building space to keep hot air trapped away from batteries and inverters;

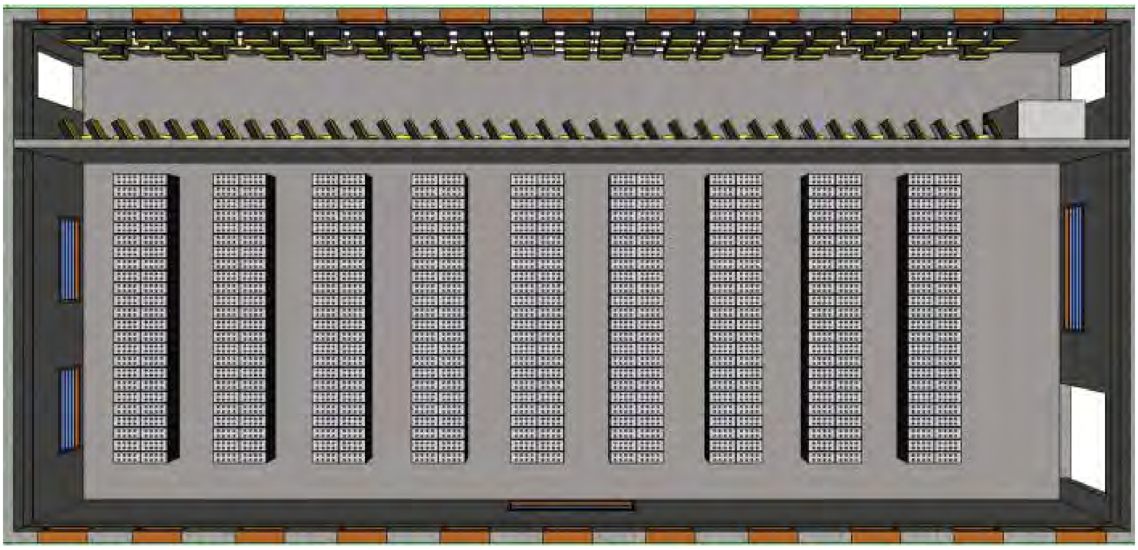
» Concrete walls to act as a large thermal mass to stay cool during the day.
» Doors at opposite ends of the inverter room, to allow for good cross-ventilation of the inverters.

On Fakaofo an old school building was used to house the inverters and the batteries, and required fan cooling as it was not originally designed for passive cooling. Insulation was installed in the ceiling cavity to prevent warm air from heating the inverter and battery rooms.

The battery buildings on Nukunonu and Atafu were built by the villages' men's group, under supervision by staff from Powersmart Solar. This was done before the arrival of the PV installation team, so that installation work could begin immediately.

FIGURE 5: BATTERY ROOM ON NUKUNONU.

FIGURE 6: THE BATTERY BUILDING ON ATAFU. THE BATTERIES ARE IN THE MAIN ROOM OF THE BUILDING, AND THE INVERTERS AND CHARGE CONTROLLERS ARE IN THE LONG NARROW ROOM.



2.3 The PV array

The PV array on the Tokelau systems uses 230 Watt Sunrise panels. These panels were selected as they were one of the first ones available on the market that were certified to the new standard IEC 61701 – **Salt mist corrosion testing of photovoltaic (PV)modules,** which tests panels for their resistance to corrosion in marine environments. Furthermore, the panels are insured by a large third-party insurance company, so if the manufacturer becomes insolvent the performance warranty can still be honoured.

Each cluster has two connection configurations, one for the panels connected to the string inverters, and one for the panels connected to the DC charge controllers. In total, each cluster is composed of 144 panels, or a total solar panel capacity of 33 kWp.

The panels are ground-mounted near the battery house, on aluminium frames bolted into the concrete foundations. Bolting into concrete was preferred over casting the frames' footings into the concrete as bolting allows a much more precise alignment of the mounting structure. This design approach was vindicated during the construction phase of the systems, when the PV installers arrived on site and noticed that the concrete foundations for the array frame were not aligned per the construction specifications. Having a bolted design allowed the installers to work around the imperfections in the foundations.

FIGURE 7: THREADED RODS CEMENTED INTO CONCRETE FOUNDATION. NOTE THAT THE RODS ARE LINED UP WHEREAS THE CONCRETE IS NOT.

The aluminium array frame members were pre-cut in New Zealand and anodized at the factory before being shipped to Tokelau. The anodization prevents corrosion, and as all the frame members were pre-cut in New Zealand no cutting in the field (and therefore cutting through the protective anodized coating) was required. Aluminium was chosen over galvanized steel as past experience in the Pacific with galvanized steel has been poor, and marine-grade 316 stainless steel is very expensive and does not provide better corrosion resistance than anodized aluminium (and in fact suffers from surface corrosion called "tea staining", which is not a structural problem but is nonetheless aesthetically displeasing). Furthermore, the handling of the aluminium members could be done by a single person, whereas steel members are heavier and more unwieldy.

FIGURE 8: ALUMINIUM MOUNTING STRUCTURE ON FAKAOFO. THE BUILDING IN THE BACKGROUND HOUSES THE BATTERIES AND THE INVERTERS.

Each row of the array is three panels high, with the panels oriented in portrait mode. Having panels in rows of three panels high was done as a good compromise between ease of maintenance (the panels are easily accessible by a single person for cleaning or replacement) and minimizing land requirements (having rows with fewer panels means that more land is required to fit the array).

The panels are tilted to 12°, which allows for self-cleaning of the panels during rainstorms. Tilting the panels at latitude angle (the atolls are approximately 9° south) would run the risk of them remaining dirty and increase the amount of manual cleaning required. The array on Atafu was noted to have more bird droppings than those on the other two atolls, so manual cleaning may need to be more regular.

FIGURE 9: FRONT ROW OF PANELS ON NUKUNONU. THE PINK BUILDING IN THE BACKGROUND IS THE PURPOSE-BUILT BATTERY BUILDING.

Each PV string (connected to a string inverter) or sub-array (connected to a

DC charge controller) is fitted with a disconnection switch at the array, so that isolation of the array may be done in case of emergencies or for maintenance. The isolators are enclosed in IP 65 rated enclosures to prevent water and dust ingress, and are located under the panels of the array to keep them protected from the sun and rain.

FIGURE 10: ALL ARRAY ISOLATOR ENCLOSURES ARE LOCATED UNDER THE PANELS TO SHIELD THEM FROM THE SUN AND RAIN.

All outdoor cabling is protected from the elements in UV-resistant conduit or aluminium capping behind the array frame. Protecting the cables in this way also prevents accidental mechanical damage.

FIGURE 11: ALL CABLES ARE PROTECTED IN UV-RESISTANT CONDUIT OR ALUMINIUM CAPPING

2.4 The inverters and charge controllers

2.4.1. String inverters

The string inverters used in the Tokelau systems are SMA Sunny Boy 3000 inverters. This model of inverter is consistent with the principles of the **Common Design Principles** as it has a transformer (hence does not have injection of a DC component into the AC grid) and does not have fan-forced cooling (hence no fans to fail).

Each cluster has 7 string inverters, for a combined inverter capacity of 21 kWp per cluster. The inverters convert the DC electricity from the panels into AC electricity that is injected into the power grid.

FIGURE 12: THE STRING INVERTERS IN A CLUSTER, WITH THE AC AND DC ISOLATORS IN THE MIDDLE.

In situations when the sun is shining and the batteries are full or nearly full, the battery inverters will increase the frequency of the grid beyond 50 Hz. This frequency shift is done to simulate a generator that is suddenly underloaded (and therefore momentarily spinning faster), and will cause the string inverters to reduce their power output[3]. The reduction in power output from the inverters is necessary to prevent voltage rising on the grid, as the amount of power produced by the string inverters must match the amount of power required by the loads and the batteries.

The string inverters are covered by a 10-year warranty.

3 This power throttling feature is a setting that must be activated on the string inverters, otherwise they will continue to inject power at their rated capacity.

2.4.2. DC charge controllers

The DC charge controllers used in the Tokelau systems are SMA's Sunny Island Charger 50. There are four of these charge controllers per cluster, for a combined power output of 9.6 kW. They convert the DC electricity from the panels to 48 V DC electricity that is fed straight into the batteries. The advantage of DC charge controllers over string inverters is that they can charge the batteries directly, whereas string inverters must first convert electricity from the PV array to AC electricity, which must in turn be converted to 48 V DC electricity to be fed into the batteries (i.e. charge controllers entail only one conversion step rather than two). Using charge controllers is more efficient for storing energy that must be used at night, whereas string inverters are more suited for delivering energy that is used during the day.

In the Tokelau system, DC charge controllers are used to maximize the amount of PV that can be integrated into the system. The battery inverters are limited in how much power they can absorb to charge the batteries, so direct charging of the batteries via DC charge controllers is necessary if more PV is required.

The four charge controllers in a cluster are controlled by the master battery inverter for that cluster. The battery inverter controls how much energy the charge controllers are to deliver to the batteries, depending on the batteries' state of charge. When the batteries are full, the battery inverters throttle back production of the charge controllers.

This power throttling is communicated to the charge controllers via dedicated communications lines from the battery inverters (whereas with string inverters the throttling is done by changing the grid's AC frequency).

Due to technical difficulties with the charge controllers, some of the panels that were connected to them had to be temporarily disconnected to limit the total PV input power to the controllers. This meant that over the entire PV array, 8% of panels needed to be disconnected. SMA will visit Tokelau in April 2013 to resolve the issue with a hardware upgrade, which is expected to allow reconnection of the panels. Otherwise, the charge controllers have been performing well.

The charge controllers are covered by a 10-year warranty.

2.4.3. Battery inverters

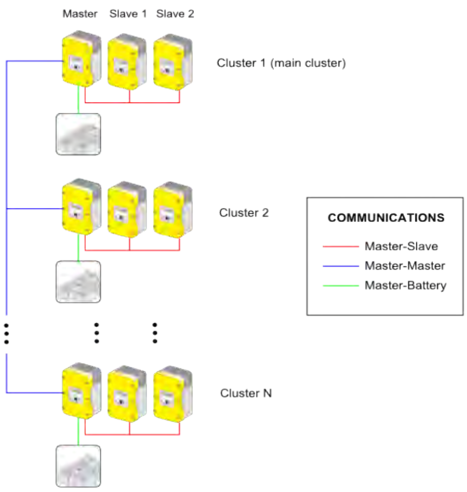
The battery inverters used in the Tokelau systems are SMA's Sunny Island 5048. They control the current flow to and from the batteries, and form the grid (i.e. set the voltage and frequency of the grid) when the generator is not active. They are set to activate an alarm when the state of charge of the batteries reaches 60%. The system operators are to manually start the backup generator to provide power to the island's loads and to recharge the batteries. More detail on the generator's dispatching strategy is given in Section 2.6.

Each cluster is composed of three battery inverters, with one battery inverter as master and the other two as slaves.

FIGURE 13: THE 3 BATTERY INVERTERS AND THE 4 CHARGE CONTROLLERS IN A CLUSTER. THE CONFIGURATION FOR THE FAKAOFO INVERTER ROOM WAS DIFFERENT FROM THAT FOR THE NUKUNONU AND ATAFU INVERTER ROOMS (DUE TO DIFFERENT BUILDING LAYOUTS)

In the overall system, there is a master cluster with a main master battery inverter that controls all the master inverters of each cluster. This main master battery inverter sets the voltage and frequency of the grid, and the cluster masters follow. The cluster masters are responsible for the management of their battery banks; the main master manages the cluster masters so that their battery banks are all at the same state of charge.

FIGURE 14: COMMUNICATIONS PATHWAYS BETWEEN BATTERY INVERTERS (ADAPTED FROM SMA LITERATURE).



The three battery inverters in a cluster are arranged to provide three-phase power, with one phase powered by one battery inverter (the Sunny Island 5048 is a single-phase inverter). Combined, the three battery inverters can provide 13.5 kW of continuous AC power at 35°C, and when all clusters on each island are combined into one system the output of the battery inverters is far more than the peak loads on the island. When the islands were entirely reliant on diesel generators for their electricity they were occasionally subjected to power cuts from generator overloads. The new PV power systems will not suffer from this problem as the capacity of the battery inverters is considerably higher than the peak loads on the island. This means that some of the measures that residents took to reduce peak power consumption, such as not turning on hot water kettles at the same time as using the microwave, are no longer necessary to prevent blackouts (although the small size of the cables on the distribution network may now restrict load growth). Others, such as the ban on electric cooking and air conditioning, should still remain as these are not only high power users, they are also high energy consumers.

The battery inverters are covered by a 10-year warranty.

2.5. The batteries

Each cluster in the Tokelau systems includes a 48 V battery bank to store excess PV energy generated during the day for use at night. The battery banks are composed of two strings of 24 batteries, and have a nameplate storage capacity of 288 kWh. They have been sized to provide enough storage to last 1.5 – 2 days without any solar input before the backup generator is turned on.

FIGURE 15: THE BATTERY ROOM ON ATAFU. EACH BANK OF BATTERIES HAS A NAMEPLATE STORAGE CAPACITY OF 288 KWH.

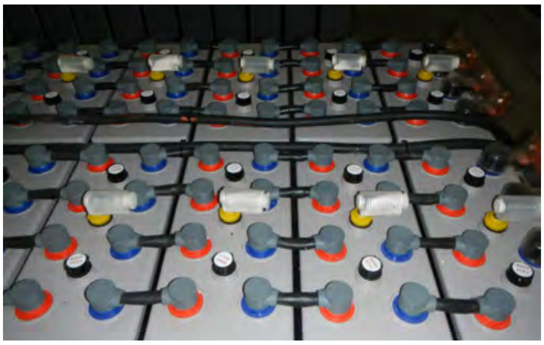
The battery cells are flooded lead-acid, and while this presents maintenance and logistical challenges that sealed batteries do not they have a proven track record and when well-maintained and can be partially restored if they get damaged.

The batteries will require regular topping up with distilled water as their electrolyte levels decrease when being charged. A deionizer was installed in the battery room of each island, as securing distilled or deionized water is vital to the long-term viability of the batteries. Rainwater is collected in a tank, and then pumped through the deioniser to be used in topping up the batteries.

FIGURE 16: THE DEIONIZER IS USED TO PROVIDE WATER FOR TOPPING UP THE BATTERIES' ELECTROLYTE LEVELS.

Catalytic combiner caps were installed on each battery cell to recombine the hydrogen and oxygen gases that escape the battery during the charging phase back into liquid water. This reduces the frequency with which the water must be added to the battery cells.

FIGURE 17: DETAIL OF THE TOPS OF THE BATTERIES. THE YELLOW AND WHITE CAPS ARE THE CATALYTIC COMBINER CAPS, AND THE BLACK CAPS ALLOW OPERATORS TO ACCESS THE BATTERIES TO TOP THEM UP WITH DEIONIZED WATER.



The batteries are located in a room separate from the inverters, as hydrogen gas is produced by the batteries during the charging process and there is a risk of explosion caused by a spark from electronic equipment. The battery room is well-ventilated to evacuate any hydrogen gas that is produced, although the catalytic combiner caps should minimize the amount of hydrogen gas released.

Lead-acid batteries are sensitive to being discharged for extended periods of time. Therefore the systems in Tokelau are configured so that an alarm is triggered when the state of charge of the batteries drops below 60%. This alarm is meant to notify the system operators to turn on the backup generators. If the state of charge drops below 30%, the battery inverters disconnect the loads from the PV system, which means that the island loses power (unless the backup generator is running).

The batteries are expected to last 8-10 years if properly maintained. Note, however, that the lifetime of a battery is defined as being 80% of its original capacity. Batteries can still be used beyond their rated life, though at a reduced capacity (<80%) and only for a limited amount of time as their usable capacity decreases rapidly after their end of life.

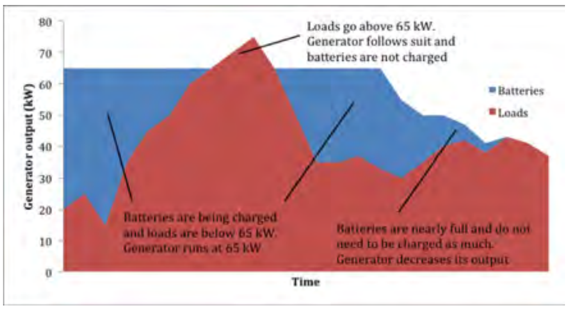
2.6. The generator

The generators that were once the sole source of electricity are now used as backup for the solar power system. They are located in the old powerhouse, near the battery building and PV array. Although the main master battery inverter can control the switching on and off of the generator, the systems in Tokelau rely on manual operation of the generators. There are three reasons for this: firstly, actively involving the operators in the running of the system means that they will be kept familiar with it and not forget how to operate it. Second, if the alarm is repeatedly triggered the operator will know that there is a problem with the system that needs to be addressed; an automatically started generator would mask problems as the power would always stay on. Third, the operator will know when it makes sense to turn the generator on. If the alarm is triggered at 5 AM and the upcoming day will be sunny, there is no point in starting the generator as the PV array will charge the batteries. Conversely, if the state of charge of the batteries is at 70% by nightfall, the operator would turn the generator on to charge the batteries for a few hours so that they may last the night.

FIGURE 18: **THE THREE GENERATORS ON FAKAOFO. AT THE TIME OF INSTALLATION OF THE PV SYSTEM, ONLY TWO OF THESE WERE OPERATIONAL. NUKUNONU AND ATAFU ONLY HAD ONE OPERATIONAL GENERATOR EACH.**

To prevent the batteries from overly taxing the generator when they need to be recharged, the generator's maximum power output is limited to a given amount (the amount varies on each atoll). For example, on Nukunonu the generator is limited to deliver 65 kW at most when charging the batteries. If loads go above 65 kW, the battery charging stops and the generator matches the load.

FIGURE 19: **LOADING REGIME ON GENERATOR IN NUKUNONU**



The generator room is fitted with a transfer switch that can isolate the PV system from the grid in case maintenance is required on the MC-Box or if the cabling between the battery building and the powerhouse is accidentally severed. This switch essentially re-creates the configuration of the grid before the PV system was installed. It is not expected to ever be required under normal operation of the system.

FIGURE 20: **THE CHANGEOVER SWITCH ON ATAFU**

One of the issues faced at the time of commissioning was that the generator's pre-existing control system does not allow the generator's frequency to vary from 50 Hz. This means that when the generator is operating and the solar production is higher than what can be used to charge the batteries and power the loads the extra power from the PV system backfeeds through the generator causing it to disconnect from the grid.

As the battery inverters follow the generator's voltage and frequency when it is running, they cannot shift the grid frequency to throttle back production from the string inverters. To work around this problem several string inverters need to be shut down at the main switchboard to prevent backfeeding through the generator (the switches are in the blue switchboard in Figure 21). In reality, the cases when the generator is turned on and solar production is significant will be very rare (the generator will be turned on to charge the batteries when they are at a low state of charge, i.e. at night or on a very overcast day, so solar production will be low. If the sun is shining the PV array will be capable of meeting loads and charging batteries, so there would be no need for the generator). In future PV/diesel hybrid systems the generator controls should allow the generator to increase frequency when it becomes underloaded, to be able to reduce power output from the string inverters.

2.7. Monitoring equipment

The systems are monitored using SMA's Sunny WebBox data monitoring systems. There are three per system, monitoring the battery inverters and charge controllers, the string inverters, and a small solar radiation measuring device on the array. The WebBoxes upload their data to the SMA Sunny Portal website, for remote monitoring and analysis. The internet connection to the battery rooms is somewhat reliable: in the first 4 months of operation the WebBoxes on Nukunonu lost their internet connection for one month (due to a faulty power supply on one of Teletok's ADSL Ethernet extenders), but the other atolls have proven reliable.

Two touchscreen computers (one in the inverter room and one at the powerhouse) and custom monitoring software were installed with each system to provide operators with a live feed of solar production, charge/discharge currents to and from the batteries, generator production, solar radiation and the loads on the grid. The computers allow access to the WebBoxes so that operators can change system parameters on the battery inverters and the string inverters. The computers are sealed against the environment and are not fan-cooled, so do not have fans to fail.

FIGURE 21: THE TOUCHSCREEN COMPUTER AND THE THREE WEBBOXES (TO THE RIGHT OF THE BLUE ALARM, NEXT TO THE PHONE)

3. Operation and maintenance

Utility technicians were given training in the regular operation and maintenance of the PV system's components, and of troubleshooting procedures and solutions. Theoretical training on Nukunonu and Atafu was given one night a week over the course of the installation of the systems on those atolls.

This was found to be extremely effective at getting technicians to retain knowledge, as it was being delivered gradually over several weeks. The theoretical knowledge was reinforced with practical training in the construction of the systems, so by the end of construction the utility personnel were proficient in the use of their new PV power systems. Unfortunately, given the nature of Fakaofo being inhabited on two motus, it was not practical to provide training in such a fashion as it would require inter-motu travel at night through reef passes, which can be dangerous. SMA therefore sent one of its maintenance technicians to provide training near the end of construction, and one of the installers spent a week with the utility personnel to train them on maintaining and running the system once it was fully operational.

FIGURE 22: NIGHT CLASS ON ATAFU.

Basic maintenance tasks on a PV system are simple and cost very little. However, they are crucial to the long-term success of the project, and must be carried out regularly and thoroughly (especially the battery maintenance procedures, as batteries are sensitive to neglect). The maintenance schedule that the operators will need to follow is given in Table 2.

TABLE 2: REGULAR MAINTENANCE PROCEDURES FOR TREP SYSTEMS

Procedure	Frequency				
	Daily	Fortnightly	Quarterly	6-monthly	Yearly
Check the inverters for operational status and check State of Charge (SOC) of the batteries at 06:00 and 18:00. If SOC is less than 75% at 18:00, run generators until either a) 75% is reached, or b) SOC is above 70% and it is past midnight.	■				
Clean inverter room and battery room floors. If tops of batteries are dusty clean them as well. Make sure all inverter heat sinks are clean.		■			
Fully charge batteries (Sunny Islands will do this automatically)		■			
Inspect water level in batteries, top up with purified water if below midway point between max and min lines on casing.		■			
Run equalization charge on batteries. This will be requested by the system automatically but use the generator in the evening if required to finish the equalization charge.			■		
Inspect and clean panels. Best done following a rainfall as panels will already be wet. Also best done early in the morning or late afternoon, when the panels are cool.			■		
Clean roof, gutters, and water tank thoroughly to prevent dirt and debris from clogging the deionizer				■	
Inspect wiring for damage and loose connections.				■	
Measure voltage and specific gravity of electrolyte in all batteries.				■	
Inspect PV array frame. Check the tightness of some of the bolts. If any are found to be loose, tighten the entire array. Same with the batteries.					■

Spare parts were provided for the ongoing maintenance of the systems, and included spare panels, inverters (battery and string) and charge controllers, fuses and circuit breakers, isolator enclosures, cabling and solar connectors, and a Sunny WebBox. A toolkit that included all the tools necessary for maintaining the solar components was also provided.

Generator maintenance is expected to be greatly reduced, as the generators are run less frequently. However, as was found on Atafu in January 2013, having a functional generator is important for reliability of electricity supply. When the batteries were drained to 60% after several days of poor weather the generator alarm was activated, but the generator was not operational and power to the grid was cut when the batteries were too deeply discharged. The generator was brought online afterwards to recharge the batteries, but power was lost for several hours over the course of two days. Despite a significant reduction in generator use, maintenance of the generators will still be important.

4. Performance

The PV systems on each atoll were sized to provide 90% of the atolls' electricity needs over the course of a year through solar electricity production.

During the sunny season (April-October) the systems are expected to provide over 100% of the electricity needs of the islands through solar energy (and "spilling" some of that energy when it cannot be stored in batteries) for weeks at a time, and in the cloudy season (November-March) the solar fraction (the percentage of electricity generated from solar power) is expected to be less.

To date, production has been tracked over four months, from November 2012 to February 2013. The results are summarized in Table 3, and the full monitoring reports are provided as annexes to this report.

The solar fraction for the first four months has not been at 90% on average as these were some of the cloudiest months of the year. January was particularly cloudy, and all three atolls suffered from poor solar radiation that month. Furthermore, the data show that the operators sometimes activate the generators prematurely. This is a good way to keep the batteries charged and lasting a long time, but comes at a cost of having to consume fuel (and thus resulting in a lower solar fraction). The operators should be commended for their vigilance in paying attention to the batteries' state of charge, but do not need to be as enthusiastic about turning the generators on as they currently are. This is expected to change in time, as the operators grow more familiar with their systems. Lastly, the 8% of panels that had to be temporarily disconnected from the DC charge controllers (see Section 2.4.2) would have helped to slightly increase the solar fraction of each of the systems. When they are reconnected in April 2013 after SMAs visit to Tokelau, the solar fraction for November 2013-February 2013 is expected to be higher.

The GoT has instituted rules concerning which electrical appliances cannot be used, and how power is to be consumed at home. Electric ovens and air conditioners are forbidden (except at the Teletok office, which needs to keep its electronic equipment cool), and residents do not turn on heavy power users (e.g. hot water kettles, microwave ovens, rice cookers) at the same time. These regulations were brought in at the request of the utility, as high power consumption was causing overloading of the generator and blackouts on the grid. The result is that there is a negligible evening peak on the atolls, and loads are relatively constant throughout the day. Users are also charged on a prepayment metering system, which has been proven many times in different utilities around the world to reduce electricity consumption. Although high power users can now be used simultaneously (the capacity of the PV systems' battery inverters is much higher than the capacity of the diesel generators), the ban on electric ovens and air conditioners should remain in effect, as they are high energy consumers and will drain the batteries quickly. If the batteries are drained quickly and regularly the generators will need to be used more often, and the batteries' lifetime will be shortened.

TABLE 3: MONTHLY SOLAR FRACTIONS FOR THE FIRST FOUR MONTHS OF OPERATION

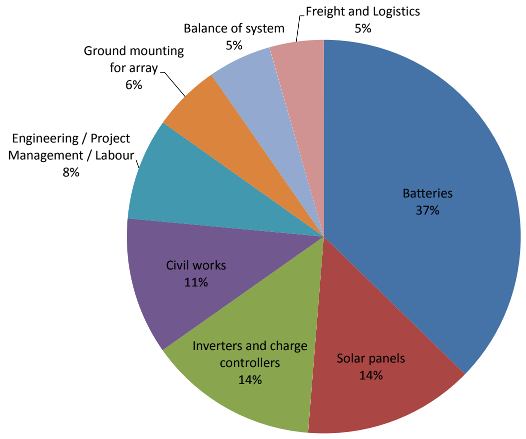
	November 2012	December 2012	January 2013	February 2013
Fakaofo	93%	80%	75%	96%
Nukunonu	100%	100%	N/A[1]	82%
Atafu	87%	90%	83%	95%

5. Financial analysis

The cost of the PV system, including civil works for the PV array frame foundations, the cost of building the battery buildings, and local labour, was NZD 8.45 million.

Most of that cost (NZD 7.5 million) was attributed to the PV equipment and its installation, with the remainder ($0.95 million) for site preparation, civil works, and the construction of housing for the battery and inverter systems. These costs are based on pricing provided in Q3 2011. If the systems were to be built today (Q2 2013) the cost would be lower as a result of lower PV prices and a lower price of batteries. Figure 23 shows an approximate breakdown of costs as a fraction of the total project cost. Note that the batteries are the highest cost component at 37%, so keeping them working as long as possible and delaying their replacement will reduce the running costs of the project over the long-term.

FIGURE 23: TREP COST BREAKDOWN[4]



Before the PV systems were installed, the fuel cost for the atolls was close to NZD 1 million per year. With the new PV system, the cost savings are expected to be approximately NZD 900,000 per year on fuel alone, and will increase with increasing diesel fuel prices (if prices increase at 3% per year for the next 25 years, the annual savings in 25 years will be NZD 2 million).

The annual running costs of the PV systems will be low, as maintenance will require little to no spare parts or equipment beyond what has already been provided as part of the project, and mostly involve labour for cleaning panels and inverters or checking batteries and topping up electrolyte levels. The major costs will occur when the batteries or the inverters and charge controllers need to be replaced. The cost of batteries is difficult to predict over a 10-year horizon, as it is highly dependent on the world price of lead. However, for planning purposes, the GoT should budget approximately NZD 3.75 million to replace all batteries[5] after 8-10 years, and NZD 1 million for replacing all inverters and charge controllers after 12.5 years.

A certain degree of fiscal discipline will be required to prevent the equipment maintenance funds from being used to cover short-term cash flow problems. While money from a capital replacement fund may be borrowed with the intention of repaying it when more money becomes available, this repayment may not occur and the funds might be insufficient to replace equipment. This is a common occurrence in Pacific governments and utilities, and should be avoided.

4 Balance of system includes cables, isolators, fuses, and all other equipment necessary to connect the system together.

5 This figure includes shipping of new batteries and removing old ones, and a small buffer for lead price increases. As the cost of batteries is very sensitive to world price of lead, the actual cost of batteries may be lower than NZD 3.75 million.

Table 4 provides the assumptions used in calculating the levelized cost of electricity for this project, and compares it to the levelized cost of diesel. Note that as the cost is levelized, it remains constant over the 25-year life of the project.

TABLE 4: TREP FINANCIAL ANALYSIS (ALL COSTS IN NZD)

	PV system	**Previous diesel system**
Capital cost	$8,450,000	N/A (assumed sunk cost)
Annual diesel costs	$100,000	$1,000,000
Operation and maintenance costs (labour)	$50,000	$100,000
Operation and maintenance costs (consumables)	$5,000	$15,000
Electricity sales	775,000 kWh	775,000 kWh
Inverter replacement cost	$1,000,000	N/A
Battery replacement cost	$3,750,000	N/A
Generator replacement cost	N/A	$210,000
Inverter lifetime	12.5 years (i.e. one replacement over 25 years)	N/A
Battery lifetime	9 years (i.e. two replacements over 25 years)	N/A
Generator lifetime	25 years (seldom used)	12.5 years
Project lifetime	25 years	25 years
Discount rate	8%	8%
Inflation rate	3%	3%
Advance repayment period	4 years	N/A
LCOE	$1.35/kWh	$1.50/kWh