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TUVALU - FUNAFUTI ROAD MAP

TA9242 REG: Pacific Renewable Energy Investment Facility: Tuvalu

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Acronym	Meaning
AC	Alternating Current
ADB	Asian Development Bank
AUD	Australian Dollars
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CIF	Consolidated Investment Fund
COE	Cost Of Energy
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
D-UPS	Diesel Uninterruptable Power Supply
EU	European Union
FSL	Finished Surface Level
GDP	Gross Domestic Product
GHI	global horizontal irradiance
GoT	Government of Tuvalu
GCF	Green Climate Fund
GWh	gigawatt hour
IMF	International Monetary Fund
IP	Ingress Protection
JICA	Japan International Cooperation Agency
kVAR	Reactive power
kW	Kilowatt
kWh	kilowatt hour
LV	Low Voltage
MW	megawatt
MWh	megawatt hour
NZ MFAT	New Zealand Ministry of Foreign Affairs and Trade
OI	Outer Islands
PAYG	Pas As You Go
PV	photovoltaic
PMH	Princess Margret Hospital
PWD	Public Works Department
RE	Renewable Energy
RMU	Ring Main Unit
SC	Synchronous Condenser
SCADA	System Control And Data Acquisition
SLD	Single Line Diagram

Acronym	Meaning
TCAP	Tuvalu Coastal Adaptation Project
TEC	Tuvalu Electricity Corporation
TREP	Tuvalu Renewable Energy Project
TTF	Tuvalu Trust Fund
TSF	Tuvalu Survival Fund
UAE	United Arab Emirates
USD	United States Dollar
WTG	Wind Turbine Generator
ZDO	Zero Diesel Operation.

Executive summary

This report details the Funafuti Road Map to 100% Renewable Energy as part of the Tuvalu Renewable Energy Project. This Road Map provides a pathway for current and future stages of renewable energy development on Funafuti towards a 100% renewable energy contribution level.

This report is a companion to the Entura Feasibility Report assessing the feasibility of increasing the renewable energy contribution for the outer islands of Nukulaelae, Nukufetau and Nui, and then adding solar PV and battery storage to the Funafuti power system.

Project Rationale

ADB is supporting the Government of Tuvalu to improve service quality, reliability, and climate resilience; and reduce its reliance on fossil fuels for power generation, with corresponding reduction in generation costs.

The main island of Funafuti constitutes the majority of electrical demand for the country, with the outer islands already on the way towards 100% renewable energy. The publicly-owned Tuvalu Electricity Corporation own and operate the generation and distribution assets.

Electricity generation is heavily reliant on diesel fuel, which has a high cost and also exposes the states to energy security risk including fuel price volatility. Tariffs are largely insufficient to recover current operating costs and there is no provision for capital works or unexpected maintenance.

Investment in renewable energy represents an opportunity to mitigate this exposure and reduce electricity costs, while also reducing greenhouse gas emissions and resulting in a more sustainable electricity system. Accordingly, the Government of Tuvalu set a target of 100% renewable electricity generation by 2025.

Consumption

Funafuti has an annual average increased demand forecast of 3.0%. Resulting in a forecast demand increase of 200% over the 25 year life of the project from 2020 annual consumption of 7,281 MWh to 14,562 MWh in 2045.

Funafuti has a current peak load of 1.35 MW which is forecast to increase to 2.82 MW in 2045.

Renewable energy resources

The available renewable energy resource options for Funafuti have been examined for a range of technologies and as a basis for the energy modelling inputs. Funafuti has moderate resources for both wind and solar. Other resources exist for wave, tidal flow, ocean thermal and waste to energy however these have not been explored in the proposed road map solutions at this time due to either cost or product/equipment development status.

Road Map

The stages to achieve 100% renewable energy contribution for Funafuti are presented below.

Table 1.1: Proposed Road Map to 100% RE Contribution for Funafuti

EXISTING

RE % year 1	RE % 25 year avg.	Cumulative PV Capacity (kWp)	Cumulative BESS (kW/kWh)	Diesel Capacity (kW)	Operating mode	Estimated CAPEX (2019 USD)	Estimated cumulative CAPEX (2019 USD)
15%	12%	735	0	1800	minimum 2 diesel units running	N/A	N/A

WORLD BANK PROJECT
- addition of 750 kWp solar PV and 1000 kW / 1000 kWh BESS
- operational in 2021

RE % year 1	RE % 25 year avg.	Cumulative PV Capacity (kWp)	Cumulative BESS (kW/kWh)	Diesel Capacity (kW)	Operating mode	Estimated CAPEX (2019 USD)	Estimated cumulative CAPEX (2019 USD)
37%	24%	1,485	1000/1000	1800	ZDO	N/A	N/A

STAGE 1 (ADB FUNDED)
– addition of 500 kWp solar PV and 1000 kW / 2000 kWh BESS
- operational in 2021

RE % year 1	RE % 25 year avg.	Cumulative PV Capacity (kWp)	Cumulative BESS (kW/kWh)	Diesel Capacity (kW)	Operating mode	Estimated CAPEX (2019 USD)	Estimated cumulative CAPEX (2019 USD)
49%	33%	1,985	2000/3000	1800	ZDO	$3.7m	$3.7m

STAGE 2 (unfunded)
– addition of 2,400 kWp of solar PV
- operational in 2023

RE % year 1	RE % 25 year avg.	Cumulative PV Capacity (kWp)	Cumulative BESS (kW/kWh)	Diesel Capacity (kW)	Operating mode	Estimated CAPEX (2019 USD)	Estimated cumulative CAPEX (2019 USD)
60%	52%	4,385	2000/3000	1800	ZDO	$6.0m	$9.7m

STAGE 3 (unfunded)
– addition of 3,300 kWp of solar PV and 1000 kW / 11,000 kWh BESS
- operational in 2025

RE % year 1	RE % 25 year avg.	Cumulative PV Capacity (kWp)	Cumulative BESS (kW/kWh)	Diesel Capacity (kW)	Operating mode	Estimated CAPEX (2019 USD)	Estimated cumulative CAPEX (2019 USD)
~100%	86%	7,635	3000/14000	1800	negligible diesel operation	$15.1m	$24.8m

To achieve a 100% renewable contribution for Funafuti by 2025 would require 7.6 MW of solar PV and 3 MW / 14 MWh of battery energy storage. Funding for the World Bank project and Stage 1 (by ADB) are assumed to be locked in. Funding for Stages 2 and 3 are unfunded and it is estimated would require cumulative capital of US$21.1m.

However, achieving the goal of 100% renewable energy is expensive, particularly the last few percentage points. Consideration should be given to revising the target to a more cost effective target of between 95% and 98% which is close to what the Outer Islands are achieving.

Implementation challenges

To achieve the goal of 100% renewable energy within six years (by 2025) will require overcoming a number of challenges;

- co-ordination between TEC and GoT to implement the Roadmap
- ensuring the Funafuti community are informed and supportive of the project
- evaluating what are the impacts on the rest of the Tuvalu economy if TEC no longer require large volumes of diesel fuel
- securing the required project funding of US$21m
- securing sites with landholder consent
- preparing tenders and securing suppliers and contractors to implement the projects
- evaluating how TEC can continue to operate with a tariff below cost recovery

Once the Roadmap is implemented there will be further challenges:

- Ensuring the skill set of TEC is able to operate and maintain the equipment
- Ensuring TEC has appropriate funding available to operate and maintain the assets to avoid reversion to a diesel based power system

Technology challenges

At this time very few projects have achieved 100% renewable energy penetration for island power systems in the MW scale, and of those that have there are fewer still examples of this achieved using inverters to replace the power system functionality normally provided by diesel generation. However, advancements in inverter technology are considered sufficient to safely deploy such technology in Funafuti.

To maintain system stability, reliability and protection discrimination with 100% RE penetration and zero diesel operation, it be important for each road map stage to ensure the following for all system operating scenarios:

- System earth reference is maintained
- Sufficient fault current is available
- Inverter voltage ride through settings and capabilities are adequate
- Inverter power output sizing is adequate to manage loss of single largest generating component at any given time

- protection discrimination and functions are proven adequate

The distribution system sizing is adequate to accommodate the currently proposed projects and system growth in the near term, however as detailed in Section 3.1.2. Distribution system sizing, particularly cabling capacity & power flow, will require re-assessment during the road map stages 2 and 3 once specific project connection points and sizing are selected to proceed.

It is anticipated that for each larger RE generation project site that a new 11kV connection point will be required. It is suggested that the Stage 3 BESS installations are co-located at the newly established distribution connection points to reduce losses and mitigate the potential for power flow issues in the existing network.

Renewable technology options

The technologies that may be required to fulfil the Road Map have been explored in this report with consideration of their suitability for Funafuti.

The overall SCADA system becomes a key consideration once zero diesel operation is targeted, particularly the need for an overall hybrid system controller managing generation and storage dispatch to maintain load/generation balance. This is anticipated to be implemented by the World Bank project however the finer details are unclear at this time; it is not known if that project will upgrade the diesel controllers or install distribution feeder controllers. As implementation is timed closely with the ADB Stage 1 project there is a risk that the two projects will either overlap with control system scope, or gaps in integration will occur. The interaction between the two projects will require careful management during procurement specification development for the ADB project, aided by open communication with TEC and the World Bank project management.

Solar, wind and BESS systems are all considered as suitable for Funafuti at this time, with floating solar product development likely to progress solutions suitable for the tropical lagoon environment and wind/wave conditions in the near term.

Project sites

A significant challenge for the Road Map will be securing sites with a large capacity which would enable economies of scale to be realized during procurement and construction.

Potential sites for solar PV in Funafuti have been identified in this report and these have been classified as:

- **Government building rooftops;** some low cost sites exist, others require structural assessments, minimum land holder agreements required. QE II Park may achieve majority of stage 2 capacity at a single site.
- **Funafuti lagoon solar;** mid cost range, floating solar products with high storm withstand capability still under development, would enable large scale deployment at single site for Stage 3 with economies of scale, may require single supplier procurement rather than open tender.
- **Government controlled land;** few suitable areas identified, medium cost profiles for raised structures, minimum land holder agreements required.
- **Community rooftops and land;** several sites identified, require structural assessments, minimum land holder agreements required.

- **Non-Government controlled building rooftops and land;** several sites identified, require structural assessments, land holder consultation and agreements required. More detailed assessments required.

Adding rooftop solar presents one of the lowest cost solutions to increase the renewable energy contribution on the island however as the renewable energy system share rises, the need for communications and control becomes greater. The other significant advantage of rooftop solar is utilisation of existing space which otherwise is of little value, compared to developing new sites on land which is at a premium. A disadvantage of rooftop solar for existing buildings is the need for structural assessments to ensure adequacy. An additional challenge in implementation of rooftop solar is the construction safety management of working at heights.

The road map plan assumes that roof top solar options will be implemented first, prior to the medium cost alternatives (elevated ground mount raised fixed structures, and floating solar).

Alternatively low risk sites with clearly identified large capacities for raised fixed structures can be considered advantageous for early implementation due to ease of implementation and possible economies gained through scale (e.g. QE II Park).

It is anticipated that by Stage 3, a floating solar solution suitable for Funafuti lagoon, similar to the circular floater/membrane type with a high storm withstand capability, will be adequately developed as a product, ready for large scale deployment.

Summary of Road Map findings

This report finds that in 2020 on the Island of Funafuti, 100% renewable power *penetration* is achievable and may be realised earlier, with increased levels of renewable *contribution* to follow progressively, targeting 2025 as the first year where 100% renewable energy contribution for Funafuti is possible.

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Appendices

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1. Background Information

1.1 Introduction

Tuvalu is on the frontline of climate change impacts. Rising sea levels, higher temperatures, reduced rainfall and increased intensity of cyclones are all being experienced in Tuvalu. The people of Tuvalu recognise this is a global issue and that they must set an example if they want the world to address one of the leading causes of climate change, CO_2 emissions. The Master Plan [1] lists one of their priorities as "*to reduce Tuvalu's "carbon footprint" and become an international role model with regard to climate change mitigation*".

Tuvalu, like many Pacific Nations, has traditionally relied on imported fossil fuels for electricity generation. This has led to the development of policies aimed at reducing reliance on fossil fuels. This will set an example on climate change, as well as having the added benefits of reducing the cost of generation, and improving security of supply.

In Tuvalu, this is articulated in the 2009 *National Energy Policy* [5] that has the goal of promoting the use of renewable energy resources and cost-effective, equitable, reliable, accessible, affordable, secure and environmentally sustainable energy systems to improve the well-being of the people of Tuvalu.

In addition, the Government of Tuvalu launched the "Enetise Tutumau" - the *Master Plan for Renewable Electricity and Energy Efficiency in Tuvalu* in 2013 [1]. This plan aims to generate 100% renewable energy by 2020 and to increase energy efficiency by 30%. The Government has subsequently extended the target date for achieving 100% renewable energy from 2020 to 2025.

Tuvalu currently (as of 2018) has approximately 16% renewable energy generation and 98% of households have access to electricity. The focus of the Government to date has been to increase the renewable energy contribution on the outer islands of Tuvalu to 100%, to be followed by increasing renewable energy contribution on Funafuti. The Northern islands (Nuitao, Vaitupu, Nanumaga and Nanumea) currently operating with RE contributions above 90%, while the Central and Southern Islands (Nukulaelae, Nukufetau, Nui) are at around 60-70% with plans to raise this above 90%. Funafuti currently operates with a RE contribution level around 14% and of the 1.8 million litres of fuel imported in 2018, 95% is attributed to Funafuti. Approximately 7-10% of GDP is spent on imported fuel (around USD $2M depending on oil prices), making energy the costliest sector of the Tuvalu economy.

This report has been prepared under the ADB Tuvalu Renewable Energy Project (TREP) and sets out a pathway to achieving 100% renewable energy contribution on Funafuti by 2025.

This report is a companion to the Entura Feasibility Report assessing the feasibility of increasing the renewable energy contribution for the outer islands of Nukulaelae, Nukufetau and Nui, and then adding solar PV and batteries to the Funafuti power system.

The report presents the following sections:

- Section 2 details the existing Funafuti power system including the existing sources of generation;
- Section 3 forecasts the future electrical demand for Funafuti;
- Section 4 outlines the typical pathway for the transformation from a diesel based power system to a high renewable energy contribution system;

- Section 5 describes the modelling methodology to prepare the roadmap;
- Section 6 outlines the Funafuti Road Map to achieve 100% renewable energy contribution;
- Section 7 provides a technology overview relevant to development of the Road Map

1.2 Country description

Tuvalu is a Polynesian country located in the Pacific region, located approximately 1200 km north of Fiji, as shown in Figure 1.1. Tuvalu has a total land area of 26 square kilometres (km2) and an Exclusive Economic Zone (EEZ) of 900,000 km2. Tuvalu is comprised of nine atolls and Islands, of which Funafuti is the most populated. Tuvalu's population is mostly from Polynesian descent (96% of the population), with a small proportion from Micronesian descent (4%), and the languages spoken include Tuvaluan, English, Samoan and Kiribati (on the island of Nui).

Current United Nations estimates[1] give 11,393 as the total current population with overall population growth around 0.2% for the period 2010-2015[2]. The most recent complete census data is from 2012 [7] which shows a small general decrease in population growth for the outer islands and a moderate increase of around 3% for Funafuti. The population trends are driven by migration from the Outer Islands to Funafuti, along with migration from Funafuti overseas. Figures vary to a small degree between the various publicly available data sources.

Table 1.1: Tuvalu summary data from the 2012 Census

Name	Area (hect)	Population Census
Tuvalu	2,563	10,782
Funafuti	279	6,152
Nanumaga	278	481
Nanumea	387	544
Niulakita	42	27
Niutao	253	606
Nui	283	542
Nukufetau	299	536
Nukulaelae	182	324
Vaitupu	560	1,555

[1] Current as of 26th June 2019, Source: Worldometers (https://www.worldometers.info/world-population/tuvalu-population/) as elaborated from data by United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2017 Revision. https://population.un.org/wpp/)

[2] As listed on http://data.un.org/CountryProfile.aspx/_Images/CountryProfile.aspx?crName=Tuvalu

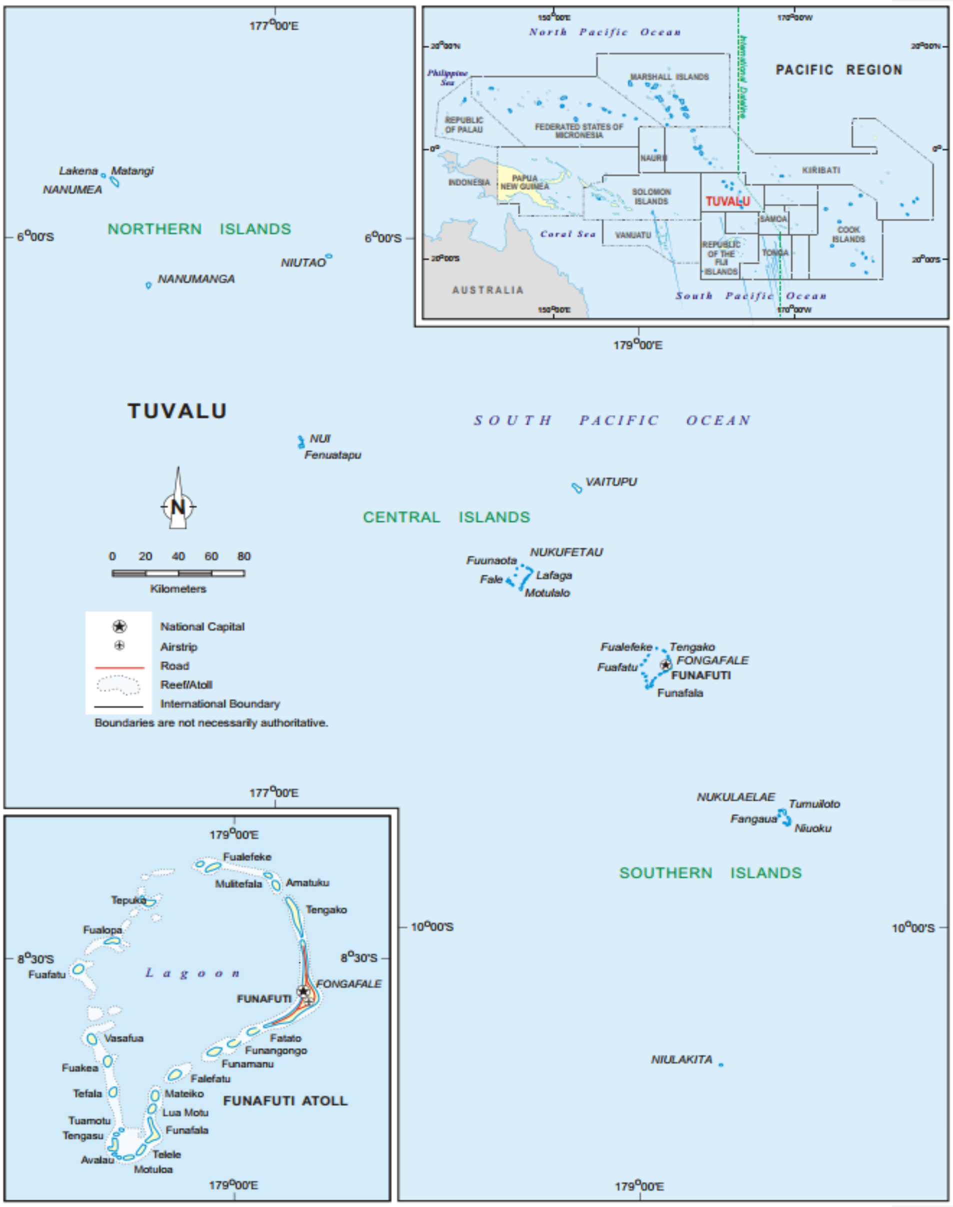

Figure 1.1: Tuvalu location and country map

1.3 Economy

Tuvalu is a micro economy in the Pacific, remote from major markets with a narrow production base, a weak banking sector which has constrained credit availability, and growth mainly driven by public expenditure. It is highly vulnerable to climate change impacts, especially loss of land and potable water due to sea level rise and salt water intrusion. The country's priorities, outlined in Te Kakeega ii and III National Strategy for Sustainable Development [2] and Tuvalu Infrastructure Strategy and Investment Plan 2016-2025 [6], are to build resiliency to climate change, broaden and diversify the production base (tourism is a leading potential growth sector), and better manage public enterprises. The International Monetary Fund (IMF) with Government of Tuvalu (GoT) concurrence, encourages the government to strengthen the banking sector to make credit for private investment more accessible and to increase domestic out-sourcing for some government functions (e.g. maintenance), in order to promote private sector development.

Current government finances are largely dependent on overseas grants and volatile fishing license fees. The domestic tax base is constrained by significant structural and compliance issues, which are being addressed. The Tuvalu Trust Fund (TTF) was set up as a partnership of GoT and international donors in 1987 and has grown in value to approximately AUD $175 million or 333 percent of GDP at end-2017. The TTF is not fully sovereign and cannot be drawn down below a defined value. When its market value exceeds a "maintained value" indexed to the Australian CPI, the difference is automatically distributed to a Consolidated Investment Fund (CIF), which is fully sovereign and stands at AUD $22 million or 42 percent of GDP at end-2017. The government draws upon the CIF to finance fiscal deficits. In addition, a Tuvalu Survival Fund (TSF) was established by GoT in 2015, to finance climate change resilience programs, and now amounts to 10 percent of GDP. Tuvalu was the first recipient (in 2017) of the Green Climate Fund's (GCF) contributions to climate change adaptation in the Pacific region. The Tuvalu Coastal Adaptation Project (TCAP), funded by GCF and administered by UNDP will run through 2025 at a total cost of 74 percent of GDP.

Fishing license fee revenues grew to 50 percent of GDP in 2017 from 15 percent of GDP in 2011, and now account for 60 percent of total fiscal revenue, due to improvements to the Parties to the Nauru Agreement (PNA)[3] for Tuvalu stemming from favourable fish migratory patterns related to El-Nino effects. Fishing revenue is a volatile income source for GoT, although the volatility has slightly decreased in recent years.

Real GDP growth fell from a high of 9.1% in 2015 to about 3.0% in 2016 and 2017. Growth is expected to increase to 4.3% and 4.1% in 2018 and 2019 respectively due to continued public sector investment in climate change resilience and other infrastructure programs. Migrant workers are contributing significantly to the economy and some 12% of GDP is from overseas remittances. Consumer price inflation has averaged 3.6% between 2015 and 2017 and is expected to moderate to about 3% in the years ahead.

The main economic risks are existential - sea level rise, loss of potable water due to salt water incursion (continued desalination for some of the public water supply has been recommended by the IMF as a means to boosting private sector confidence), and loss of remaining arable land. Financially, fishing license revenues will remain volatile and reliance on grants will remain high. There is considerable financial resilience built in to the set of trust funds for Tuvalu that ensure the adequacy of investment capital for climate adaptation (at least for the medium term) and financial recourse

[3] The PNA is a regional agreement among Pacific countries (FSM, Kiribati, Palau, PNG, RMI, Solomon Islands, and Tuvalu) accounting for around 30 percent of the world's tuna supply.

during periods of fiscal distress. The IMF judges, however, that Tuvalu may become more vulnerable to debt distress as grants gradually decline and borrowing requirements increase in the future.

The IMF projects that real GDP will grow at 4 percent in the medium term, moderating to 2 percent in the long term due to structural economic weaknesses (limited capacity, weak competitiveness, and inefficient SOEs). Natural disasters are expected to cost the country on average about 1 percent of GDP per year. Revenues from fishing licenses will fall to 46 percent of GDP in the medium term from 50 percent in 2017 due to a waning El Nino cycle. Fiscal deficits will widen from 5 percent of GDP in the medium term to 7 percent in the long term.

Urbanisation (in-migration to the capital from the outer islands) seems to be the key to growth in Funafuti. According to the 2012 Census [7], migration between islands in Tuvalu has historically been fluid, as different services are available on certain islands and not others (e.g., the only high school is in Vaitupu). Nevertheless since national Independence in 1978, Funafuti has been the only location of growing population in Tuvalu, whereas the outer islands have declined. Between 1973 and 2012, Funafuti grew from 15% of the national population to over 57% (and increased from 47% since 2002) and correspondingly the outer islands fell from 85% to 43%. At present, the Funafuti population stands at around 6,100, and will undoubtedly grow more (in proportion) over the next decade or two. Urbanisation has been a Pacific-wide phenomenon for years, against which the prospect of increasing urban poverty doesn't seem to be a barrier to the migrants. Overcrowding is a likely prospect for Funafuti.

1.4 Tuvalu Electricity Corporation

TEC is a state-owned enterprise (SoE), a vertically integrated electricity utility operating in the capital of Funafuti and the outer islands of Nukulaelae, Nukufetau, Nui, Nuitao, Vaitupu, Nanumaga and Nanumea. It was established by an Act of Parliament in 1990 and is mandated by the Act to be managed with prudent commercial principles with a view to profit.

An annual budget for TEC is prepared by the finance division with inputs from all other divisions and approved by the Board. It consists of a commentary of key points in the year under consideration, a forecast of electricity sales feeding into the budgeted financial statements and the budgeted capital expenditure.

Electricity demand grew at 6% per annum from 2013-2017. Renewable energy generation grew from 0% in 2013 to 16% by 2017 for TEC overall. In 2015, TEC received grant funding from the government of New Zealand (NZ MFAT) and the European Union (EU) for solar-diesel-battery hybrid systems in the outer islands. The renewable energy investments in Funafuti were funded by New Zealand (NZ MFAT) and the United Arab Emirates (MASDAR) in addition to its medium speed thermal power station funded by Japan in 2007. Although, these investments resulted in operational efficiencies due to thermal displacement, the bottom line of TEC has continued to report a loss from 2013 to 2018.

Two main reasons can be seen for the continued losses at TEC. The tariff has remained unchanged since it was legislated in January 2008, and does not recover costs, although TEC has benefitted recently from reduced global oil prices and increased renewable energy generation. The second reason is the accounting treatment of the grant funded renewable assets, where TEC has fully written-off these investments on the grounds of impairment, although the assets continue to be in use and generate revenue through reduced fuel costs. Instead, the correct accounting treatment would have been to capitalize and depreciate the assets while at the same time amortizing the grant as deferred revenue to profit.

Due to the impairment loss of AUD 20.7 million in 2015, the TEC Balance Sheet is undercapitalised and weak. Although the Balance Sheet does not carry any external debt, debt from customers in the form of unpaid electricity bills has continued to mount in recent years. At the end of 2017, gross receivables were AUD 2.1 million of which 68% were past due for more than three months indicating difficulty in eventual collection. At the end of 2018, gross receivables were AUD 2.2 million of which 72% were past due for more than three months. Approximately AUD 0.8 million of receivables outstanding were from Government. The receivables are being financed by an expensive Bank Overdraft which has increased sharply to AUD 0.9 million at the end of 2018 from AUD 0.45 million a year earlier. This cash flow predicament is not sustainable and has resulted in TEC having to postpone essential maintenance on its Funafuti thermal plant and also hold back payments of taxes to Government. Approximately AUD 0.5 million in taxes have not been remitted by TEC, which contravenes with the law.

The addition of renewable energy for Funafuti will substantially reduce the operating costs for TEC, of which diesel fuel costs comprise over 60% of the budget (around AUD$2.5 m per year).

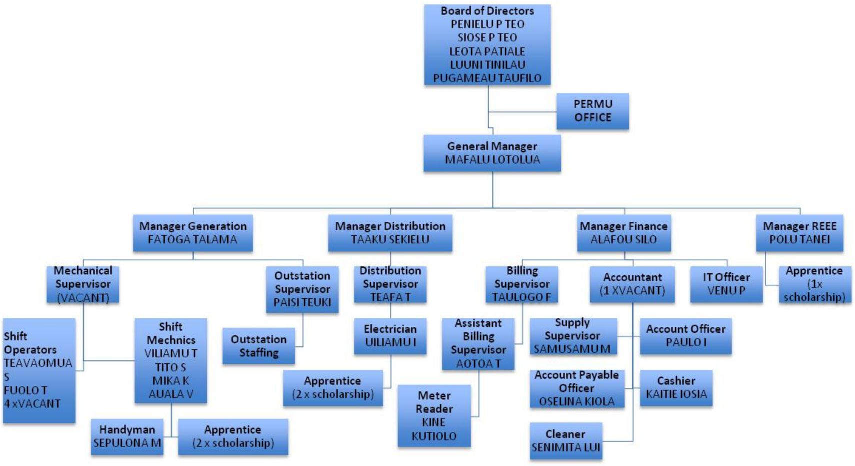

Figure 1.2: TEC organization chart

1.5 Government of Tuvalu renewable energy plan

The Government of Tuvalu (GoT) prepared *Enetise Tutumau* 2012-2020 Master Plan for Renewable Electricity and Energy Efficiency [1] that provides the framework for developments in the energy sector in Tuvalu. *Enetise Tutumau* was published and endorsed by the Government of Tuvalu in February 2013. The Master Plan set a target for electricity to be 100% from renewable energy by 2020 (subsequently revised to 2025) and for energy efficiency to be increased by 30%. The Master Plan is linked to *Te Kakeega II* the National Strategy for Sustainable Development (2005-2015) [2], *Te Kaniva* the National Climate Change Policy (2012) [3], the National Strategic Action Plan for Climate Change and Disaster Risk Management (2012-2016) [4] and the Tuvalu National Energy Policy (2009) [5].

Per the Master Plan, the priorities for the electricity sector in Tuvalu are:

(a) To provide a reliable and affordable electricity supply to all the people of Tuvalu;

(b) To safeguard Tuvalu from future diesel price shocks;

(c) To improve the efficiency of electricity utilisation and further reduce the already low energy consumption per person and per GDP; and

(d) To reduce Tuvalu's "carbon footprint" and become an international role model with regard to climate change mitigation.

As a first step in a path towards 100% renewable energy, the Government of Tuvalu set two goals:

1. To generate electricity using 100% renewable energy by 2025
2. To increase energy efficiency by 30% on Funafuti and later in the Outer Islands.

The Master Plan provided a framework for the achievement of these goals which it estimated would require a total renewable electricity generation capacity of 6 MW involving a capital investment of A$52 million (in 2012 dollars).

The key elements of the renewable electricity programme were:

1. Development of renewable electricity generation supplemented with batteries initially on the Outer Islands;
2. The provision of additional renewable electricity generation capacity on Funafuti;
3. The implementation of an energy efficiency programme on Funafuti initially followed by a programme on the Outer Islands;
4. Conversion of supplementary generation from diesel to bio-diesel fuel.

Assessing the programme in 2019, element 1 is almost complete, with all outer islands now based on hybrid solar/battery/diesel power systems, with many of the islands operating for long periods without any diesel generator usage.

With the completion of element 1, element 2 is now ready to be implemented. Currently there is a World Bank funded energy project that will increase the renewable energy generation and the overall renewable energy contribution with the addition of 750 kW of solar PV and a 1 MW / 1 MWh battery energy storage system (BESS). The World Bank project is also providing pre-paid meters to be deployed throughout Tuvalu that will assist with element 3 of the renewable electricity programme.

This report outlines a plan to transform Funafuti through to 100% renewable energy contribution by 2025.

1.6 Previous studies

There have been a number of studies and reports assessing renewable energy and the Funafuti power system over the last 10 years. Many of these were used in the preparation of the Master Plan [1], precursory to the existing PV generation systems or form the foundation of the current World Bank energy project. These are used or referred to in the formulation of this roadmap. A list of the most relevant studies is provided here, along with a full reference list in Section 9:

- *Overarching Roadmap Report Renewable Energy Generation for Tuvalu*, January 2013, Opus International Consultants Ltd. [8]

- *Funafuti Atoll, Tuvalu Distributed Renewable Generation Study: Integrating PV Solar and Wind Generation with the TEC electric system*, 2013, DNV KEMA [9]
- *Quantification of the Power System Energy Losses in South Pacific Utilities: Tuvalu Electric Corporation, Tuvalu*, May 2012, KEMA International B.V [10]
- *Funafuti Wind Energy Report,* 30 January 2013, GL Garrad Hassan [16]
- *Tuvalu Wind Power Development Wind Study and Feasibility Report,* May 2010, Ecology Management Aps [11]
- *D4 – Draft Interim Report and Model for Tuvalu Electricity Corporation (Tuvalu),* October 2018, Ricardo [12]

1.7 Previous energy sector projects in Tuvalu

Since 2008 the EU, UAE, Japan, Italy and NZ MFAT have invested in a number of energy sector projects that have helped Tuvalu increase their renewable energy generation up to current estimated levels of 16%, through solar PV installations on the main island of Funafuti, and hybrid solar PV-diesel-battery mini-grids on the outer islands as listed in Table 1.2.

The focus of the GoT has been to get the outer islands as close to 100% renewable energy first, followed by increasing RE penetration on Funafuti.

Table 1.2: Donor funded renewable energy projects in Tuvalu since 2008

Location	Description	Capacity	Funding Agency	Year
Funafuti sports field	Solar PV demonstration	40 kWp	Japan (e8 Group)	2008
Vaitupu Secondary School	Solar integration project	46 kWp	Italy	2009
Funafuti PWD compound	Solar PV	66 kWp	Japan	2013
Nukulaelae, Nukufetau, Nui	Solar and BESS hybrid systems	45kWp, 576kWh 87kWp, 1008kWh 77kWp, 864kWh	EU	2015
Vaitupu, Nanumea, Nanumaga, Nuitao	Solar and BESS hybrid systems	400kWp, 3120kWh 195 kWp, 1560 kWh 205kWp, 1716 kWh 230kWp, 1872kWh	NZ MFAT	2015
Funafuti – Government Office and Media Building	Rooftop solar PV	170 kWp	NZ MFAT	2015
Funafuti TEC Compound	Solar PV	500 kWp	MASDAR (UAE)	2015

1.8 Inputs

Prior to and during the formation of this road map report the Entura team have been able to acquire a large amount of information, reports, maps, and data for Tuvalu and Funafuti. This includes:

- power system details including drawings, specification, and generation data
- tariff and metering information
- bid documents for the World Bank project
- maps and aerial photos
- anecdotal information from discussions with GoT and other stakeholders.
- financial and economic data
- site visit observations

1.9 Assumptions

The following assumptions have been made in preparing this report:

- The sub-project life for each stage of the roadmap will be 25 years. In reality, the project life could be considerably longer than this as components can be replaced as they fail or it becomes financially attractive to replace them.
- Demand data provided for Funafuti will be reflective of the demand for the foreseeable future. Increases, decreases or changes in the daily usage patterns have been accounted for by using variability in the modelling, however significant unexpected changes to the demand profiles would have an impact on the modelling results included in this report.
- The battery energy storage system to be implemented as part of the World Bank project will enable the Funafuti power system to operate in zero diesel mode.
- It is assumed that solar PV presents the most viable solution for renewable generation in the roadmap timeframe. The implications of this to achieve high levels of renewable energy contribution are that large battery storage is required to time shift generation from the daytime into the overnight period. If a renewable energy source can be utilised that has an overnight component this could substantially reduce the amount of solar and battery required. Alternatively, lowering the renewable energy contribution requirement from 100% to a slightly lower level (still greater than 90%) could also substantially reduce the amount of solar PV and battery storage required.
- It is assumed that funding can be made available to finance all stages of the roadmap. This could be from within Government of Tuvalu, from donor agencies or a combination. More crucial to the success of the Roadmap will be to secure sufficient ongoing funding for operations and maintenance requirements of TEC.
- It is assumed that sites can be secured within the timeframes to meet 2025 timetable. This will require co-ordination between TEC and Government of Tuvalu, planning to ensure sites aren't used for other purposes, and substantial community consultation to ensure the projects have support of the Funafuti population.
- Measured electrical system losses recorded in 2017 will be sustained into the future. These are largely related to the distribution network and it is assumed that there will be no fixes or upgrades to the network.

- Forecast growth in electrical consumption will average 3% per year out until 2045. Any changes in this will affect the future performance of the power system and may require additional renewable energy and/or battery storage.

1.10 Limitations

Entura recognises that there are number of limitations associated with this study:

- Specific studies for projects as part of Roadmap Stages are beyond the scope of this report including review of the tariff structure, detailed environmental impact assessments and community engagement.
- Securing future renewable generation sites and land holder agreements is beyond the scope of this report
- Cost estimates are based on recent tenders and market information from the Pacific region and are suitable for the purposes of this report to assess the most likely options. Future costs are best estimates, variation between changes for each technology type may lead to changes in optimal capacities in the future.
- Detailed protection coordination studies are required with each stage project implementation to manage appropriate discrimination of diesel, solar, wind, BESS and feeder protection system.
- Entura has not assessed the ability of the power system to provide black start capability. It is assumed that the system will have this ability in the event of an outage, diesel systems will be maintained and BESS systems will have sufficient capability (most systems on the market have this capability, however, it typically requires consideration at detailed design stage to properly integrate).
- Solar data has been sourced from Meteonorm 7.1 software. A project of this size does not warrant more rigorous analysis of the solar resource and local irradiance data is unavailable.
- Accuracies of modelling outputs are a function of various assumptions and physical behaviours; resource variability, actual PV modules supplied (performance), variability of load growth estimate (shifting actual demand required) and actual supplied equipment efficiencies.

2. Existing Funafuti power system

2.1 Existing Funafuti power system

Current generation costs in Funafuti are high due to reliance on diesel for the bulk of generation. Reliance on diesel fuel also exposes the country to energy security risk through fuel price volatility. Previous donor projects and local investments on Funafuti have made small reductions in the diesel fuel use however the Island is still dependent on the running of the diesel generators to meet demand.

Current generation costs in Tuvalu are high. With correct accounting treatment through capitalisation and depreciation of 2015 energy projects, the estimated cost recovery is currently estimated to AUD$ 0.82 per kWh. Current average tariffs are at AUD$ 0.51 per kWh, that would have resulted in a funding shortfall in 2018 of over AUD$2m (actual shortfall was over AUD$1m), mostly due to Funafuti where 95 % of all diesel fuel is used.

Summary Funafuti generation and sales data in Figure 2.1 shows the benefit from the addition of solar PV generation in 2015 and annual demand for the 5 years 2013to 2017.

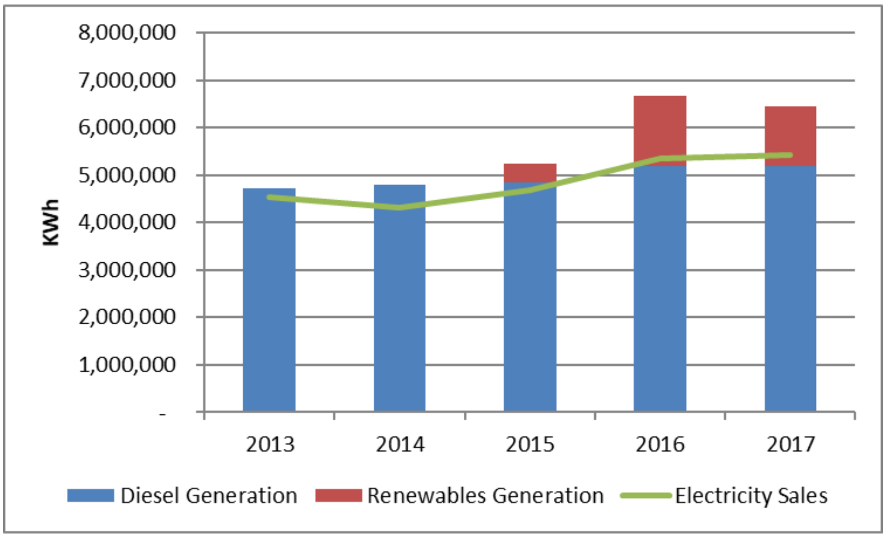

Figure 2.1: Summary Funafuti generation and sales data for the period 2013 to 2017. (Source; consultants estimate)

The existing Fongafale power system on Funafuti Island consists of the following major components:

- 3 x 600kW diesel generation at TEC, with SMA ‘fuel saver’ control system
- Peak Load – 1,362kW
- 735 kWp of installed, operational solar PV capacity

Of the three diesel units, one has been out of service since mid-2018, leaving no redundancy in the system. Anecdotally, there were reports of brief planned system wide outages for operational maintenance. Major maintenance is due on the two running units, the third unit would have to be brought back online to enable this. Little redundancy is provided by the total number of units, if simultaneous generator faults or breakdowns were to occur then extended system wide outages would be inevitable. Further, the generators are aging and will come to the end of their design life in around 5 years, with no budget set aside for replacement.

The system has an SMA 'fuel saver' control system installed that applies an effective limit on solar PV output of 415 kW. The combination of this limit and inadequate redundancy in the system requires that diesel generation remains the main source of electricity production.

The power system is manually operated, with the diesel generation likely set to load following mode. There is little or no visibility of the distributed solar generation by the controllers

The World Bank project proposed will consist of a 1MW/1MWh battery energy storage system (BESS) and 750 kWp solar PV for Fongafale. The indications from TEC are that the project will commence installation within the next 12 months (before mid-2020).

The addition of a BESS will alleviate much of the solar PV curtailment, while the associated BESS control system will automate the power system and provide better optimisation of the generation.

Table 2.1: Funafuti, modelled existing diesel generator assets

Unit Number	1	2	3
Installation year	2007	2007	2007
Capacity (kW)	600	600	600
Minimum loading	30%	30%	30%
Speed (RPM)	750	750	750
Running hours as at Dec. 2018	58,920	56,520	58,480
Derating	85%	no	85%
Alternator Manufacturer	Toshiba	Toshiba	Toshiba
Manufacturer/Model	NSDK/JEC-2150-2000	NSDK/JEC-2150-2000	NSDK/JEC-2150-2000
Fuel intercept ($L/kW_{cap}/hr_{operation}$)	0.0322	0.0322	0.0322
Fuel slope ($L/kW_{prod}/hr_{operation}$)	0.2067	0.2067	0.2067

2.1.1 Existing solar PV installations

There is currently 735 kWp of installed solar PV capacity that is operational in Funafuti. The current installed sites are as follows:

- 75 kW PV, PMH (Princess Margaret Hospital)

- 42 kW PV, at Sports field (non-operational due to equipment condition)
- 65 KW PV, ground mounted at Public Works Department (PWD) compound
- 350 KW PV, at TEC integrated into the generation plant
- 75 kW PV, Marine Warehouse
- 130 kW PV, Government Offices
- 40 kW PV, Media Building

A 42 kW solar PV system installed at the sports field is offline due to network cable damage, panel degradation, failure of the containerised inverter mounting and DC cable failures. It appears that the array has been in this state for quite some time and local operators and management are aware that it is at the end of its useful life. Some components appear salvageable for re-deployment by TEC.

2.1.2 Review of HV/LV distribution network capability

The existing 11kV network is made up of early 2000's era oil filled RMU's connected with 11 kV 3 core 50 mm^2 and 25 mm^2 Cu cables. The noticeable exception to this is "RMU 9" installed as a part of the solar works at the power house. This RMU is an ABB SF6 insulated Safelink CCF in a modular 750kVA substation. The consumer voltage stepped down at each substation and reticulated is 415/240V from the distribution transformers. The network is arranged in a ring around the main central population area at Fongafale, with radial feeders extending to the northern and southern island strips.

Assessments by DNV Kema [9] and Entura [13] indicate that the distribution system sizing is adequate to accommodate the currently proposed projects and system growth in the near term. Spare 11kV connection points are limited for future projects and will be required to be established for Stages 2 and 3 of the road map outlined in Section 6 depending on selected project locations. Distribution system sizing, particularly cabling capacity and power flow, will require re-assessment during the project design once specific connection points and sizing are known.

Other matters for consideration in future project designs for the Road Map include:

- Trenching and associated land easement issues for new connections.
- LV network voltage rise.
- Undocumented or poorly designed inverter ride through settings.
- Reactive power support
- It is recommended to carry out detailed protection coordination study to manage appropriate discrimination of diesel, solar, wind, BESS and feeder protection system.

The updated Funafuti 11kV distribution Single Line Diagram (SLD) for the existing system is attached in Appendix C.1.

3. Funafuti electrical demand

This section forecasts the future electrical demand on Funafuti for inclusion in modelling of generation requirements for the Road Map.

Forecast electricity demand change is generally dependent on three factors: change in the consumer base (increase in electrification rate or new connections), consumer income growth (economic growth and remittances from abroad), and reaction to changes in the real tariff levels.

For the purposes of this study it has been assumed that there is no changes to the tariff, although it is noted that this is likely in need of a review as the current settings have been in place for over 10 years, TEC is currently operating at a deficit (i.e. below cost recovery), and there will be a significant change in TEC's cost structure if the Road Map is implemented in full.

It is also assumed that there will be no increase in the consumer base with electrification rates already close to 100%.

The forecast annual demand is built up from examining the existing annual demand, system losses, considering any efficiencies that are likely to be gained, before finally estimating and applying forecast growth. These are all discussed in this section.

3.1 Existing demand

The annual demand records from TEC customer billing data for Funafuti for 2013 to 2017 is presented in Table 3.1 and Figure 3.1. The billing data for the year ending 2017 is used as the basis for the annual demand used in preparing the roadmap.

Table 3.1: Funafuti TEC Sales data from 2013 to 2017

Funafuti (kWh)	2013	2014	2015	2016	2017
Domestic	1528352	1564255	1776159	1946916	2077003
Commercial	1550018	1457039	1496220	1679030	1649580
Government	1275962	1297208	1408909	1731228	1700574
Total	4534332	4318474	4681288	5357174	5427157

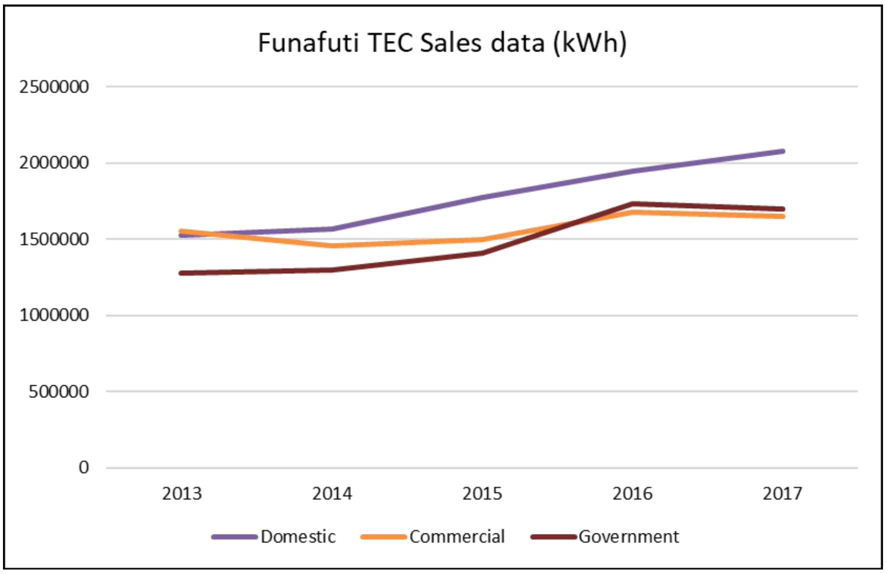

Figure 3.1: Funafuti TEC Sales data from 2013 to 2017

3.2 Daily demand profile

The daily demand profile data utilised in the DNV Kema 2013 Report [9] is shown in Figure 3.2 for reference and validation of the daily demand profiles utilised in this road map. It shows a steady low overnight demand, consistent morning ramping from 6am until around 9:30am followed by steady daytime demand. Demand then ramps down at the end of the working day from 4pm to 6pm, then a moderate evening load rises and remains steady and trails off again to the overnight reduced demand level.

The daily demand profile data for Funafuti provided by TEC was limited to several typical profiles from 2014 as only limited SCADA system logging is available. The measured TEC profiles from 2014 are shown in Figure 3.3.

There is visible correlation between the DNV Kema 2013 Report load profile in Figure 3.2 and the weekday 2014 profile in Figure 3.3. The 2014 profile from TEC was sourced from reliable measured data on site, and as such this was utilised as the basis in modelling. The weekday load profile was scaled to match the required annual load and peak load then modified with a limited percentage of random variability within the model.

The resulting daily demand profile used for Funafuti is shown in Figure 4.3, with the monthly demand profile and variation shown in Figure 4.2.

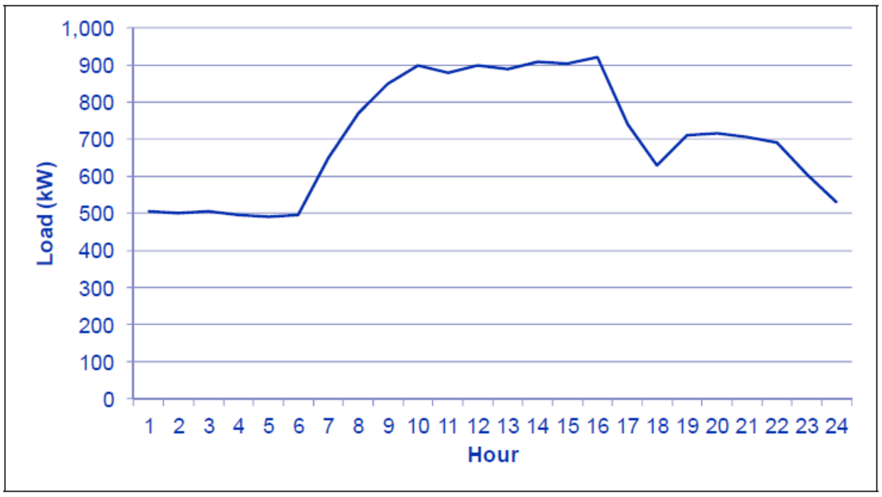

Figure 3.2: daily load profile from the DNV Kema 2013 Report [9]

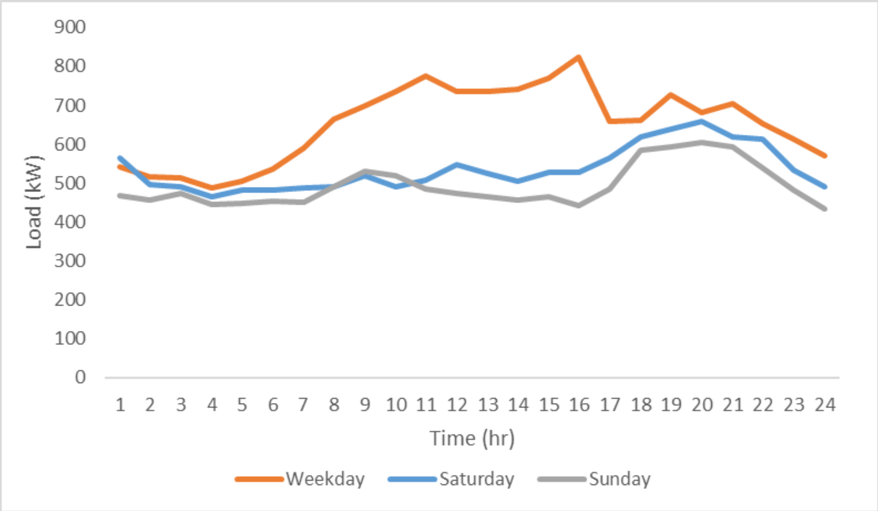

Figure 3.3: daily load profile from 2014data provided by TEC

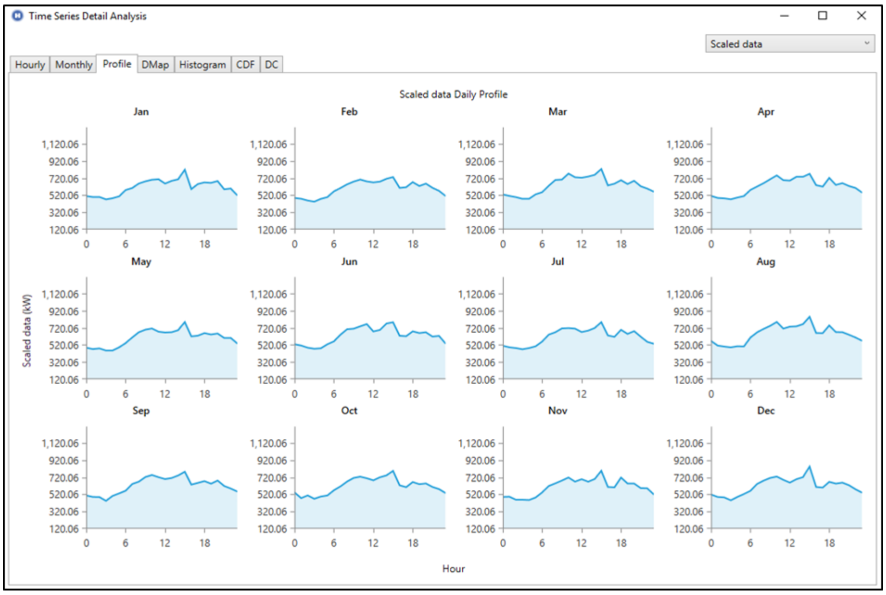

Figure 3.4: Daily demand profile and variation used for Funafuti (2020 load)

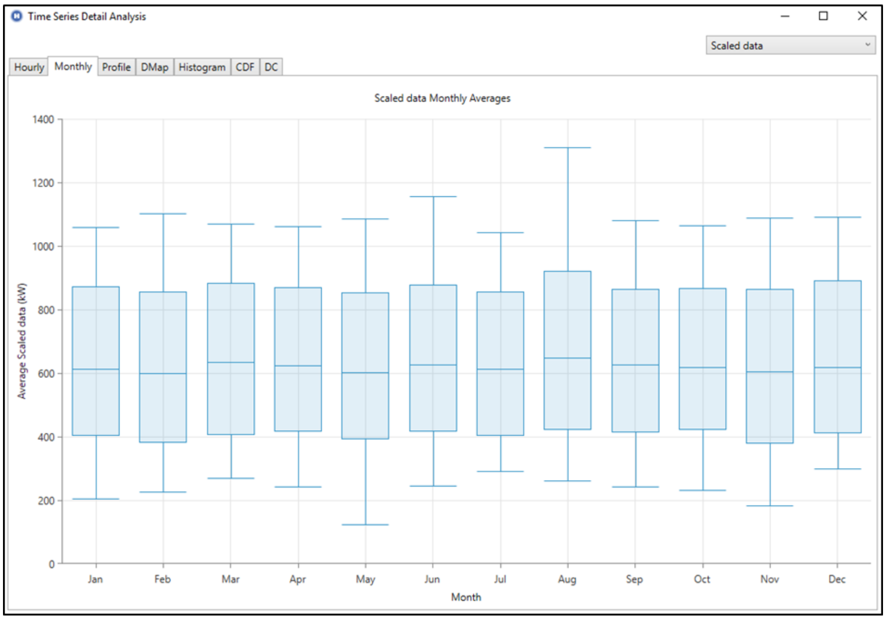

Figure 3.5: Monthly demand profile and variation used for Funafuti modelling

3.3 System losses

System Losses were examined and reported in detail by KEMA in 2012 [10]. Their report summarises the losses as follows:

- 3.62% in technical losses (I^2R equipment and cabling losses),
- 3.53% in non-technical losses (inaccurate meters, meter tampering or by-passing, theft, meter reading errors, irregularities with prepaid meters, administrative failures, wrong multiplying factors, others),
- 1.00% in unbilled usage,
- 8.63% in power station auxiliary,
- 16.78% in total,

Annual generation demand has been sourced from TEC generation data and summarised in Table 3.2 2013 levels are noted as similar in scale to the losses determined in the KEMA report. Comparing the historic TEC losses data for the last five years, the total losses have gradually increased to 28%. The loss increase captured in the TEC data is attributed to a rise in distribution losses. The most recent recorded loss levels are utilised in the basis for the roadmap.

Table 3.2: Calculated annual system losses from billing and generation data.

year	2013	2014	2015	2016	2017
Generation losses (%)	13%	18%	19%	26%	28%

3.4 Energy efficiencies

A significant factor which is likely to affect demand is the imminent introduction of Pay As You Go (PAYG) customer energy metering forecast to be rolled out across Tuvalu. The meters will assist TEC with their collections, whilst customers will be able to better manage their usage. Typically this results in some extended drop or leveling of annual demand as customers become more aware of their use, costs, and have to provide payment up front. Research literature (*European Smart Metering Alliance Final Report*[4]) indicates that savings from direct energy feedback provided by pay as you go metering are typically in the order of 10%. Other authors (B. Kelsey Jack, Et. Al[5]) suggest this can be in the order of 12 to 15 percent. There are also indications that high energy demand customers have a higher response to this when displays or indications present the significance of high demand periods. Additionally there are also numerous opportunities for energy efficiency measures that could also reduce demand.

[4] *The European Smart Metering Alliance Final Report* by BEAMA, located online at https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/esma_publishable_report_en.pdf

[5] *Charging ahead: Prepaid metering, electricity use and utility revenue* by B. Kelsey Jack, Et. Al, located online at https://www.tse-fr.eu/sites/default/files/TSE/documents/sem2017/environment/jack.pdf

Accordingly a 10% reduction in demand has been applied to the domestic component of the generation requirement, resulting in a 4% reduction overall.

3.5 Forecast growth

Funafuti's population census data since 1979 is presented in Table 3.3. Unlike the outer islands, this data shows a fairly steady small population growth on Funafuti although the data resolution over the period is low. Considering only the last two census figures from 2002 and 2012, these indicate an average annual rate of growth of around 3.2%.

Table 3.3: Funafuti population information from Tuvalu government census.

Census year	1979	1985	1991	2002	2012
Funafuti	2,120	2,810	3,839	4,362	6,025

Source: http://www.citypopulation.de/Tuvalu.html

According to the TEC 2016 Annual Report and TEC's 'logistics.xlsx' spreadsheets, electricity consumption in Funafuti grew at more than 10% p.a. between 2014 and 2018. The three consumer categories that TEC uses are: (i) Government, (ii) Commercial, and (iii) Private – the latter referring to Residential. Each of these categories accounts for roughly a third of total consumption (30.1%, 32.7%, and 37.2% respectively over the period) though the residential category is slightly dominant and its consumption grew the fastest (10.8% p.a. from 2014-2018).

As discussed in Section 1.3, an increasing proportion of the national population will choose to reside in Funafuti for the foreseeable future, and that increases in residential demand will be the main driver of changes in overall electricity consumption. In view of the limited land area of Funafuti and the long term economic prospects, consumption growth is likely to moderate considerably from the recent past. To be financially conservative, i.e., employ a growth assumption that places prudent requirements on TEC financial capacity to support and financially sustain solar investments, it is proposed that a long term growth rate in electricity consumption for Funafuti of 3% per year is assumed, responding mainly to urbanisation dynamics. In consideration of the population data and annual demand growth figures it is anticipated that sustained growth at these levels is unlikely to continue beyond the near term, as the Island is limited in available land and economic opportunities. Hence, a conservative 3% annual load growth over the 25 year project life has been assumed for modelling purposes, in line with the World Bank Funafuti project assumptions.

3.6 Forecast demand for 2020 to 2045

The basis for the forecast demand for the Funafuti Roadmap are presented in Table 3.4, with the resultant demand in year 1 of each stage of the Roadmap presented in Table 3.5. The forecast demand out to 2025 is presented in Figure 3.6

Table 3.4: basis of demand forecast

2017 billed customer demand (kWh)	Annual growth rate (%)	System losses (%)	System efficiencies (%)
5,427,157	3%	28%	-4%

Table 3.5: Funafuti demand requirements in year 1 of each stage of the roadmap

	2017	Stage 1	Stage 2	Stage 3
Annual generation requirement (MWh/year)	6,668	7,281	7,724	8,195
Daily generation requirement (kWh/day)	18,268	19,948	21,162	22,452
Demand profile peak (kW)	1,350	1,410	1,496	1,587

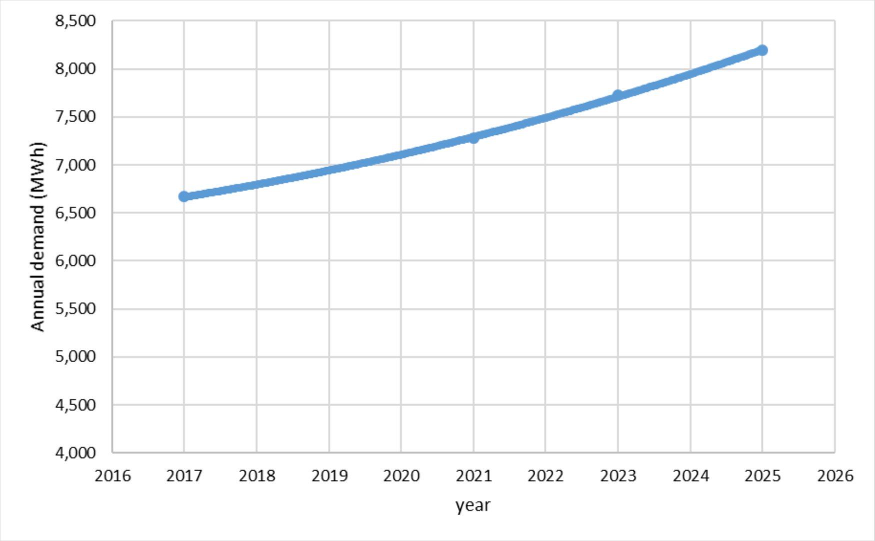

Figure 3.6: Funafuti demand requirements to 2025

4. Isolated power systems: pathway to 100% renewable

This chapter presents a typical pathway for an isolated power system on a journey to achieving 100% annual renewable energy contribution to give the reader context of the path for TEC and the government of Tuvalu, and discusses the qualities various technologies provide for successful integration of increasing amounts of renewable energy. Technical challenges are minor for the smaller outer Islands to reach 100% RE as the power systems are simpler and easier to manage for the given system sizes. For larger power systems similar to Funafuti, the pathway becomes more complex, as detailed below within this section.

The amount of renewable energy in a power system is referred to by two different terms: contribution and penetration. Renewable energy *Contribution* refers to the portion of load over a *period of time* that is met by renewable energy. For example a 65% renewable energy contribution would mean that over a year an average 65% of the system energy use is met by renewable energy. Renewable energy *Penetration* refers to the portion of load met by renewable energy at a *single point in time*.

Isolated power systems are built to supply the needs of communities or industries which are located far from the modern, interconnected, large-scale power systems. They are typically found in island communities, remote off-grid communities and industry (mine) sites, and in most cases, consist of a single central power station and a radial distribution network.

In isolated power systems, diesel generators have often been utilised as they have provided all the requirements for a reliable power supply. The use of diesel generators was scalable for a range of loads, had a low upfront capital cost, and was very attractive in the past when the price of diesel fuel was relatively low.

Over the last 15 years, the cost of diesel fuel has increased, and with it, operational costs of isolated power systems. This has also focussed remote communities on their dependence of imported energy and provoked a desire to be self-reliant through the use of renewable energy. At the same time, the availability of solar and wind energy has increased, with significant reductions in the capital cost of solar and wind energy, particularly in the last few years. There has also been a greater awareness of the impact on the world as a result from the pollution from the combustion of diesel fuels.

This has provided the basis for an uptake of renewable energy in many isolated grids, so that they become hybrid power supplies with a mixture of diesel and renewable energy. In the last decade, a number of isolated power systems around the world were transformed to various levels of renewable energy penetration. The experience from building and operating hybrid diesel renewable systems has shown that the price of electricity can be decreased using renewable energy. It has also shown however, that renewable systems if not managed correctly can have a negative effect on the stability of a power system, and could decrease the reliability of power supply, without the assistance from other technologies.

The purpose of a hybrid power system is the same as for any diesel-only system; provision of reliable power to a remote community. This needs to be done not only considering the amount of power provided but the quality of the power or system reliability. In technical terms, for the system to be reliable, **all** of the seven basic power system regulation requirements must be met. The requirements are technical and are outlined in the following list:

1. Regulation of voltage within a certain narrow band, such as 240V, ±5%,
2. Regulation of frequency around 50Hz, ±0.5Hz,
3. Provision of sufficient amount of real (kW) power,
4. Provision of sufficient amount of reactive (kVAR) power,
5. Limiting the excursions of frequency through provision of system inertia,
6. Maintaining the system stability through provision of fault currents, and
7. Provision of a sufficient amount of spinning reserve.

While renewable energy can provide cheaper real (kW) power, it may not provide all of the other six basic system reliability requirements if too much is included. This is the core issue with the implementation of renewable energy sources into isolated grids.

The solution of having reliable hybrid systems lies in the careful **integration** of renewable energy into existing isolated power systems. Higher levels of renewable energy in the power system require new system components which would smooth the output of renewable energy and maintain power system stability. These technologies are called **enabling technologies**.

Isolated power systems which embark on a journey from diesel-only to 100% renewable systems typically transition through four different stages:

- Diesel-only isolated power systems
- Low renewable energy contribution systems (1% - 30%)
- Medium renewable energy contribution systems (25% - 60%)
- High renewable energy contribution systems (50%+)

With each stage, more renewable energy is installed into the system, and more enabling technologies are added. The overlap of RE penetration occurs due to local factors depending on the load profile, available RE resource and the enabling technologies in use.

For a system to achieve a high annual renewable energy contribution it must be able to operate reliably for sustained periods at high renewable energy penetration.

This remainder of this chapter provides a description of the operation of each of the types of isolated power systems, a description of the generation technologies and what they provide to the power system, and a description of the enabling technologies and how they assist the power system. The technologies are presented at the lower penetration system that they can be utilised.

Hydro Tasmania has taken two of its island power systems, King Island and Flinders, through the entire range of renewable energy penetration from low to high, including the ability to achieve 100% renewable energy penetration.

Typically 100% renewable energy penetration has been readily achievable for small systems under around 300kW through hybrid battery/solar/diesel systems for some time, however once systems are near of above the MW range then speed of control becomes more critical and provision of fault current for extended distribution networks becomes more of a challenge.

4.1 Diesel-only isolated power systems

Diesel-only isolated power systems derive all of their energy from diesel fuel, and are the most used generator in isolated power system across the globe.

Some diesel-only power systems can be more efficient than others. With proper maintenance, and effective, precise operation of diesel generators, significant operational costs can be avoided.

Traditionally, isolated power systems had chosen two ways of achieving cost-effective diesel-only systems:

- by operating machines in the region of their maximum efficiency, preferably by using automatic operation and generator scheduling, or
- by using more efficient diesel generators, such as medium or low speed diesel engines.

4.1.1 Diesel generators

Diesel generators are a well proven technology over 100 years old and are capable of delivering all 7 of the requirements of the power system listed previously in this section. They are relatively cheap to buy and install, require little maintenance, have a life of up to 100,000 hours, have a small footprint and historically have had low operating costs.

Diesel generators also have the following operational characteristics:

- They can operate in the region of 30-100% of their nameplate capacity (preferably around 90%),
- Cold start-up of 10 minutes and 1 minute warm start-up times, and
- Are able to respond to variable load by raising the output from 30% to 100% within seconds.

In addition, they are capable of supporting the power system by responding to all seven basic power system requirements:

Table 4-1: Diesel generator power system capabilities

1.	**Voltage Control**	√
2.	**Frequency control**	√
3.	**Real (kW) power**	√
4.	**Reactive (kVAR) power**	√
5.	**Inertia**	√
6.	**Fault currents**	√
7.	**Spinning reserve**	√

4.2 Low renewable energy penetration systems

Low renewable energy penetration systems require small amount of renewable energy, little or no enabling technologies and are not an integration challenge.

Low renewable penetration systems are the first step in the integration of renewable energy on the pathway to 100% annual renewable energy contribution. A small amount of renewable energy is introduced into the system to offset some of the energy provided by diesel generators, at a lower cost than the diesel generation.

An example of operation of such a system is presented in Figure 4-1. A diesel generator, which used to constantly supply 100% of a power system load, is for a short time, partially replaced by a small amount of solar energy.

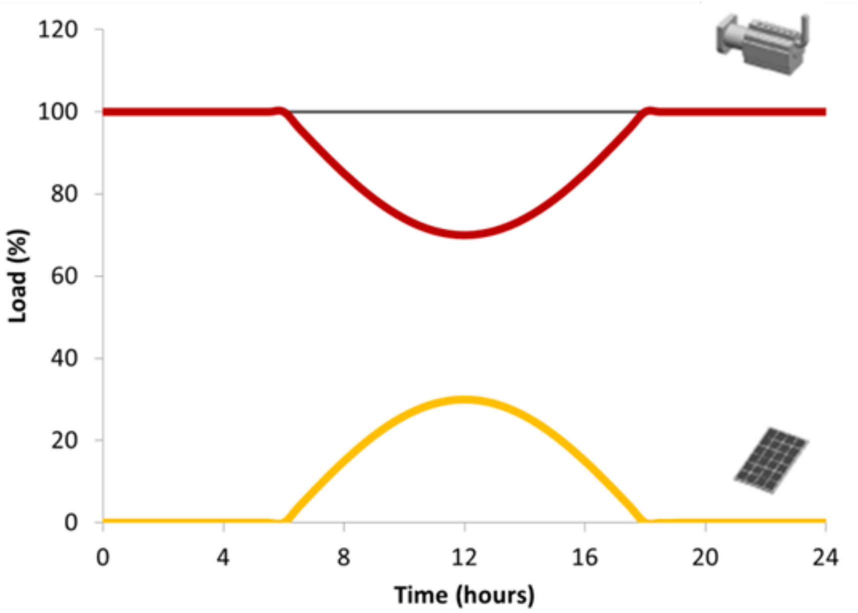

Figure 4-1: Low renewable penetration system.

Note that the output of the diesel generator is presented as a percentage of the actual load

While the amount of energy provided by a renewable source can be as high as 30%, the diesel generator sees this influx of energy as a negative load. In other words, it responds to it just like it would respond to a smaller power system load. Since the influence of solar panels in this case is limited, no direct control of renewable resource is necessary.

The positive aspect of having a small amount of renewable energy in the system is that all renewable energy produced can be safely absorbed by the system. This small amount usually does not produce any negative effects, as diesel generators are still providing all of the seven basic power system requirements.

4.2.1 Solar photovoltaic (PV)

Solar PV panels are a maturing technology. While solar PV panels are well established, with over 50 years of world-wide operation, their control and more precisely, solar PV inverters are still developing.

The benefit of solar PV is that it is relatively quick and easy to install, almost maintenance-free, is abundant throughout the world, and the energy input is free. In the Pacific region, solar energy is the prime source of locally available energy.

Solar PV performance over the basic seven power system requirements is given in Table 4-2:

Table 4-2: Solar PV system capabilities

1.	**Voltage Control**	√
2.	**Frequency control**	X
3.	**Real (kW) power**	√
4.	**Reactive (kVAR) power**	√
5.	**Inertia**	X
6.	**Fault currents**	X
7.	**Spinning reserve**	√

Solar PV panels are used from low renewable to high renewable penetration systems.

4.2.2 Wind power

Wind turbines are the most used renewable energy technology across the world (excluding hydro power). Where the wind resource is good, they can be the most economical renewable energy resource.

One of the main benefits of the wind resource is that is a natural complement for solar energy as the wind resource is available during the night and cloudy periods.

Wind turbines require more effort to install than solar PV and they can have a higher noise and visual amenity impact, but use less land area than solar PV. They have higher maintenance requirements than solar PV, but less than diesel generators.

There are a wide variety of wind turbine manufacturers and models that utilise differing technologies that offer differing levels of assistance to the power system. The most common wind turbine in use through the Pacific is designed to withstand the cyclones prevalent in the region using tilt-up technology that allows it to be lowered prior to the storm arriving.

Wind turbines performance over the basic seven power system requirements is given in Table 4-3 (although some WTGs are capable of providing some of these features):

Table 4-3: Wind turbine generator capabilities

1.	**Voltage Control**	√
2.	**Frequency control**	X
3.	**Real (kW) power**	√
4.	**Reactive (kVAR) power**	√
5.	**Inertia**	X
6.	**Fault currents**	X
7.	**Spinning reserve**	X

Wind turbines are used from low renewable to high renewable penetration systems.

4.3 Medium renewable energy penetration power systems

Medium renewable energy penetration power systems require renewable energy greater than the peak load, enabling technologies and pose an integration challenge.

In medium penetration systems, the renewable resource is large enough to supply most of the power system load during short periods of time, and often in excess of the peak load. Diesel generators are operating in the system however they are reduced to a smaller percentage of the load. Funafuti will be an example of this once the World Bank Project is implemented.

When the amount of renewable energy in an isolated power system becomes significant, if not controlled, it can cause major system reliability issues. In Figure 4-2, the solar generation becomes larger than the peak load of the power system. As a consequence, the diesel generation tends to zero or negative loading, when the solar generation exceeds the load. During this scenario, the system may become unstable and a blackout of the system may occur as the solar generation cannot provide the power system requirements.

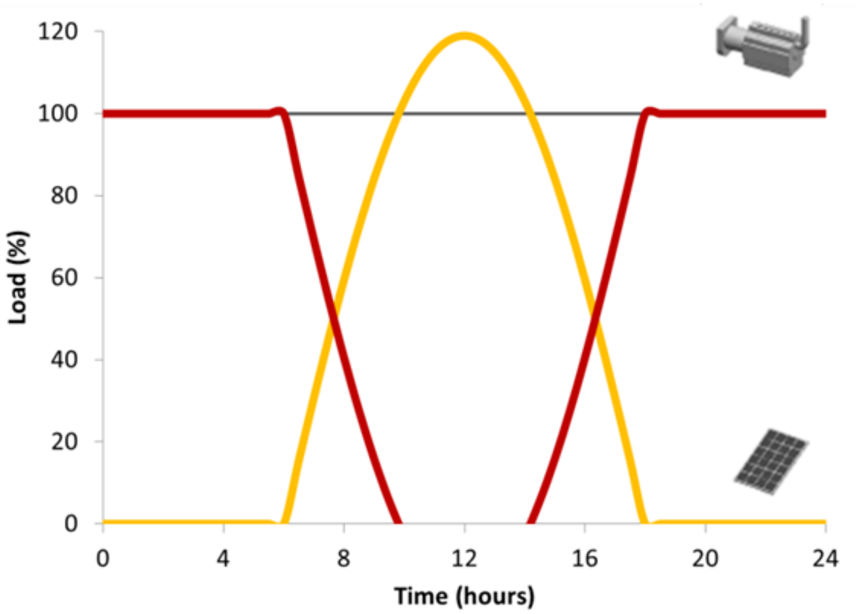

Figure 4-2: Medium renewable penetration system

Size of the renewable resource is large enough to cause power system reliability issues.

The first solution to this problem is to dynamically control the output of the solar PV generation. By limiting the output of the renewable resource, as shown in Figure 4-3, the diesel generator remains in operation at their minimal loading of 30%. This approach causes large amount of available renewable energy to be curtailed (or spilled). By curtailing the renewable energy and allowing diesel generators to operate in the system at reduced loading, it allows the diesel generator to provide all of the basic power system requirements and prevents issues in the power system.

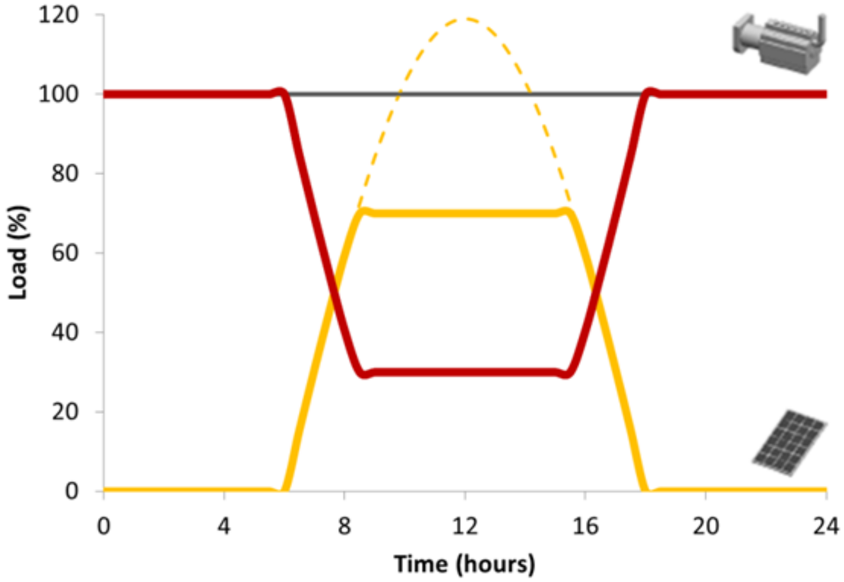

Figure 4-3: Medium renewable penetration system.

By using an integration and control system, output of the renewable resource is severely limited.

However, the purpose of installing renewable energy generation is to generate as much cheaper and cleaner energy as possible. Curtailment of the renewable energy generation is a valid technical solution, but may not represent the most economic outcome and in such cases is an undesirable situation.

The next option towards integrating a higher amount of renewable energy into a power system is the introduction of an appropriate enabling technology. Figure 4-4 shows the addition of a battery to a medium renewable penetration system. Instead of curtailment, excess energy is stored in a battery. Whilst not increasing the instantaneous penetration this in effect is artificially increasing the load of the power system, and allowing all renewable energy to be utilised over time.

A dynamic resistor performs a similar role, however, the renewable energy sent to the resistor is spilled rather than stored for later use. This is still preferable to straight curtailment as it allows the diesel generator to operate at minimum load for longer periods for no risk of reverse power events. A dynamic resistor can also represent a significantly cheaper alternative to energy storage depending on the situation.

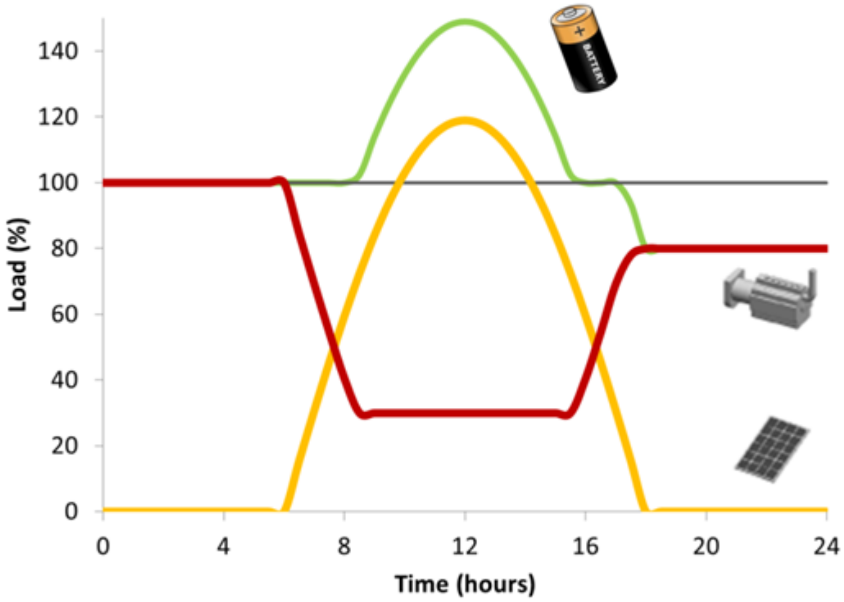

Figure 4-4: Medium renewable penetration system

By adding an enabling technology, utilisation of the renewable resource is increased.

Enabling technologies such as batteries do not directly contribute to decreasing the cost of energy, but indirectly, through an increased utilisation of the available renewable energy generation, and by reducing diesel generation towards a minimum.

4.3.1 Integration and control system

Medium renewable energy penetration systems are a complex type of isolated power systems. Even if the instantaneous renewable energy penetration is not too high, it needs to be controlled on a constant basis because the renewable energy generation can vary rapidly.

Benefits of an integration and control system lie in the operational cost reduction through accurate control, better insight into the operation and condition of the equipment, timely warning and alarm recognition, and in improved reliability performance.

Medium and high renewable energy penetration systems are very dynamic compared to diesel-only and low renewable penetration systems. Dynamics of these systems need to be controlled on a millisecond basis throughout the year, which poses an impossible task for a manual operator approach. Therefore, an integration and control system is a crucial component in medium and high renewable energy penetration systems.

Through use of forecasting systems for renewable generation, advanced hybrid control systems can calculate variability indexes to prioritise different types of generation to manage system load balance, effectively enabling provision of spinning reserve from renewable generation sources and ensuring system security.

Figure 4-5 symbolically shows an integration and control systems as a heart of an advanced hybrid power system. Information is being collected from all power system elements, processed, and commands are sent back in a matter of milliseconds.

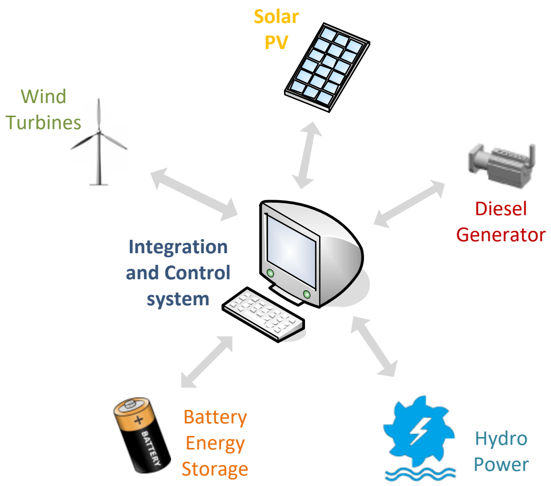

Figure 4-5: Integration and control system is an essential component for medium and high renewable penetration isolated power systems

4.3.2 Battery energy storage systems

Battery energy storage systems (BESS) are used in isolated power systems for the provision of short term power support or long term energy shifting.

Short term power system support is necessary for smoothing an output of a renewable resource, for provision of power through short fluctuations in renewable energy generation that may prevent a diesel generator responding, or to allow sufficient time for a diesel generator to be started and connected into the system (can take up to 10 minutes). BESS solutions for short term storage consist of a larger inverter and can store enough energy for a shorter period of time (less than 1 hour).

Long term energy shifting is a large BESS solution which accumulates energy during an abundance of renewable resource (such as solar PV during the day) and discharges it during renewable energy deficiency (such as for solar PV overnight). It usually consists of a similar inverter to short term storage, but it has significantly larger capacity to store energy. Without any other energy storages in the power system, a large BESS is necessary for achieving prolonged periods of 100% renewable energy operation.

BESS is still a maturing technology. Various types of technologies for batteries used in power systems exist on the market today. While individual technologies offer different advantages, the part that is most important for power system regulation is the battery inverter. Similar to inverters for Solar PV, battery inverter technology is still in the development phase and their capabilities are improving all the time, and their costs are reducing as their production increases.

BESS performance for the seven power system requirements is shown below:

Table 4-4: BESS capabilities

1.	**Voltage Control**	√
2.	**Frequency control**	√
3.	**Real (kW) power**	√
4.	**Reactive (kVAR) power**	√
5.	**Inertia**	√[6]
6.	**Fault currents**	√[7]
7.	**Spinning reserve**	√

Battery energy storage technologies can be used in medium and high renewable penetration systems to increase annual renewable energy contribution.

While a BESS has better performance than solar PV technologies, it cannot necessarily solely be relied upon to drive the entire isolated power system (depends significantly on scale and characteristics of power system and particular BESS control system capabilities). BESS capabilities are rapidly developing in this area and in some instances can negate the need for other enablers, particularly where they have grid forming capabilities, fault ride through capabilities and are combined with an advanced hybrid control system.

4.3.3 Simple dump resistive banks

Resistive banks are a technology which is used to quickly dissipate surplus renewable energy in an isolated medium or high renewable energy penetration power system. Resistive banks have the capability of dumping the load quicker than any generator can accept it, making them the perfect provider of 'spinning reserve', or spare energy in the system which can respond quickly to load or generation changes in an isolated power system. Resistive banks are an important enabling technology in medium to high renewable penetration systems.

[6] BESS systems can provide 'synthetic' inertia, with recent developments and performance demonstrating that they can drive increasingly large systems.

[7] BESS systems can provide fault current at lower levels relative to continuous load than a synchronous generator, through careful management of protection systems and adequate equipment sizing. This can be complemented through the use of a synchronous condenser to address reactive power needs, increase short-circuit strength and thus system inertia.

Resistive banks performance over the basic seven power system requirements is:

1.	Voltage Control	X
2.	Frequency control	X
3.	Real (kW) power	X
4.	Reactive (kVAR) power	X
5.	Inertia	X
6.	Fault currents	X
7.	Spinning reserve	√

Resistive banks can be used in medium and high renewable energy penetration power systems.

4.3.4 High renewable energy penetration power systems

High renewable energy penetration power systems require a very large amount of renewable sources, a number of enabling technologies and have multiple integration challenges.

In high renewable penetration power systems, there is enough renewable capacity which can, with support from enabling technologies, provide all the power needed by an isolated power system for prolonged periods of time, leading to a higher annual renewable energy contribution. During these times, diesel generators are switched off. This is known as zero diesel operation (ZDO).

An example of a high renewable energy system is presented in Figure 4-6. There is an abundance of renewable energy fluctuating with time (green line). The presence of enabling technologies enables the diesel generators (red line) to be switched off for periods of time, with the enabling technologies meeting the power system requirements and enabling the load to be met at each time step. Depending on the size of the system, the amount of renewable capacity, and the enabling technologies utilised, this state can last from hours to days.

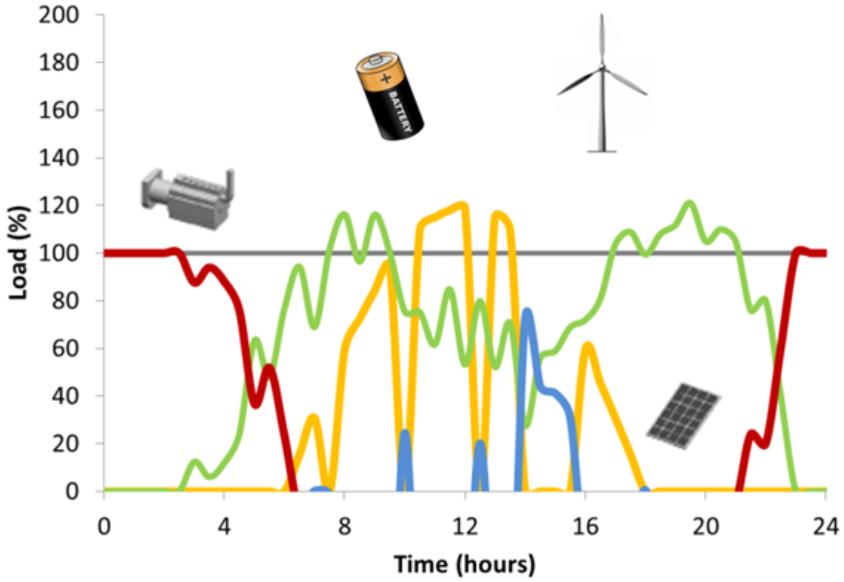

Figure 4-6: High renewable energy penetration system.

In this example, a number of technologies complement each other to replace the functionality of a diesel generator.

High renewable penetration systems are capable of achieving a very high reduction of diesel fuel use. At the same time, all of those technologies working together require a very sophisticated integration system to precisely control their operation.

4.3.5 Dynamic resistor

A dynamic resistor is a special type of resistive load used to control the system frequency, in addition to 'burning' a surplus of energy like the simple dump resistor. In high renewable penetration power systems where the diesel generator is switched off, and a battery cannot control the frequency, a dynamic resistor can perform this service.

Similar to normal resistive banks, dynamic resistors are capable of providing spinning reserve in an isolated power system.

Dynamic resistor performance over the basic seven power system requirements is presented in Table 4-5.

Table 4-5: Dynamic resistor power system capabilities

1.	**Voltage Control**	X
2.	**Frequency control**	√
3.	**Real (kW) power**	X
4.	**Reactive (kVAR) power**	X
5.	**Inertia**	X
6.	**Fault currents**	X
7.	**Spinning reserve**	√

A dynamic resistor is normally used in high renewable energy penetration power systems, but can be used in lower penetration systems as an intermediate step to a high penetration system.

4.3.6 Synchronous condensers and Diesel Uninterruptable Power Supply

Synchronous Condensers (SC) are used to provide support to power systems. They are an old technology used to regulate parts of conventional interconnected power systems, or to complement large wind farms. In isolated power systems, they are used on a smaller scale.

Synchronous condensers are synchronous machines without the prime mover (diesel engine). While operating, they offer all the benefits of the synchronous machines and provide reactive power, voltage support, inertia, and fault currents without burning the diesel fuel.

Coupled with a diesel generator via a clutch, they make an excellent isolated power system support enabling technology called a D-UPS (Diesel Uninterruptible Power Supply) and can be necessary at times in large scale high renewable penetration systems with zero diesel operation.

Synchronous Condenser (SC) performance over the basic seven power system requirements is:

1.	**Voltage Control**	√
2.	**Frequency control**	X
3.	**Real (kW) power**	X
4.	**Reactive (kVAR) power**	√
5.	**Inertia**	√
6.	**Fault currents**	√
7.	**Spinning reserve**	X

Synchronous condensers are normally used in larger high renewable penetration power systems (of a scale equivalent to Funafuti). However recent improvements in the performance, control, integration and cost reductions for BESS is seeing a shift away from expensive Synchronous Condenser solutions. Often, requirements are driven by a need for a specific level of fault current to ensure adequate operation and discrimination is maintained in the distribution protection systems and this can be determined by a protection co-ordination study.

4.4 Summary - Building a high renewable penetration isolated power system

While renewable energy sources can potentially provide cheaper and cleaner energy alternatives to diesel generation from locally available resources, they alone cannot provide all the power system needs. Hence, enabling technologies, power system integration and control systems are the key to building high renewable penetration power systems. Figure 4-7 provides a graphical explanation of this statement.

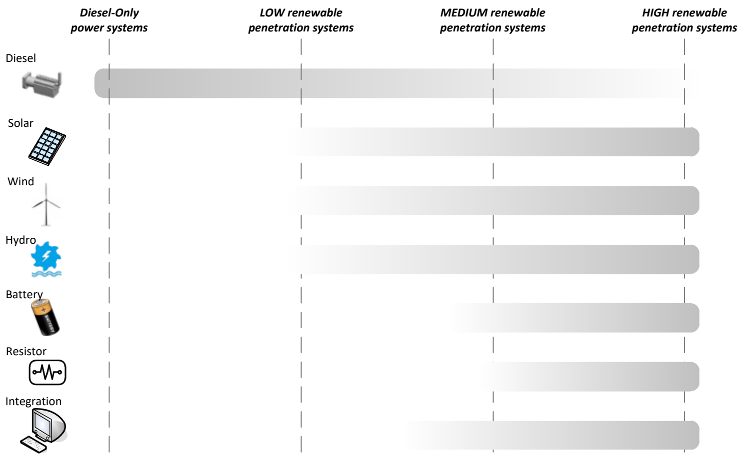

Figure 4-7: Overview of renewable and enabling technologies used in renewable systems.

Table 4-6 shows the comparison between technologies in diesel-only and high renewable penetration systems, and presents a blueprint for building a high renewable energy penetration system. The ability of a power system to achieve high renewable energy penetration with high levels of reliability and system security is critical to achieving a high annual renewable energy contribution.

Table 4-6: Diesel generator only power system v high RE power system

	Diesel-only power systems	High renewable penetration systems
1. Voltage Control	Diesel generator	SC, Battery, Solar PV, Wind
2. Frequency control	Diesel generator	Dynamic resistor, Battery
3. Real (kW) power	Diesel generator	Solar PV, Wind, Battery
4. Reactive (kVAR) power	Diesel generator	Solar PV, Wind, Battery, SC
5. Inertia	Diesel generator	SC, Battery
6. Fault currents	Diesel generator	SC, Battery
7. Spinning reserve	Diesel generator	Battery, Dynamic resistor, Solar PV, Wind

5. Funafuti modelling

Section 4 details the typical pathway towards 100% renewable energy contribution for a power system such as that operated by TEC in Funafuti and is the basis of the approach used to formulate the Funafuti Road Map presented in this report.

As renewable energy generation is increased within the Funafuti power system, the existing diesel units will be progressively turned off, and the period they are turned off for will be gradually extended until the system reaches a point where it can operate without any diesel generation. In order to do this, enabling technologies are required to be added to the system to provide the functions that were previously provided by the diesel generators to support the normal operation of the Funafuti electricity grid.

This requires careful management of the stages of development to ensure adequate system control, and that enabling technologies are installed when required for the system to remain stable, reliable and secure.

This section details the modelling used to develop the Funafuti Road Map, including the inputs and assumptions.

5.1 Available renewable energy in Funafuti

5.1.1 Available land

The biggest challenge for increasing the amount of renewable energy in Funafuti is the lack of available land to install solar PV, wind power or other forms of renewable energy. With the total land area small, and the population increasing, any available land needs to be used to deliver the maximum benefit for Tuvalu.

During the course of investigations undertaken few land areas were identified with sufficient space for the implementation of a single large solar generation site.

The lack of available land for typical ground mount solar arrays makes more expensive alternatives worthy of consideration including; floating solar, raised fixed framing structures and roof structural/material upgrades to enable roof top solar on older buildings. These options are examined in subsequent sections of this report.

5.1.2 Solar resource

The solar resource is critical to the performance of the proposed solar PV plants. S*olar resource* is a general term referring to the irradiance falling on a unit area over a given period. The solar resource varies between locations on the Earth's surface owing to differences in latitude and any local climate effects (i.e. cloud cover, dust, humidity etc.).

Solar PV cells use incident irradiance within a particular wavelength spectrum to create and maintain a DC voltage under load. Solar resource assessment quantifies the available incident irradiance.

Data relating to the average irradiance falling on a horizontal plane (*global horizontal irradiance*, or *GHI*) over the course of a typical year is sufficient for conducting yield forecasts to a reasonable degree of accuracy. Yield forecasting is necessary to assess PV projects and size PV arrays.

For fixed tilt solar PV arrays, irradiance striking the plane of the array can be increased above GHI by tilting the array towards the equator, such that the average angle of incidence on the panel is 90°. In the Southern hemisphere, this is because the sun is primarily in the Northern sky, rather than overhead, and vice versa in the Northern hemisphere. Mathematical methods are used to estimate the in-plane irradiance when only horizontal irradiance data is available.

Long-term solar data from ground-based monitoring installed at the proposed site are most desirable for yield forecasting. However, this is not available for Funafuti.

Estimates of global horizontal irradiance (GHI) derived from satellite imagery are more widely available but less accurate.

5.1.2.1 Meteonorm Data 7.1

A common source of GHI data is Meteonorm. Meteonorm collects satellite data imagery from 5 geostationary satellites and calibrates this data with measurements from ~1,700 ground-based weather stations. Data resolution is 1/8°, and therefore superior to NASA-SSE. In the Pacific, if the distance to the nearest ground-based weather station is less than 30km, then data from this weather station is used. Between 30-200km from the nearest weather station, satellite and ground-based data is blended from 0% satellite at 30km, up to 100% at 200km. For 200+km, data is 100% satellite. In Tuvalu, all data is satellite data, as the nearest Meteonorm weather station is in Fiji.

A summary of the solar resource (Global Horizontal Irradiance (GHI) and Diffuse Irradiance) and climate data (temperature and wind speed) for Funafuti is provided as follows:

Table 5.1: Solar resource and climate data for Funafuti from Meteonorm 7.1 (2010-2014)

Interval beginning	GHI (kWh/m^2.mth)	DHI (kWh/m^2.mth)	Ambient temperature (°C)	Wind Speed (m/s)
January	139.8	79.1	28.63	3.2
February	131.2	84.1	28.65	3
March	151.4	83.3	28.64	2.2
April	167.8	69.9	28.58	2.5
May	137.4	73	28.91	2
June	131.6	58	28.26	3.19
July	137.7	69.2	28.54	3.3
August	140.4	69.8	28.46	3.5
September	149.8	77.8	28.49	3.5
October	160.2	88	28.79	2.8
November	149.6	81.7	28.46	2.49
December	171.8	82	28.86	2.59
Year	1768.7	915.9	28.61	2.86

Source: Meteonorm 7.1

- Global Horizontal Irradiance (GHI) - The total energy from the sun striking a horizontal surface over the specified period
- Diffuse Horizontal Irradiance (DHI) - The energy from the sun, excluding that from the direction of the sun, striking a horizontal surface over the specified period
- Temperature - Ambient dry bulb air temperature averaged over the specified period
- Wind Speed – wind velocity in meters per second at ground level.

Meteonorm estimates the uncertainty of Meteonorm 7.1 data as 2-10%. In light of the remoteness of Tuvalu, the uncertainty that applies to the data above would be at the high end of this scale.

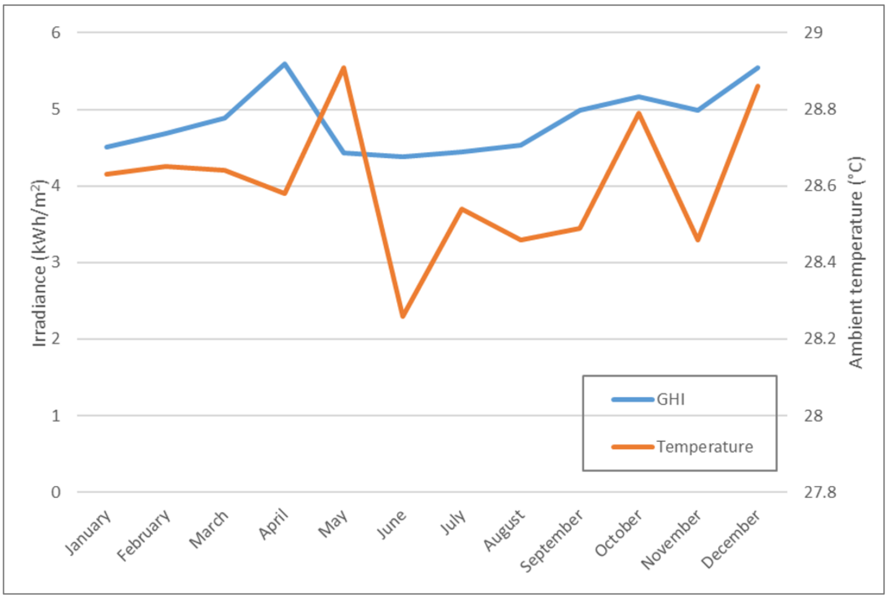

Figure 5.1: Monthly variation in irradiation

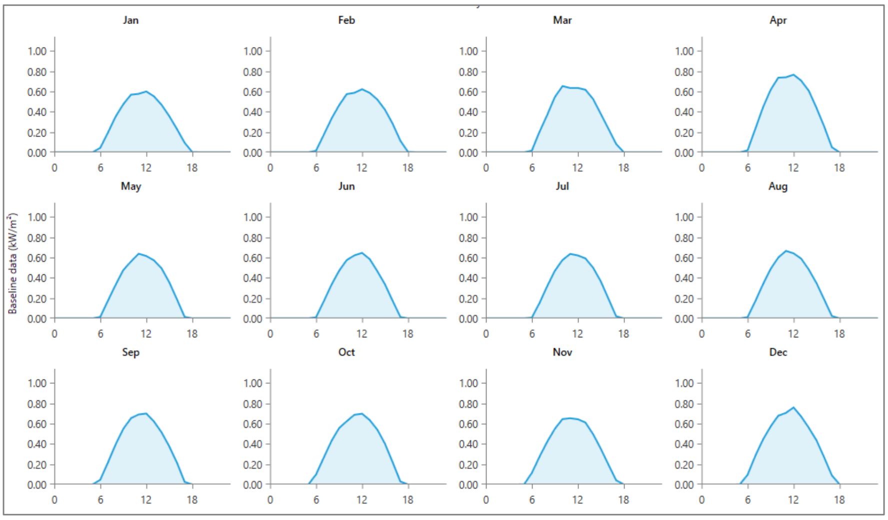

Figure 5.2: Monthly average daily GHI profiles

5.1.3 Wind resource

A 29 m wind monitoring mast was installed on Funafuti in May 2007 and collected measurements at heights of 20 m and 29.2 m until March 2010 – a period of 2.6 years. The mast was located at the rear of the TEC compound on the coastal side. Two reports have been prepared assessing the wind potential of Funafuti based on these measurements – Ecology Management ApS Randers [11] in 2010 and GL Garrad Hassan in 2013 [16].

The GL GH report identified a number of issues with the potential quality of the wind data recorded, including potential shielding from trees and buildings, lack of information on the mast setup, maintenance, instrument calibration and mounting. Further, the instruments were possibly part of a batch subject to Dry Friction Whip (a manufacturing issue) that causes instruments to read artificially lower speeds. Thus, they consider the data to have a high uncertainty.

The report by Ecology Management ApS Randers using only the mast data estimated the average annual wind speed to be 5.79 m/s at 29.2 meters above ground level (as shown in Table 5.2). GL Garrad Hassan performed correlations with long-term records and estimated the long term average wind speed at 29 m to be 5.4 m/s. For various hub heights of 15 m, 30 m and 55 m (corresponding to three different wind turbines considered) they estimated long term average wind speeds of 5.1 m/s, 5.4 m/s and 5.7 m/s respectively.

Both reports concluded the prevailing wind direction was east or east-south-east.

Table 5.2: Funafuti monthly average wind speeds from the Ecology Management ApS Randers report

Interval	Wind Speed (m/s) @ 29.2 meters high	Wind Speed (m/s) @ 20.0 meters high
January	5.41	4.68
February	5.9	5.03
March	5.33	4.61
April	5.42	4.70
May	4.36	3.89
June	6.47	5.83
July	6.65	6.01
August	6.87	6.27
September	6.23	5.59
October	5.3	4.76
November	5.75	5.15
December	4.91	4.31
Year	**5.79**	**5.14**

GL Garrad Hassan also calculated the air density for Funafuti from measurements at the Airport and concluded it to be 1.149 kg/m^3, 1.147 kg/m^3 and 1.144 kg/m^3 at heights of 15 m, 30 m and 55 m.

Both reports considered the potential for adding wind power to Funafuti, and identified a number of potential issues or considerations that would need to be overcome. These are discussed in Section 7.3.

5.1.4 Biofuels

Biofuels may present a clean and cheap contribution to the energy mix in Tuvalu, either complementing traditional fuel or as a replacement. Several biofuel sources are commonly used however for Tuvalu the local resource availability would be the determining factor.

5.1.4.1 Coconut Oil Biofuel

Coconut oil has been widely used as a biofuel in equatorial areas as it is often available locally, can be produced with relative ease, has low raw material costs and is more environmentally sustainable.

For diesel engines there are three main applications:

- an additive to petroleum diesel
- the primary biodiesel ingredient
- a full petroleum diesel substitute.

To use in engines in its raw form requires either engine fuel system adaptions or usage at low blend ratios. Production of biodiesel requires a chemical facility and addition of methanol, with associated cost.

Tuvalu does not have a substantial local Copra (coconut meat) oil industry at present and the extent of available resources is unclear. While it is estimated that the coconut supply on Funafuti would be low due to available land area, other islands in Tuvalu with larger areas of available land and established trees may have the capacity to provide a useful resource. Cost per coconut and extraction labour costs specific to Tuvalu have not been examined in detail in this study.

While the substitution of diesel by coconut oil could reduce fuel costs and diversify fuel sources, significant investment in mechanical extraction plants would likely be required to make this viable in comparison to alternative options.

Coconut Oil Biofuel Benefits and challenges:

- Decrease in gas emissions and particulate matter
- A renewable fuel resource
- Potential for creation of a local industry
- Reduced reliance on foreign fuel imports and price volatility
- High initial infrastructure costs for fuel system adaptions, chemical processing and mechanical extraction
- Can be cheaper than petroleum diesel, subject to price variations

Reference’s regarding Coconut Oil production and feasibility include:

- 2014 PPA Annual Conference paper: Coconut Oil Biofuel – Clean and Competitive, by Jan Cloin, SOPAC, Published at: http://prdrse4all.spc.int/system/files/ppa_annual_conference_paper_-_coconut_oil_biofuel-_clean_aoeukh.pdf
- Engineers Without Borders Australia , Post and discussions published at https://www.ewb.org.au/resources/52/950
- Biodiesel from Coconut Oil, Md A. Hossain Et Al, World Academy of Science, 2012. Published at: https://waset.org/publications/2808/biodiesel-from-coconut-oil-a-renewable-alternative-fuel-for-diesel-engine

5.1.4.2 Biogas

Pig waste conversion to biogas can be utilised to produce significant amounts of electricity. Initial capital costs are high for automated systems, however if undertaken in conjunction with initial development of industrialised pig farming facilities the costs may be offset.

The waste to energy process for a piggery is summarised as:

1. Automated waste collection
2. Texture processing
3. Anaerobic digestion
4. Gas purification
5. Electricity generation

A specific site feasibility study would be required to determine the viability of such a project on Funafuti or elsewhere in Tuvalu.

A useful recent example as reference is the Berrybank Farm Energy Recovery project:

- Supported by the Victorian Government, 2017, Posts and discussions published at https://www.energy.vic.gov.au/renewable-energy/bioenergy/turning-piggery-waste-into-electricity

5.1.4.3 Waste to energy

Waste to energy plants take household, industrial and vegetation materials and convert them to energy through controlled incineration processes. An assessment of the amount, type and value of the waste material on Funafuti would be required before such a project could proceed.

Waste to energy benefits and challenges:

- Reduced landfill, and subsequent landfill space requirements.
- Depending on content of waste can count towards renewable energy generation
- An opportunity to reduce diesel generation
- Use of waste oil in fuel mix (offsetting waste oil disposal costs)
- Emission of poisonous and toxic gases
- Biomaterials may otherwise be composted
- Available waste resource quantities or composition may be insufficient for viability
- Social/political acceptance of burning materials for energy production

- Estimated CAPEX cost of around US$ 5/W is higher than solar PV + BESS

Steps required to complete a pre-feasibility assessment of waste to energy system on Funafuti:

1. Obtain data from waste collection service of quantities (tonnage per day)
2. Determine content ratio's and types
3. Calculate Calorific fuel content & predicted energy production
4. Assess Financial and Economic feasibility measures
5. Complete economic feasibility comparisons to solar PV + BESS

Reference's regarding alternative resource and feasibility include:

- *Concept Design and Pro Forma for Waste-to-Energy on Pohnpei,* ADB FSM Energy Feasibility Projects, October 2018.
- Vietnam: Municipal Waste-to-Energy Project, ADB Project Datasheet, published at https://www.adb.org/projects/50371-001/main#project-pds

5.1.5 Ocean thermal energy

Ocean thermal energy conversion utilises water temperature differences between deep water and shallow water to generate electricity and desalinate water.

Tuvalu is listed as having access to the required ocean thermal resources for this technology in the ADB wave energy conversion to thermal energy report[8], however this report also suggests that conversion plants for this technology are not financially viable below 50MW. This indicates it would not be suitable for Funafuti, until smaller scales are commercially viable.

5.1.6 Wave and tidal energy

Tidal energy can be separated into three categories;

1. Tidal range – utilising the height difference between low and high tides with a barrage or dam to generate electricity (typically low head Kaplan turbine devices). These systems are well established and have been applied since the late 1960's, but require suitable sites and incur high upfront capital costs.
2. Tidal current – these are technologies that place turbine like devices in the tidal flow streams (enclosed or open, horizontal or vertical arrangements). These systems are generally still in early development, although some have been established commercially.
3. Hybrid systems – tidal range technologies incorporating other infrastructure (roadways, coastal defence infrastructure, water storage reservoirs, pumps, barges, etc.). These systems are in an early developmental and innovative stage.

An advantage of both tidal range and tidal current energy is that they are highly predictable with daily, bi-weekly, biannual and even annual cycles over a time span of a number of years.

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[8] https://www.adb.org/sites/default/files/publication/42517/wave-energy-conversion-ocean-thermal-energy.pdf

Wave energy systems are weather dependant in the short term and more challenging to predict daily outputs, although seasonal fluctuations are highly predictable. Another advantage of this technology with respect to Tuvalu is low land use, most infrastructure is underwater and land requirements are low.

Wave energy systems are broadly categorised into five types based on their mechanical characteristics:

- Absorbers,
- Attenuators,
- Oscillation water columns,
- Overtopping, and
- Inverted- Pendulum devices.

These emerging technologies mostly remain in developmental and innovative stages with little large scale commercial deployment.

Of the available wave technologies, few are considered suitable for Tuvalu. Of the suitable technologies, few are fully developed and available in the commercial market. A further barrier to ocean energy generation in Tuvalu is the high initial capital cost and ongoing maintenance requirements.

The Funafuti Lagoon entry/exit tidal channels may be suitable for tidal current systems depending on flow speeds (for existing tidal stream/current technology, the stream speed needs to be at least 1.5-2 meters per second). Detailed assessments by technology experts and site specific measurements would be required to confirm viability.

Open ocean wave resources in Tuvalu are low, typical of equatorial latitudes in the western Pacific as seen in Figure 5.3. The wave resource estimate for mean wave energy flux of 7.53 kW/m is only just above the 7 kW/m level considered by the recent SPC report [17] as worthy of further investigation. The costing range estimate for wave energy generation in Funafuti presented in the SPC report is well above the estimates provided in this road map report for solar PV + BESS. Wave energy costs are likely to have fallen since the time of the report, however the low available resource relative to other locations is still likely to make wave energy in Funafuti unattractive for the near future.

Further challenge to deployment of wave generation technologies on the outside of the atolls is the steep ocean floor drop-offs and depths, limiting opportunities for shallow depth/low cost anchoring systems. The ability to service a wave energy conversion device with locally available vessels may also be a constraint on wave energy in Tuvalu. Custom vessels are typically required for deployment and recovery.

Further information on wave and tidal technology is available in a report prepared by the International Renewable Energy Agency (IRENA) [18].

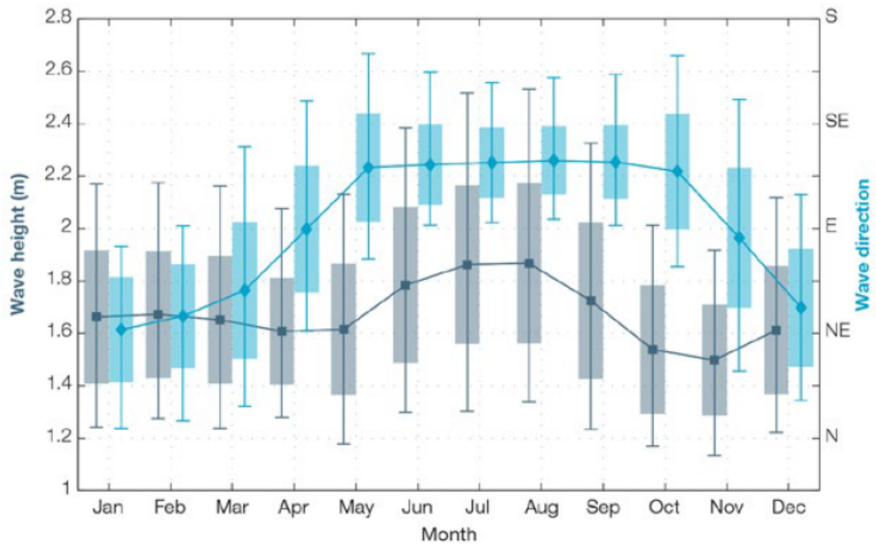

Figure 5.3: Mean annual cycle of wave height and mean wave direction for Funafuti, (image courtesy of PACCSAP Program report referenced below[9])

5.2 Modelling description and inputs

To assess the proposed additions of renewable energy (solar only in this case) and enabling technologies (such as BESS) to the Funafuti power system there are two forms of modelling required to be undertaken:

- Energy balance modelling
  - Energy balance modelling is conducted for a typical year of operation (as well as sensitivity scenarios) at a given time interval (one hour in this case).
  - At each interval, it calculates the system load, required capacity (including reserve capacity), and then schedules generation from the available installed generators to provide the required capacity.
    - For Funafuti it has been assumed that the first BESS to be installed (either World Bank project or ADB project) will be able to operate in grid forming mode and that there will be times during the daylight hours when no diesel is in operation. In this mode the BESS is providing the spinning reserve, and assumed to be capable of providing sufficient capability to maintain the quality of the power system.

[9] Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports | Chapter 15 Tuvalu, by Pacific-Australia Climate Change Science and Adaptation Planning Program, 2014. Published at: https://www.pacificclimatechangescience.org/wpcontent/uploads/2014/07/PACCSAP_CountryReports2014_WEB_140710.pdf

    - In this situation, renewable generation (solar power) is scheduled first, but if the combined output exceeds demand it may be dispatched to energy storage (if battery capacity is available) or curtailed (spilled). If the renewable energy output is insufficient to meet capacity requirements, firstly the BESS is discharged and if there remains insufficient capacity then a diesel generator is scheduled.
    - When a diesel generator is scheduled it must generate at a minimum level of its capacity (nominally 30%) which can then reduce the BESS or renewable input in that given time step.
  - The energy balance modelling produces estimates of the individual plant production, renewable energy generation, renewable energy contribution to generation, fuel consumption, and ability to meet demand under any scenario studied. It is the primary source of performance metrics for the subproject assessment.
- Power systems modelling
  - There are shortcomings in the energy balance modelling that are addressed through power systems modelling.
    - Energy balance modelling does not capture control system requirements of short term events (e.g. in the sub 1 second range) that a BESS would need to respond to in order to ensure diesel generators operate within their allowable limits, and maintain acceptable levels of voltage fluctuation.
    - Energy balance modelling only considers real power, and does not assess the generator capability to provide reactive power requirements to the grid.
    - Energy balance modelling does not model a distributed network, and does not capture issues such as local voltage rise, fault levels and equipment ratings.
    - Energy balance modelling does not capture fault events, and the ability of the network to ride through faults in generators or feeders.
  - The above issues are critical determinants of the reliability of the system. They must be addressed to demonstrate the requirement that the system offer similar or better reliability to the current situation.

5.2.1 HOMER model inputs and assumptions

Entura has undertaken energy balance modelling using HOMER Pro software[10]. The model was used to determine the optimal combinations of solar PV and BESS size to achieve the lowest overall cost and highest RE contribution in stages to achieve 100% RE contribution for Funafuti.

PVSyst[11] was used to assess PV generation system losses and establish a base line Performance Ratio. These outputs were used to calibrate the solar generation in the HOMER model.

The key inputs and assumptions used in preparing a Homer model for Funafuti are as follows:

- Demand data as per Section 0.

[10] www.homerenergy.com

[11] https://www.pvsyst.com/

- Diesel generator capacity: 3 x 600kW diesel generation at TEC with 30% minimum loading.
- The existing diesel generators are sufficient to meet forecast increases in demand assuming all existing renewable generation is maintained and replaced as needed
- Assumed project life of 25 years commencing in 2020
- Solar resource data as per Section 5.1.2
- The solar PV model included an AC-derating factor (Performance Ratio) of 82.61%
- All solar installations assumed to degrade at 1% per year, and replaced after 25 years from installation date
- Battery cells and inverters replaced at 10 years and 15 years respectively, solar inverters replaced at 15 years
- BESS allowed to operate in grid forming mode (i.e. zero diesel operation)
- Load following method of control dispatch used
- The 30% minimum diesel unit loading is typical of industry practice to avoid machine damage and maintain unit life expectancy. It should be noted that units can be run at lower levels for short periods of time, as long as loading is controlled in real time and periodically cycled through higher levels to avoid internal glazing and carbon build-up. It is possible to implement a controlled regime of low loading to maximise renewable penetration. It is noted that Opus [8] assumed levels of as low as 10% in their report, while Ricardo use 20 % in their Draft report [12].

6. Funafuti Road Map

This section sets out a plan to achieve 100% renewable energy contribution for the Funafuti power system, primarily by examining generation requirements to meet demand forecasts as set out in Section 3. The investigation of optimal sizing of generation and enabling technologies along the way to 100% renewable has been undertaken by looking at different levels of renewable energy contribution percentages that can be achieved by enabling different levels of system control and the amount of additional equipment required.

The Road Map for Funafuti to achieve 100% RE Contribution is presented in Table 6.1. To achieve a 100% renewable contribution for Funafuti by 2025 would require 7.6 MW of solar PV and 3 MW / 14 MWh of battery energy storage. Funding for the World Bank project and Stage 1 (by ADB) are assumed to be locked in. Funding for Stages 2 and 3 are unfunded and it is estimated would require cumulative capital of US$21.1m.

Table 6.1: Proposed Road Map to 100% RE Contribution for Funafuti

EXISTING							
RE % year 1	**RE % 25 year avg.**	**Cumulative PV Capacity (kWp)**	**Cumulative BESS (kW/kWh)**	**Diesel Capacity (kW)**	**Operating mode**	**Estimated CAPEX (2019 USD)**	**Estimated cumulative CAPEX (2019 USD)**
15%	12%	735	0	1800	minimum 2 diesel units running	N/A	N/A
WORLD BANK PROJECT - addition of 750 kWp solar PV and 1000 kW / 1000 kWh BESS - operational in 2021							
RE % year 1	**RE % 25 year avg.**	**Cumulative PV Capacity (kWp)**	**Cumulative BESS (kW/kWh)**	**Diesel Capacity (kW)**	**Operating mode**	**Estimated CAPEX (2019 USD)**	**Estimated cumulative CAPEX (2019 USD)**
37%	24%	1,485	1000/1000	1800	ZDO	N/A	N/A
STAGE 1 (ADB FUNDED) – addition of 500 kWp solar PV and 1000 kW / 2000 kWh BESS - operational in 2021							
RE % year 1	**RE % 25 year avg.**	**Cumulative PV Capacity (kWp)**	**Cumulative BESS (kW/kWh)**	**Diesel Capacity (kW)**	**Operating mode**	**Estimated CAPEX (2019 USD)**	**Estimated cumulative CAPEX (2019 USD)**
49%	33%	1,985	2000/3000	1800	ZDO	$3.7m	$3.7m
STAGE 2 (unfunded) – addition of 2,400 kWp of solar PV - operational in 2023							
RE % year 1	**RE % 25 year avg.**	**Cumulative PV Capacity (kWp)**	**Cumulative BESS (kW/kWh)**	**Diesel Capacity (kW)**	**Operating mode**	**Estimated CAPEX (2019 USD)**	**Estimated cumulative CAPEX (2019 USD)**
60%	52%	4,385	2000/3000	1800	ZDO	$6.0m	$9.7m
STAGE 3 (unfunded) **–** addition of 3,300 kWp of solar PV and 1000 kW / 11,000 kWh BESS - operational in 2025							
RE % year 1	**RE % 25 year avg.**	**Cumulative PV Capacity (kWp)**	**Cumulative BESS (kW/kWh)**	**Diesel Capacity (kW)**	**Operating mode**	**Estimated CAPEX (2019 USD)**	**Estimated cumulative CAPEX (2019 USD)**
~100%	86%	7,635	3000/14000	1800	negligible diesel operation	$15.1m	$24.8m

6.1 Discussion of Road Map

6.1.1 Renewable energy contribution

The Road Map details the renewable energy *contribution* for the first year of operation and for the average over a 25 year project life. Both numbers are worth considering to appreciate the effects on projects and their expectations from the known predictable effects (PV module degradation over time) and the more subtle and less certain effects; diesel fuel price, equipment replacement costs and electricity demand load growth. The 25 year average figures are based on the assumption that the subsequent road map stages do not proceed. Note that average RE% project lifetime figures are based on PV module degradation which should be mitigated by an O&M program of investment for equipment replacement at end of life.

6.1.2 Future diesel generation needs

If the Road Map were not to proceed beyond the World Bank project, with the forecast growth in demand additional diesel generation would be required in 2023 and then again in 2033. Given the short timeframe until 2023, and the current status of TEC's financial position which does not have any provision for replacement or acquisition of assets, unless a donor could be found to fund a new diesel generator, then Funafuti could potentially face shortages of supply during periods of peak load.

6.1.3 Stage scope and control system operating mode

Stage 1 of the Road Map includes significant BESS capacity. The BESS is oversized relative to the renewable energy available and thus enables the future addition of solar PV without requiring addition to the BESS. This has largely occurred due to the ADB funding available, and the land/rooftop space immediately available for the addition of solar PV in Stage 1. This will shift the renewable penetration from low to high, with short periods of 100% renewable energy penetration (known as zero diesel operation (ZDO)) and load shifting from the BESS.

Stage 2 is composed of 2,400 kWp of solar PV and is sized based on the optimum capacity of the already installed BESS as shown in Figure 6.1 at the point where the cost of energy (COE) reaches the lowest point. This will increase the renewable energy contribution and duration of high penetration, with extended periods of ZDO and longer load shifting duration.

Stage 3 includes the final additions of solar PV and BESS capacity to increase the renewable energy contribution from 60% to 100%. This will lead to negligible diesel operation and full overnight load shifting provided by the BESS.

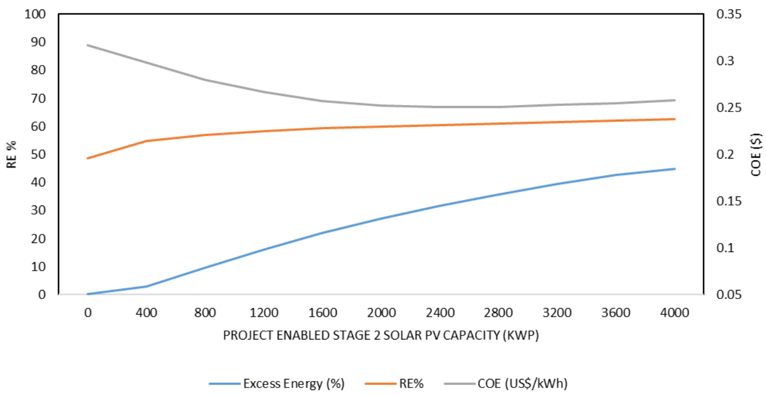

Figure 6.1: Analysis of the optimum solar PV capacity for stage 2 enabled by the World Bank and Stage 1 BESS

6.1.4 Incremental cost of getting to 100% RE contribution

As shown in Figure 6.2, as the RE contribution exceeds 98% the cost of energy becomes a lot flatter, indicating that the increase in renewable energy at this point has marginal benefit and becomes more expensive. Increasing the solar PV included in Stage 3 from 1 MW to 3.3 MW only leads to a 0.4% increase in the RE % contribution for a cost of around US$6m.

Squeezing out the last few percentage of renewable energy contribution levels using only solar PV and BESS is expensive and the cost effectiveness of a 100% renewable energy target should be examined. It may be more prudent to consider 95% renewable energy contribution as the better solution, with some overnight diesel usage from time to time. Alternatively, an overnight RE source like wind would complement the solar profile and reduce the required storage capacity. The GoT energy policy in regard to renewable energy contribution may be satisfied at around the 98% with negligible diesel use, given the increased cost per unit of energy for the final few increments towards 100%.

This has been the successful approach with the Outer Islands, and in many other island power systems through the Pacific.

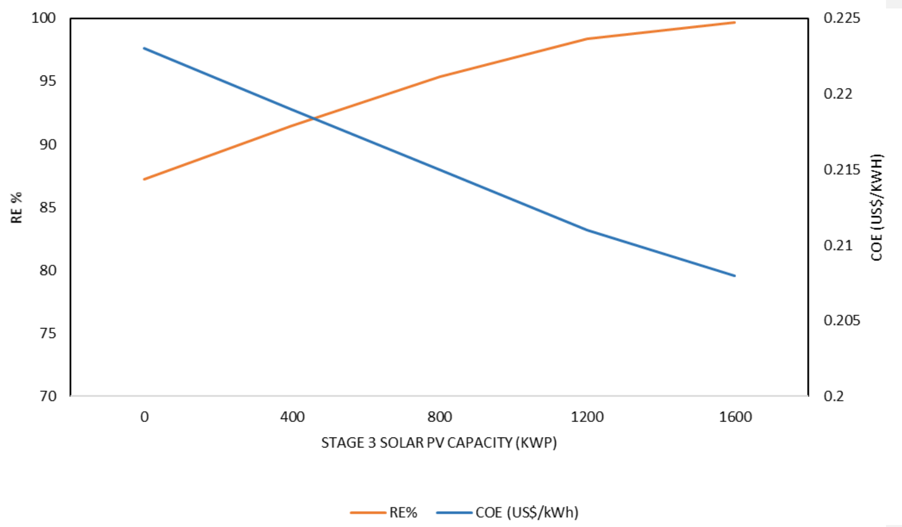

Figure 6.2: decreasing RE% change verses decreasing drop in relative cost of energy for the final shift in RE% from ≈95% to 100%.

6.1.5 Zero diesel operation

For increased levels of RE % generation there comes a point in the Road Map where instantaneous renewable *penetration* of up to 100% (periods of ZDO) is required for cost effective integration and feasibility. Once renewable generation power capacity is large enough to match the load or exceed it then having a system that allows for switching off the diesel units will reduce the need for curtailment or spilling of energy. As discussed in Section 4.3, enabling technologies and/or storage are required to enable this. Without enabling ZDO, the diesel units operate below their optimum efficiencies and also need to be kept above minimum loading to avoid damage and limit the risk of blackouts.

The existing Funafuti generation system is low to medium penetration, with solar constrained (see Figure 6.3) and spilled at a defined percentage in order to maintain minimum diesel loading and system stability, with two units online at all times as spinning reserve to cover solar generation variability.

In Table 4.4 the scenario where ZDO is anticipated to first occur is when the BESS for the World Bank project is installed. However the proposed BESS sizing does not match peak power load and its islanding capability will be limited to times of suitable demand and PV output (see Figure 6.4). ZDO should be achievable at that time for limited daytime periods. The ADB Project Stage 1 BESS storage time capacity will be utilised to extend these periods with future BESS power capacity required to reach 100% RE contribution.

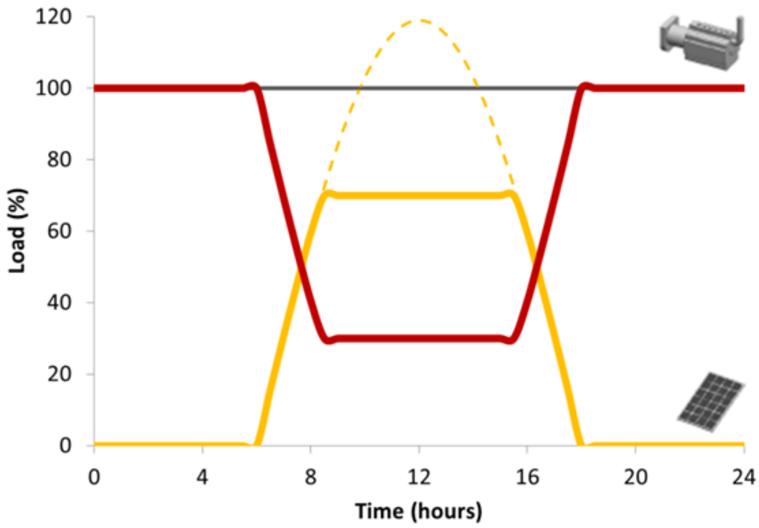

Figure 6.3: Example of existing Funafuti power system showing constraint of solar PV generation

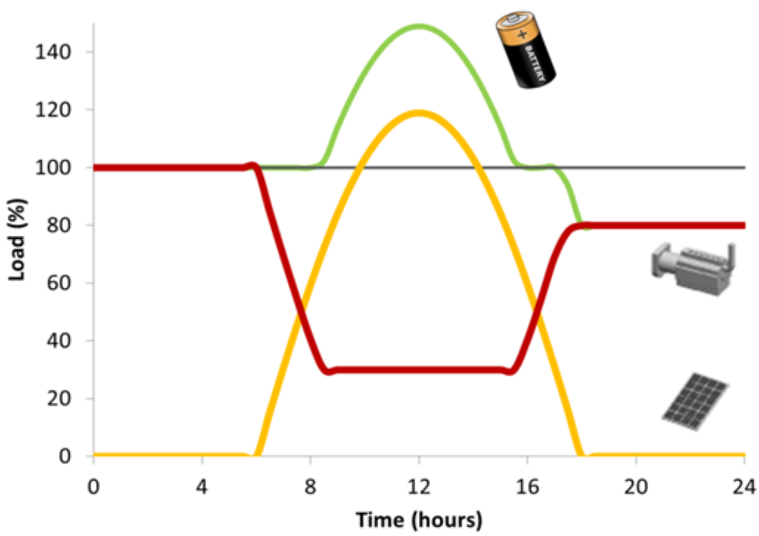

Figure 6.4: Example of Funafuti power system with addition of battery with diesel operating at minimum rating

BESS inverter sizing is an important consideration at each project size, particularly once the system is allowed to operate in ZDO (without any diesel or synchronous machines on line). To assist with the

Road Map, limited power system modelling to assess the system suitability for renewable energy expansion in stage 1 has been undertaken by Entura [13].

In general terms the power system study found that the power system is in a condition capable of supporting the short term increased renewable energy targets and system stability. System protection equipment functions may require additional enablers to ensure correct operation and discrimination in future road map stages, with dynamic modelling of actual inverter models required as a component of detailed design studies during project implementation to confirm frequency response during system events and to confirm voltage ride through capabilities.

Further dynamic analysis of varying system configurations is detailed in the 2018 Ricardo Report [12] through the use of their Generation Dispatch Analysis Tool where they discuss estimated inverter sizing requirements to manage frequency response. This Roadmaps Stage 3 BESS total inverter sizing is in alignment with their findings for frequency response in a similar system configuration.

As the latter stages of the roadmap are implemented, they will again change the system dynamics including the ability of the generation system to maintain frequency on loss of a generating unit, and network power flow. Therefore, for each future project stage the network stability, capacity and project interactions will need to be assessed through dynamic power systems studies incorporating specific models of the supplied BESS inverter equipment. Also, each project stage will need to be integrated into overall control system.

For each project stage it will also be critical to confirm that correct protection system discrimination can be maintained. This may be another determining factor for the need for a synchronous condenser or diesel flywheel if sufficient fault currents cannot be provided by the combined BESS systems. This can be determined by undertaking a protection and coordination study in conjunction with the contractor’s detailed design which may require some form of special protection scheme.

Another consideration for ZDO will be maintaining an earth reference in the system. This is currently provided through the diesel generators star point when they are online, however these will be disconnected during ZDO. Installation of an earthing transformer may be required to facilitate the diesel off functionality. This may be implemented during the World Bank Project, details have not been provided to Entura at this time.

At this time very few projects have achieved 100% RE penetration for Island systems in the MW scale, and of those that have there are fewer still examples of this achieved by a BESS only enabler solution (no flywheel system, dynamic resistor or synchronous condenser). However, it is anticipated at this time that advancements in BESS technology should negate the need for a flywheel system on Funafuti.

In summary, by 2020, 100% renewable power *penetration* should be achievable at times. This will be extended by the ADB project Stage 1. Increased levels of renewable *contribution* can follow progressively, targeting 2025 as the first year where 100% RE contribution for Funafuti should eventuate.

6.2 Challenges for implementation

Implementing the Road Map will have its challenges for TEC and the Government of Tuvalu. The most significant challenge in implementing the Road Map is identifying sites with sufficient capacity to meet the requirements of each Stage of development.

Consideration will need to be given to whether there may be impacts on other sectors of the economy as a result of a significant reduction in diesel imports if TEC no longer require the volume they consume each year. Reduced import volumes may lead to increased prices or a lower reliability of supply. This may affect fishing and shipping industries and the discounts they might otherwise receive, as well as residents who rely on fuel based vehicles for their mode of transportation. The Government of Tuvalu should examine and quantify risks in this area or effects on other sectors to assess if policy changes are required or other mitigations needed.

There are other challenges that will be faced by TEC if the Road Map progresses. The transformation from a manual, fossil fuel based power system to an automated, IT based control system, relying on inverter technology for much of the power system functionality will require completely new skills. Can the existing workforce be sufficiently trained in the short time frame available to manage this transition or do new employees need to be found and trained?

To implement the roadmap it will be vital to get community and stakeholder support given the short window for implementation to meet the Government objectives. This will be critical for securing sites and communicating benefits.

Finally, finding funding to pay for Stages 2 and 3 of the Road Map. Up to US$21.1m is required to fund these stages with most of that required for Stage 3. Are there donor agencies ready to fund such projects or does the Government need to find the money from its own balance sheet? Time will be of the essence to meet the 2025 timeframe.

6.2.1 Available sites and land for solar PV and BESS

Funafuti is a small Island with limited free space and land is at a premium. The land, sea or roof top area required for the Stages is dependent on the selected technology and physical arrangement. For example typical tilted ground mount arrays are spaced into rows to provide access for maintenance, whereas raised fixed PV structures are often in one larger plane subsequently requiring less space. Similarly for rooftop solar; if tilted framing systems are used then additional space is required. Rooftop solar is also constrained by the shape of roof pitches along with the need for clearances from edges and existing equipment. Area footprint for floating solar is dependent on the selected supplier technology type. Hence the area summaries provided in Table 6.2 are generalized across the range of technologies as space requirement is specific to the installation type.

Table 6.2: Total area range required for Solar PV

	Stage 1	Stage 2	Stage 3
Solar Array area (m^2)	2340 to 7030	11,250 to 33,750	15,230 to 45,700

Consideration also needs to be given to the area required for installation of the BESS. Although the World Bank and Stage 1 are likely to fit within the existing TEC Compound, the area required for Stage 3 (see Table 6.3) could be substantial depending on the preferred technology. Consideration would also need to be given to whether it was best to place all batteries in a single central location or to have them disbursed around the power system.

Table 6.3: Footprint area required for BESS by Stage and technology

	Stage 1	Stage 2	Stage 3
Modular Li-Ion Cabinets (m^2)	14.9	N.A.	150
Containerised Li-Ion Racks (m^2)	29.8	N.A.	300
Flow Batteries, Lead Acid and others(m^2)	119	N.A.	1200+

6.2.2 Technical expertise and capacity within Tuvalu

While solar PV and battery systems require ongoing monitoring and maintenance, the regularity and effort is typically less than that of diesel systems with equivalent capacity. It is likely that for operations and maintenance purposes the staffing level required will be the same as existing levels, with reduced diesel mechanical maintenance offset by battery and solar maintenance tasks.

A training and capacity building program will be required to assist with the development of the required physical maintenance and management skills to maintain the transformed power system. This should be incorporated into project specifications and implementation. Some specific technical skills will be required including; monitoring and physical testing of solar PV equipment, inverter testing and replacement, battery system maintenance and new SCADA system operation. Additionally to this, as the system becomes more IT based and automated through SCADA improvements, there will be an increased need for data management and analysis skills to monitor, detect and correct performance issues.

Existing diesel systems should be maintained and kept operational, even if towards the latter years of the roadmap when their use becomes minimal as they are likely to continue to form a key part in system black start functions and provide a level of system backup and redundancy in the case of other generating equipment failure.

Funding for operations and maintenance has not been allocated in the Roadmap. It is anticipated that TEC will re-allocate a portion of current diesel fuel expenditure towards the ongoing operation and maintenance costs of new renewable projects, as these directly offset the existing fuel costs.

Evidence suggests maintenance and equipment replacement levels for existing renewable energy project equipment has been only performed at low levels due to TEC allocating limited funds, a consequence of tariffs not fully recovering costs. It will be important once the power system has been fully transformed to a high renewable energy system that TEC are properly funded to perform operations and maintenance tasks to avoid costly repairs or replacement, or reverting to a diesel based power system.

6.2.3 Power system upgrades

6.2.3.1 Communications and control

The Islands main communications network predominately consists of the older copper network style infrastructure, complimented by 3G and 4G network technology and various Wi-Fi hotspots. Dedicated communications links for the larger distributed solar PV generation will be required. Small distributed solar PV generation can be adequately managed through frequency control without communications links, up to a penetration level of around 40%.

6.2.3.2 Distribution network

The distribution system sizing is adequate to accommodate the currently proposed projects and system growth in the near term, as detailed in Section 2.1.2. Distribution system sizing, particularly cabling capacity & power flow, will require re-assessment during the road map stages 2 and 3 once specific project connection points and sizing are selected to proceed.

It is anticipated that for each larger RE generation project site that a new 11kV connection point will be required. It is suggested that the Stage 3 BESS installations are co-located at the newly established distribution connection points to reduce losses and mitigate the potential for power flow issues in the existing network.

6.3 Potential solar PV sites

Adding rooftop solar presents one of the lowest cost solution to increase the renewable energy penetration on the island however as the renewable energy system share rises, the need for communications and control becomes greater. The other significant advantage of rooftop solar is utilisation of existing space which otherwise is of little value, compared to developing new sites or land which is at a premium on Funafuti. A disadvantage of rooftop solar for existing buildings is the need for structural assessments to ensure adequacy. An additional challenge in implementation of rooftop solar is the construction safety management of working at heights.

The road map plan assumes that roof top solar options will be implemented first, prior to the higher cost alternatives (elevated ground mount raised fixed structures, and floating solar). Alternatively low risk sites with clearly identified large capacities for raised fixed structures can be considered advantageous for early implementation due to ease of implementation and possible economies gained through scale (e.g. QE II Park).

Discussions with ADB, TEC and various Government ministries agreed that Entura will assess the capacity and estimate the installation cost for rooftop PV on a number of government owned rooftops around Funafuti. The capacity assessments for sites are based on currently available cost effective module power outputs. In the future it is highly likely that these will increase as technology improves and solar PV costs fall.

Options for floating solar are explored in the next section. Site specific detail for floating solar, ground mounted solar and raised structures over water or roadways are also explored and assessed in Appendix C.

A summary of solar expansion options matching Road Map stages for Funafuti is presented in Table 6.4. See Appendix B for identified sites, site detail and capacity assessments.

Table 6.4: Summary solar expansion options for Funafuti

Road Map Stages	PV Site	Site totals (kWp)	Cumulative System capacity (kWp)
Existing	Government building	130	**735**
	Hospital	75	
	Media building	40	
	Fisheries main warehouse	75	
	Public works department	65	
	TEC power station	350	
World Bank Project	World Bank solar site	750	**1,485**
ADB Project, Stage 1	Government building rooftops	500	**1,985**
Road Map Stage 2	FassNet wetlands pilot floating solar project	100	**4,385**
	Other Government controlled buildings or land	580	
	QE II Park rooftop and raised framing structures	1,720	
Road Map Stage 3	Floating solar in Funafuti Lagoon	2000+	**7,635**
	Other government controlled land	500+	
	Non-government organisations rooftops or land	500+	
	Raised fixed structure (roads or alternative sites)	750+	
	Non-Government organisation building rooftops	500+	

6.4 Tariffs

As part of the Roadmap, an analysis has been undertaken to assess what impact the introduction of each stage has on the cost of generation for TEC relative to the current tariff. Summary results are presented in Figure 6.5.

The analysis assume that existing and new generation assets are capitalised and depreciated correctly by TEC. The tariff is then split into fixed costs and fuel costs to assess the impact of fuel use reductions.

As the renewable energy contribution increases, the fuel charge goes down to almost zero (as expected). However, the fixed charge increases with the increase in depreciation. The cost recovery tariff does not get close to the existing average tariff, although is lower than the existing cost recovery tariff for TEC over the projected period out to 2030.

The Government of Tuvalu and TEC will need to consider this outcome and formulate an appropriate response as it indicates that the Government of Tuvalu will need to subsidize TEC into the future, or change the rate of the existing tariffs (which have been in place since 2008).

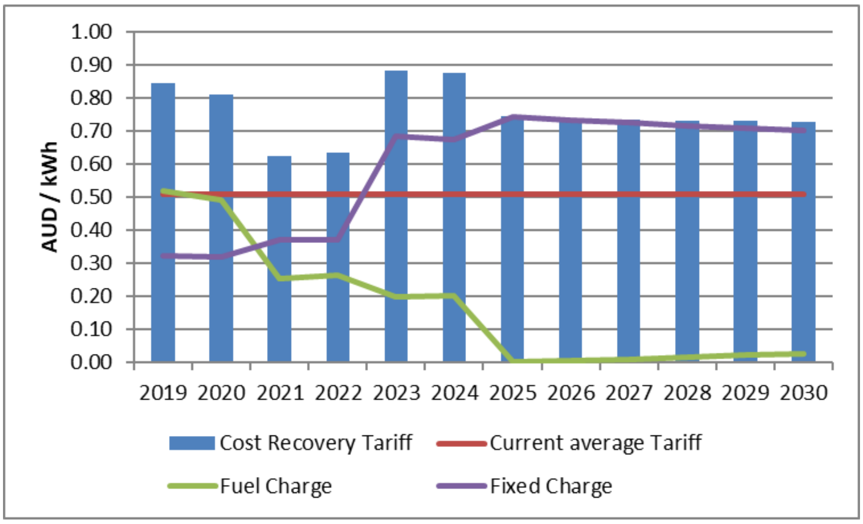

Figure 6.5: Projected charge components and tariff analysis for Funafuti

6.5 Asset planning beyond 2025

Beyond 2025, work will be required to maintain renewable energy generation supply levels through a program of maintenance and ongoing equipment replacement to account for anticipated degradation of equipment. If demand growth continues into the future then further generation sources will be required to maintain balance in the system and continue the diesel use offset. Population movements, climate change impacts and economic change are all points for continued assessment and discussion to ensure the adequacy of the power system and its ongoing ability to meet the 100% renewable energy contribution targets.

6.6 Climate change risks

Climate risk screening and assessment was carried out using AWARE for Tuvalu and is discussed in the Tuvalu Feasibility Study companion report [20]. Three main areas of risk were identified for Funafuti:

- Sea level rise was identified as a High Risk because the project is located in a Low Elevation Coastal Zone (LECZ), which could be affected by sea level rise. Sea level rise could result in storm surge flooding of ground mounted solar PV, cable trays, generator sets, battery and inverter sheds. Note that some elements of the projects may not be affected because they are above the predicted flood levels e.g. roof mounted solar.

- Solar Radiation Change was identified as Medium Risk because the design of the project may have to be slightly modified to cope with the impact of changes in solar radiation. A reduction in solar radiation could lead to a lower power output.
- Precipitation increase was identified as a low risk because the project design would be unaffected by increased rainfall.

The adaptation measures that have been identified for inclusion in the final design for the renewable energy projects on Funafuti for managing the climate risks are described below:

- Install low voltage (LV) cable trays above predicted flood levels (e.g. 1.0 m above FSL)
- Install pillar mounted collector boxes above predicted flood levels (e.g. 1.5 m above FSL)
- Ensure inverters and batteries are installed so that the bottom of the inverter is located 1.5 m above FSL and therefore above the predicted flood levels.
- Ensure inverter and battery housing is located on a raised concrete slab (e.g. 300 mm above FSL) raising them above the predicted flood levels.
- For ground mounted solar; Design and construct the perimeter fencing around the ground mounted solar PV at a higher standard to prevent flood debris from entering the site and damaging solar panels and associated infrastructure. Ensure debris is cleaned away after flood events. Ensure ground vegetation in and around the solar farm kept low to allow flood water clear passage. Install ground mounted solar PV panels on taller mounting frames so that the lowest part of the solar panel is above predicted flood levels, up to 1.5 m above finished surface level (FSL).

7. Renewable energy power system technologies

This section examines the potential range of renewable energy generation technologies available that are likely to be considered for implementation for the Funafuti roadmap.

7.1 Control system and communications

The existing SCADA system at the Funafuti power station is limited to the SMA fuel saver system and the underutilized Yokogawa controller's for the diesel units. The two systems are not fully integrated. Distribution indications are limited and there are no existing feeder controllers. Data logging and trending information is very limited.

The most recent report to detail upgrade requirements, options and project plans for Funafuti's existing SCADA system is the Ricardo Report [12]. The fourth section of the Ricardo report presents the results of an assessment of the needs for SCADA and Energy Management System (EMS) specifically for Funafuti. In summary it recommends a staged approach to increasing distribution system equipment status visibility, however it does not fully link the need for overall hybrid system control features implemented when the first stage when energy storage is added. Regardless of this, it is expected that the current World Bank energy project will install a control system associated with the BESS installation that will be the master control for the Funafuti power system. It is anticipated, yet unconfirmed that this will have the capability to handle future growth and it that control system modifications will be required for integration of future storage or RE generation expansion. Generally once zero diesel operation is targeted, the control system will be required to provide:

- Monitoring, management and control all generation or enabling technology, providing a reliable, secure supply and demand balance.
- Predictive forecasting and optimisation of renewable energy and enabler technology dispatching
- Remote monitoring, alarming, logging and reporting of all system equipment
- Provide spinning reserve management/ diesel unit start/stop control.
- Renewable energy generation curtailment to prevent diesel reverse power and manage system power balance,
- Provide auto/manual controls for the P and Q set-points,
- Enable utilisation of the BESS(s) P and Q outputs as power system ancillary services,
- Ensuring that P and Q set-points are safe for the power system stability.
- Demand-side management

It is assumed that the BESS included in the World Bank project will provide a control system that will either integrate with the existing diesel controllers or replace them with new units and be adequate for the overall hybrid system control for the entire system.

7.2 Battery energy storage systems (BESS)

While BESS equipment may be considered an established and proven technology, the deployment for Island grids has typically been at a small scale in the past up to around 300kW and it is only recently that 1MW and above systems have been utilised on larger islands in quantity for balancing of supply and demand. This shift has been largely driven by the falling cost of Lithium-ion battery technology and a push towards 100% RE systems. The BESS technology required has several key requirements. Key requirements are:

- The battery shall be expandable in terms of energy storage capacity, without any requirement to increase its inverter capacity.
- The battery inverter will be able to operate in parallel with at least one diesel generator, and have full grid forming capability to ensure that the system can operate without a diesel generator when conditions present themselves. In zero diesel mode, the battery inverter will be responsible for setting grid frequency and voltage.
- The inverter must be able to moderate reactive power to support the loads on the grid.
- The battery cells themselves must be capable of efficient operation and retaining charge and life, and must have high power output capability to support (or displace) the diesel generators.
- The battery cells and power conversion system will need to be modular, and typically small unit size / weight to assist with transport and logistics.
- The battery cells should be self-containing for fire or explosion risk. Containerised BESS systems, layouts and surrounds should be designed to mitigate fire risks. Briefs from suppliers or contractors may be required for emergency services response.
- While battery technology is not strictly limited, a high power density technology such as lithium-ion would be advantageous in keeping battery housing requirements to a minimum (and the associated logistics and costs of transporting building / housing materials).
- High cycle life and tolerance to low states of discharge are also important to minimise lifetime O&M costs (particularly battery replacement). Lead-acid batteries will likely require replacement sooner than a comparable lithium-ion battery.
- BESS must be fully capable of self-regulation and protection, and operating / surviving for their design life in the site environmental conditions. This includes the provision of forced cooling of inverter and battery systems where required. The conditions are consistently in the low-mid 30s°C during the day.
- Equipment and materials designed and warranted to suit site specific environmental conditions; Marine grade corrosion systems, high temperatures and humidity.
- Flooding/inundation risk is to be managed through the detailed design process with equipment layouts elevated to levels above anticipated storm events.

There are several existing products available in the market that suit the above requirements.

7.3 Wind turbines

Wind turbines and their use in island power systems of similar scale to Funafuti is considered a proven technology solution. Two reports [16] [11] have assessed the wind resource in Funafuti previously, with a modest assessment of potential locations for wind turbines in Funafuti. Neither report could be considered to be of a feasibility level with no assessment of available land or environmental issues (including noise impacts).

The inclusion of wind power is likely to be complementary to solar PV, however is likely seasonal due to the trade winds, with long periods of the year when the wind barely blows.

Domestic scale wind turbines (<10 kW) are unlikely to be competitive with solar PV based on the available wind resource.

Larger wind turbines such as those used in other parts of the Pacific (New Caledonia, Vanuatu, Yap, Tonga) may be suitable and cost effective if suitable land (or shallow water) could be found that had sufficient buffer from residents to avoid noise impacts.

Such wind turbines are capable of surviving cyclones (such as Cyclone Pam that devastated Vanuatu – the wind turbines survived), however they do need specialised equipment to perform operations and maintenance activities to lower and raise the wind turbines. This aspect may prove to be too difficult to incorporate into Funafuti.

Further to that, consideration would need to be given to the aviation pathways and the area that needs to remain clear around the airstrip.

7.4 Solar PV technology

Solar PV equipment is now considered an established and proven technology. However there are several key requirements to make it fit for purpose in the Funafuti environment. The key Funafuti requirements are:

- Equipment and materials designed and warranted to suit site specific environmental conditions; Marine grade corrosion systems, high temperatures and humidity.
- High Ingress Protection (IP) ratings on DC connectors and isolators to protect against high rainfall and humidity. Breather valves may also be considered for DC isolators and combiner boxes.
- Inverter controllers and communications connections to be provided and integrated into overall control system.
- Provision of warranty to address the required design life by manufacturer and install contractor.
- Monitoring of system, equipment performance and degradation during a contract defects period as a quality control measure.

7.5 Funafuti Lagoon solar PV options overview

This section provides a summary of the different technology options available for Funafuti Lagoon; including floating structure types, raised fixed structures, and tensile solar structures. An example of each main technology type is presented and discussed, considering leading manufacturing company technology offerings. Commercial availability, suitability, current deployment and technology development status are also examined.

7.5.1 Floating solar

Proponents of floating solar PV technology highlight the following reasons why this type of system may have an advantage over conventional land-based PV projects in certain applications:

1. It enables the use of previously unutilized land area, which is particularly advantageous where land is expensive or otherwise constrained (e.g. limited area, or higher priority uses for the land).

2. PV modules are more efficient at lower operating temperatures and the ambient air temperature over water is generally lower than over land. Water could also be used to actively cool PV modules in some concentrated solar applications.
3. Floating solar PV reduce water evaporation through shading of the water surface by the array.

In Entura's view, the first item is valid for Funafuti where there are significant geographic constraints which limit the installation opportunities on the main island and no single on-island site has been identified which has the capacity to meet 100% of the energy generation requirements. However the economic opportunity to install generation elsewhere exists over a range of smaller sites and is likely to negate this point to a fair extent. Furthermore, risk exists from cyclone damage through wind and wave action to structures directly on the water.

The second point regarding PV module efficiency is based on the inverse relationship between operating temperature and module output. As PV module temperature increases, its output decreases. For example, if a particular PV module has a temperature coefficient of -0.4%/°C, then a 5°C increase in module temperature will result in approximately a 2% decrease in module power output (with all other conditions being the same). The magnitude of this efficiency gain will be dependent on the technology used, and site specific factors. However, as a guide, ground mounted PV modules typically operate at about 50°C in full sunlight. With floating solar PV modules fully thermally coupled to the water, their temperature would be around 15°C, implying potential performance improvements in the order of 15%. Practically, however, floating solar PV modules are not fully thermally coupled and the response is not linear. The maximum benefit of this effect is considered to be closer to 10%, although detailed modeling to account for the local lagoon temperatures in comparison with the on-island temperatures would be required to fully quantify the effect. There is a further argument that this effect allows concentration of solar irradiance on PV modules, by providing inherent cooling.

The third item regarding reduced water evaporation does not apply in any useful way to sea based systems.

There are a number of considerations for the structure, including scale, rigidity, and anchoring/mooring approach. Larger pontoons are likely to be more stable and rigid, with the modules installed at a greater height above the supporting water level. However, a larger system introduces transportation issues and would likely require more extensive assembly/construction on site, and with it added cost. Anchoring/mooring options will be influenced by a number of site and technology specific factors. For example, the maximum water depth, wind conditions, the difference between highest and lowest water levels, and the distance to shore from each side of the array.

Alternatively, small modular components, which can be used to build large arrays, are easier to transport and assemble on site. However, these modular systems are likely to be less rigid, with some flexibility and relative motion in rough water conditions. The most mature company in the industry delivering this type of technology at the present time is Ciel & Terre and while their current offering appears rated up to category 3 wind conditions, its ability to withstand the effect of cyclone category 5 conditions has not been demonstrated. Another modular approach is the Circular Floater/surface membrane solution by Ocean Sun which may demonstrate the ability to withstand extreme wind and wave events.

Three leading floating solar options are presented in the following sections.

7.5.1.1 Larger pontoon floating structures – Swimsol

The Swimsol Lagoon system is a floating platform with a footprint of around 14 m x 14 m with 112 PV modules installed in a fixed tilt east-west arrangement (see Figure 7.1). Single platform systems (28 kWp using 250 Wp modules) have been installed in the Maldives, and Swimsol have proposed plans for scaling up to 1 MWp and 10 MWp projects. The Swimsol system uses PV modules and other materials suitable for saltwater environments. While this system could be used in a freshwater application it appears that the company is targeting the tropical island market. Cyclone wind ratings for this system are undetermined.

Figure 7.1: Swimsol Lagoon product[12]

7.5.1.2 Small modular floating structures - Ciel & Terre

The Ciel & Terre Hydrelio system uses two different float systems as shown in Figure 7.3. The 'main' float supports a single PV module, while the 'secondary' float provides maintenance access and additional buoyancy. The two types of float are connected together on site, and can be scaled up to form large arrays (multi-MW scale).

The Hydrelio system uses a fixed orientation, with a relatively shallow tilt angle of only 12 degrees which is likely related to wind loading design constraints. The main float can support a conventional 60 or 72 cell PV module in landscape orientation. Combiner boxes installed on the floating platform collect the DC power from the modules and are connected by cables to one or more inverters onshore.

The Ciel & Terr solution has moderate ratings claimed for their ability to withstand wind and wave action, these are unconfirmed as suitable to withstand cyclonic weather risks.

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[12] Image sourced from http://www.irena.org/EventDocs/Maldives/3FloatingsolarPVinvestmentcaseSwimsol_15.1110.pdf, accessed June, 2019.

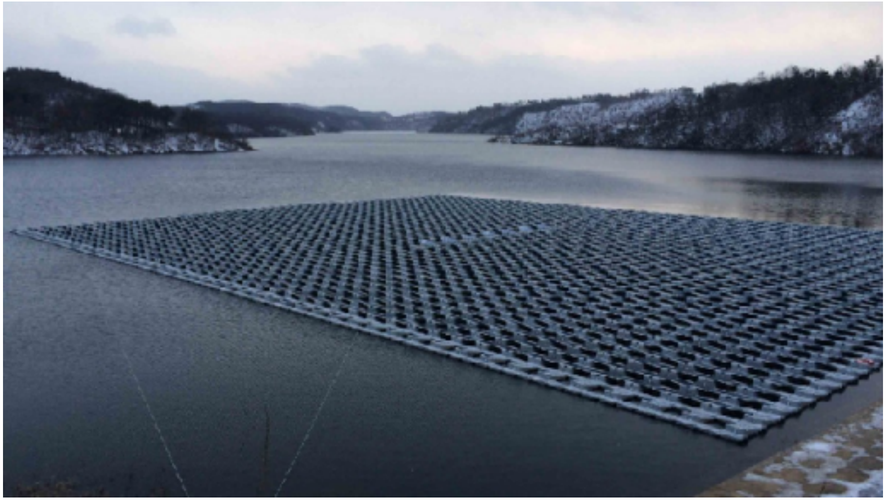

Figure 7.2: Ciel & Terre, O-Chang project (South Korea), 494.5 kWp[13]

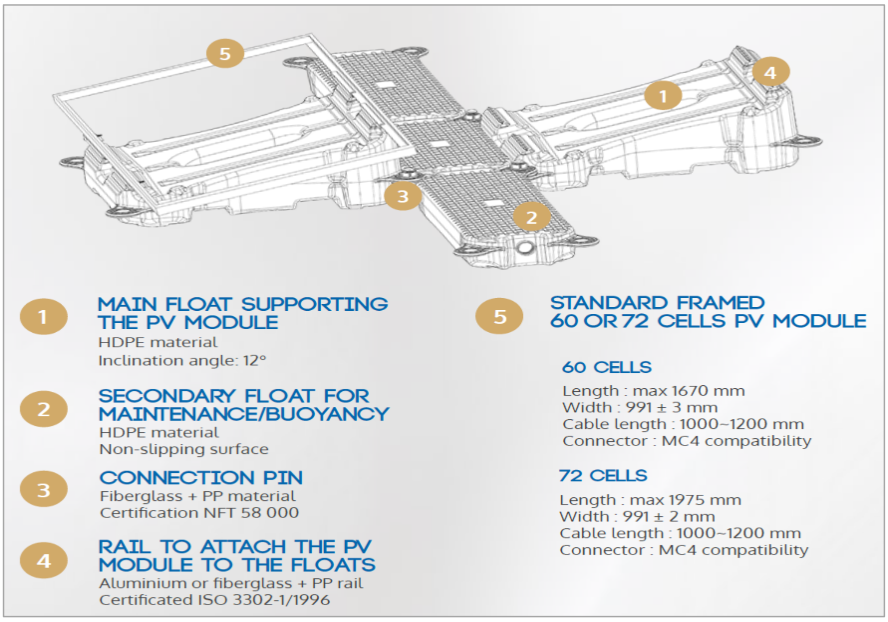

Figure 7.3: Ciel & Terre Hydrelio system overview[14]

[13] Image sourced from http://www.ciel-et-terre.net/essential_grid/floating-solar-system-o-chang/#, accessed June 2019.

7.5.1.3 Circular Floater/membrane array systems – Ocean Sun

Figure 7.4: Ocean Sun's Circular Floater/membrane array systems – sourced from their website[15]

Ocean Sun's Circular Floater (above in Figure 7.4) features a buoyant thin polymer membrane to carry the PV modules and a circular floater rim/rail design similar to that of salmon farm systems. Its anchoring system is also reflective of salmon farming technology, utilizing proven and established standardized mooring arrangements for rapid deployment. A concept plan view of this arrangement can be seen in Figure 7.5.

In this system the modules are directly thermally coupled with the water surface to take full advantage of temperature efficiencies created by the waters cooling effects. Water accumulation on the membrane during high rainfall events is managed through the use of small bilge pumps.

The Ocean sun solution currently has the highest ratings offered in the market for their ability to withstand wind and wave action, with claims that their modeling shows the system is able to withstand typhoon category 4 winds of 275 km/h (equivalent to southern hemisphere Severe tropical cyclone category 5 ratings).

[14] Image sourced from "Company Profile C&T Hydrelio - update July 2016.pdf ", provided to Entura by email on 18/7/2016

[15] Image sourced from "https://oceansun.no/benefits/", accessed June 2019.

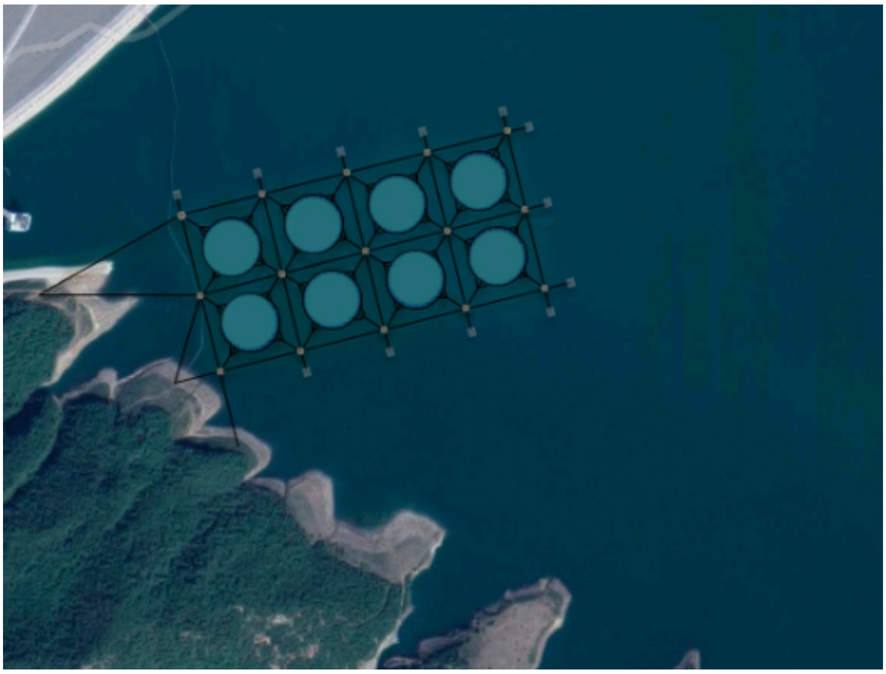

Figure 7.5: A concept plan view of the Ocean Sun mooring arrangement. sourced from their website[16]

A recent feature article in the PVTech Power Report[17] discusses their module performance advantages and pilot installation testing in more depth.

Of their indicative product range the 200 kWp circular floater is the smallest floater offered for harsh weather conditions, with a diameter of 50 m and an area of approximately 2000 m^2. However deployment levels are still low and the product appears to be still in the development stages. Ocean Sun have recently partnered with a module manufacturer to develop a PV module unit optimized for deployment with their Circular Floater system.

7.5.2 Raised fixed structures

Raised fixed structures, similar to those installed at TEC power station, can be deployed over water, similar to the Nukufetau solar PV array. The significant advantage of this approach compared to floating solar is the removal of any direct impact from surface wave action, although significant cost is added through the need for pillars through water into the lagoon sea bed below. This option may be better suited to the near-shore sand flats south of town or other areas where water depths are

[16] Image sourced from "https://oceansun.no/benefits/", accessed June 2019.

[17] PVTech Power Report: FLOATING SOLAR, 2019, available on their website at https://www.pv-tech.org/technical-papers/at-the-heart-of-floating-solar-singapore

shallow to reduce the cost and effort involved with pillar installation. Cyclone wind ratings for this system are likely to depend on site specific designs.

Figure 7.6: P4P Energy's over water raised fixed structure system implemented at scale.[18]

7.5.3 Tensile solar structures – P4P Energy

Tensile solar structures are a new development in solar technology utilizing tensioned cables for suspension technology. The significant advantage of this approach is an absolute minimal ground footprint, significant spans without intermediate supporting pillars can be achieved with low material quantities. These can be applied over land or water, however the anchoring challenges in ocean conditions are unclear for this specific site and would require further consideration if this technology is perused for Funafuti Lagoon. P4P Energy claims that systems are designed to withstand hurricane force winds but the actual cyclone category rating has not been confirmed at this time.

[18] Image sourced from "http://p4penergy.com", accessed June 2019.

Figure 7.7: P4P Energy's over water suspension system.[19]

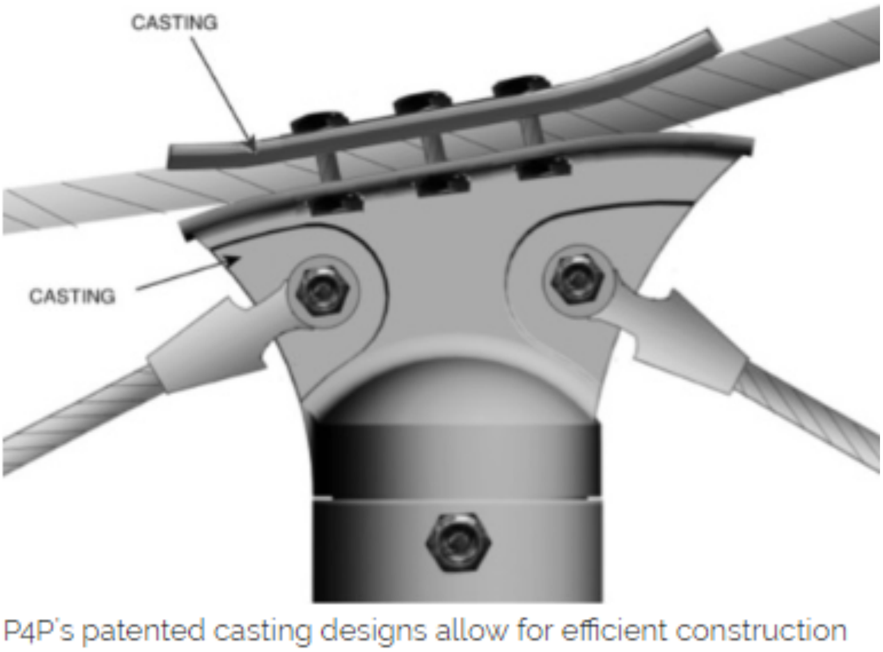

Figure 7.8: P4P Energy's over water suspension system.[20]

[19] Image sourced from "http://p4penergy.com", accessed June 2019.

7.5.4 Environmental considerations

Various environmental considerations would require detailed feasibility investigations if the Funafuti Lagoon solar options are pursued further, including:

- Impact on marine life
- Private and public rights for activities; Boating, fishing, water recreation, etc.
- Visual impact
- Sea floor habitat
- Anchorage/mooring line drag/scouring (technology dependent).
- Bird life

7.5.5 Other considerations

Various items would require detailed feasibility investigations and attention during procurement if the Funafuti Lagoon solar options are pursued further, including:

- Impact of debris during large westerly storm or cyclone event.
- Cost overruns and delays due to construction difficulties (technology dependant)
- Land/area use and tenure
- Soiling from bird droppings
- DC wiring insulation failures (reduced performance and longevity)
- Corrosion of poorly specified materials

[20] Image sourced from "http://p4penergy.com/technology/", accessed June 2019.

8. Conclusion

The Government of Tuvalu prepared *Enetise Tutumau* 2012-2020 Master Plan for Renewable Electricity and Energy Efficiency [1] that provides the framework for developments in the energy sector in Tuvalu. The Master Plan is linked to *Te Kakeega II* the National Strategy for Sustainable Development (2005-2015) [2], *Te Kaniva* the National Climate Change Policy (2012) [3], the National Strategic Action Plan for Climate Change and Disaster Risk Management (2012-2016) [4] and the Tuvalu National Energy Policy (2009) [5].

Per the Master Plan, the priorities for the electricity sector in Tuvalu are:

(a) To provide a reliable and affordable electricity supply to all the people of Tuvalu;

(b) To safeguard Tuvalu from future diesel price shocks;

(c) To improve the efficiency of electricity utilisation and further reduce the already low energy consumption per person and per GDP; and

(d) To reduce Tuvalu's "carbon footprint" and become an international role model with regard to climate change mitigation.

As a first step in a path towards 100% renewable energy, the Government of Tuvalu set two goals:

1. To generate electricity using 100% renewable energy by 2025
2. To increase energy efficiency by 30% on Funafuti and later in the Outer Islands.

This report has outlined a pathway to transform Funafuti to 100% renewable energy contribution by 2025 (see Table 6.1). However, achieving the goal of 100% renewable energy is expensive, particularly the last few percentage points. Consideration should be given to revising the target to a more cost effective target of between 95% and 98% which is close to what the Outer Islands are achieving.

The available renewable energy resource options for Funafuti have been examined for a range of technologies and as a basis for the energy modelling inputs. Funafuti has moderate resources for both wind and solar. Other resources exist for wave, tidal flow, ocean thermal and waste to energy however these are not considered ready for deployment in the timeframe for the Roadmap.

To achieve the goal of 100% RE within six years (by 2025) will require overcoming a number of challenges;

- co-ordination between TEC and GoT to implement the Roadmap
- ensuring the Funafuti community are informed and supportive of the project
- evaluating what are the impacts on the rest of the Tuvalu economy if TEC no longer require large volumes of diesel fuel
- securing the required project funding of US$21m
- securing sites with landholder consent
- preparing tenders and securing suppliers and contractors to implement the projects
- evaluating how TEC can continue to operate with a tariff below cost recovery

Once the Roadmap is implemented there will be further challenges:

- Ensuring the skill set of TEC is able to operate and maintain the equipment
- Ensuring TEC has appropriate funding available to operate and maintain the assets to avoid reversion to a diesel based power system

This report finds that in 2020 on the Island of Funafuti, 100% renewable power *penetration* is achievable, with increasing levels of renewable *contribution* to follow progressively, targeting 2025 as the first year where around 100% RE contribution for Funafuti should eventuate if budget is available and road map stages are progressed.

9. References

[1] "Enetise Tutumau" *Master Plan for Renewable Electricity and Energy Efficiency in Tuvalu* , 2013, Government of Tuvalu

[2] *Te Kakeega II National Strategy for Sustainable Development* 2005-2015 and *Te Kakeega III, National Strategy for Sustainable Development 2016-2020,* Government of Tuvalu

[3] *Te Kaniva National Climate Change Policy* 2012, Government of Tuvalu

[4] *National Strategic Action Plan for Climate Change and Disaster Risk Management* 2012-2016, Government of Tuvalu

[5] *Tuvalu National Energy Policy* 2009, Government of Tuvalu

[6] *Tuvalu Infrastructure Strategy and Investment Plan 2016-2025*, Government of Tuvalu

[7] *Tuvalu National Population and Housing Census 2012*, Central Statistics Department of Tuvalu

[8] *Overarching Roadmap Report Renewable Energy Generation for Tuvalu*, January 2013, Opus International Consultants Ltd.

[9] *Funafuti Atoll, Tuvalu Distributed Renewable Generation Study: Integrating PV Solar and Wind Generation with the TEC electric system*, 2013, DNV KEMA

[10] *Quantification of the Power System Energy Losses in South Pacific Utilities: Tuvalu Electric Corporation, Tuvalu*, May 2012, KEMA International B.V

[11] *Tuvalu Wind Power Development Wind Study and Feasibility Report,* May 2010, Ecology Management Aps

[12] *D4 – Draft Interim Report and Model for Tuvalu Electricity Corporation (Tuvalu)| Assessment of Variable Renewable Energy (VRE) Grid Integration, and Evaluation of SCADA and EMS system design in the Pacific Island Counties*, October 2018, Ricardo Energy & Environment .

[13] *THE FUNAFUTI – TUVALU Power System Study*, 14 December 2018, Entura

[14] *The European Smart Metering Alliance Final Report*, JANUARY 2010, BEAMA

[15] *Charging ahead: Prepaid metering, electricity use and utility revenue*, March 2017, B. Kelsey Jack, Et. Al

[16] *Funafuti Wind Energy Report,* 30 January 2013, GL Garrad Hassan

[17] *Waves and Coasts in the Pacific - Cost analysis of wave energy in the Pacific,* 2015, Bosserelle, Reddy and Kruger

[18] *Tidal Energy Technology Brief*, June 2014, IRENA

[19] *Tuvalu Solar Project Structural Review Revision:1*, 12 September 2013, Aurecon.

[20] *Tuvalu Feasibility Study*, July 2019, Entura

Appendices

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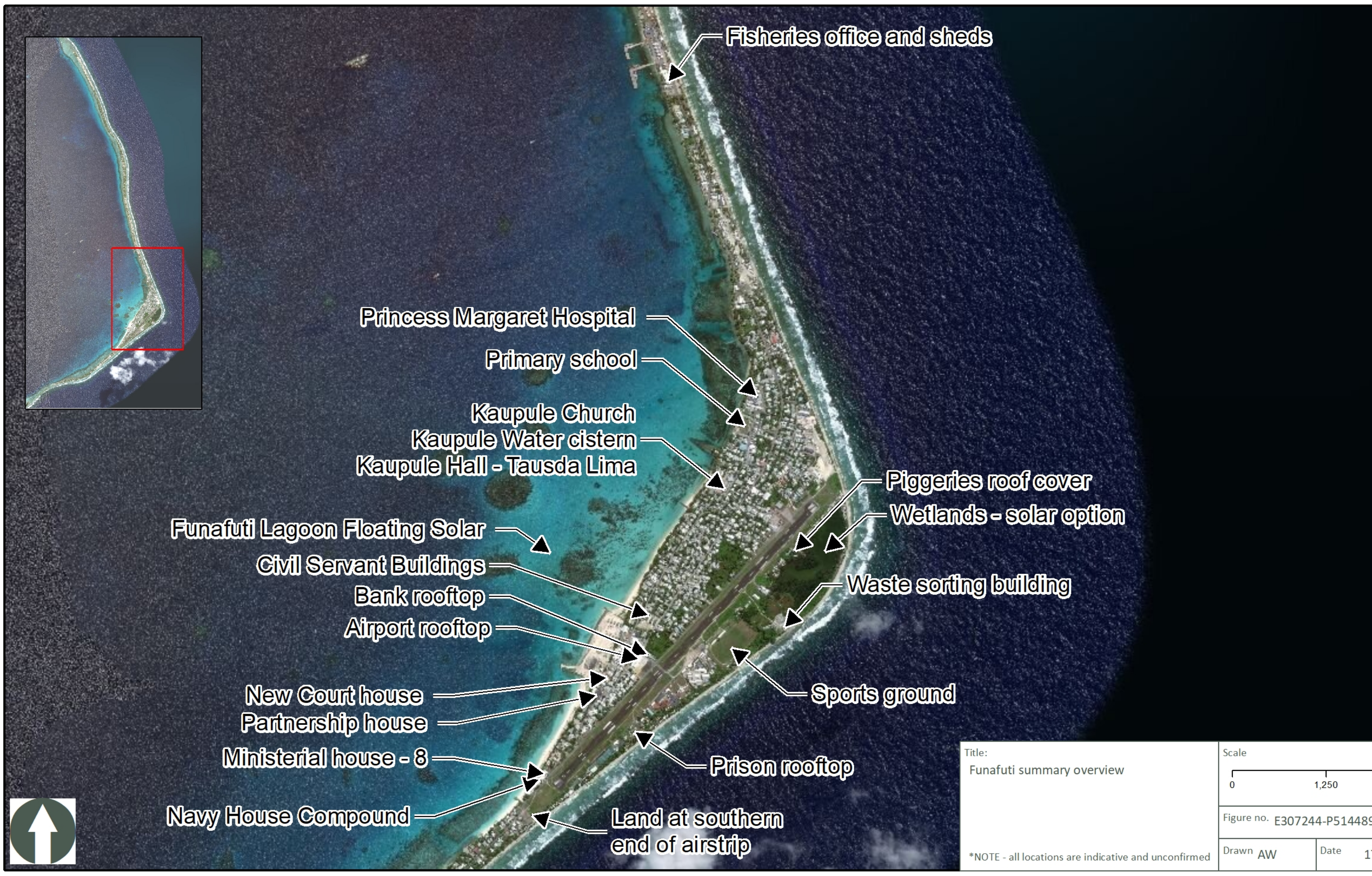
A Funafuti solar PV site locations

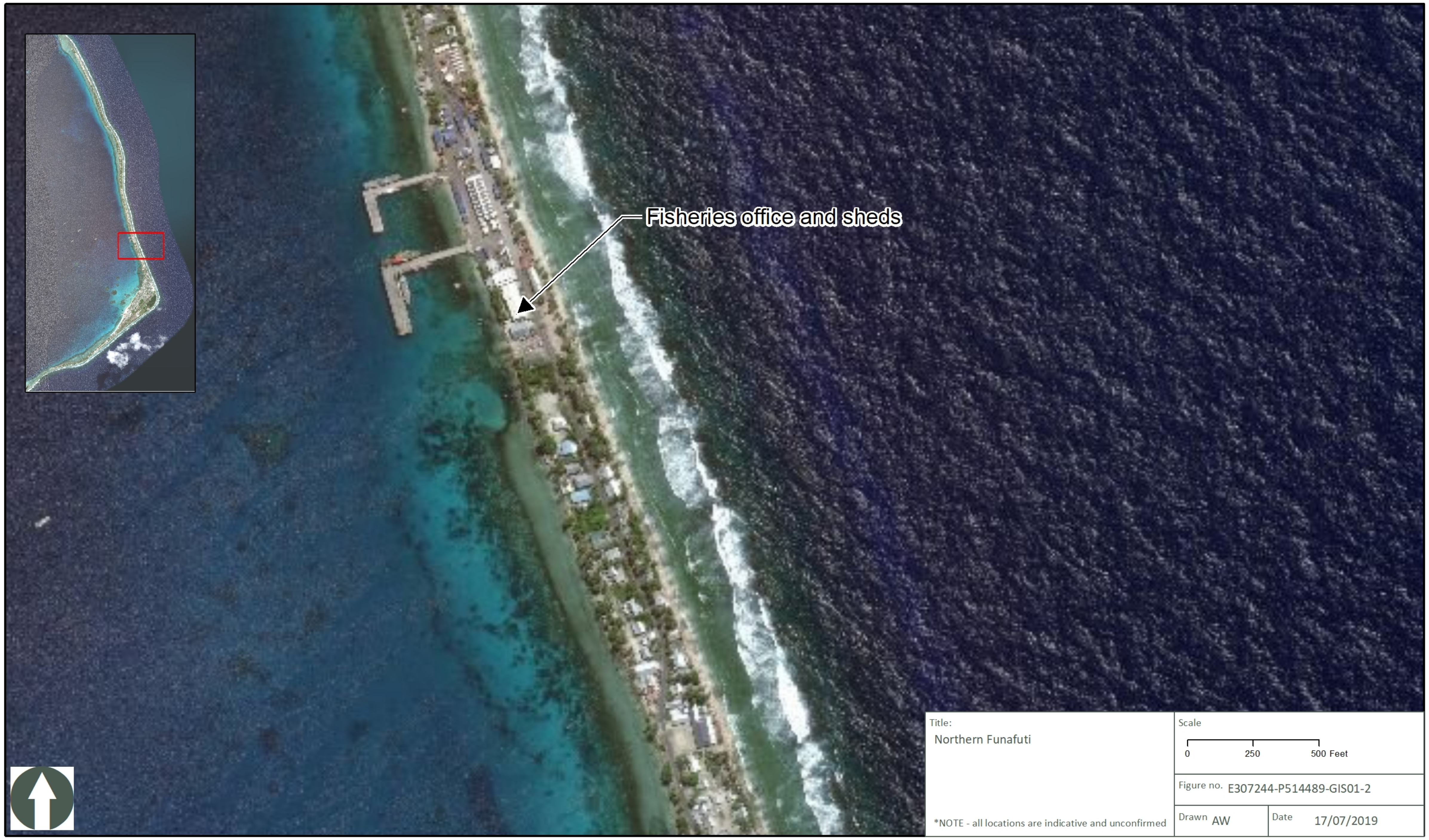
A.1 Funafuti summary overview of potential solar site locations

Figure "C:\Project\Tuvalu\P514489_GIS_Fugafale.mxd"



Data source(c): Building: Fieldsurvey; Basemap: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

A.2 Northern Funafuti



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Data source(c): Building: Fieldsurvey; Basemap: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

A.3 Central Funafuti

Data source(c): Building: Fieldsurvey; Basemap: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

A.4 Southern Funafuti

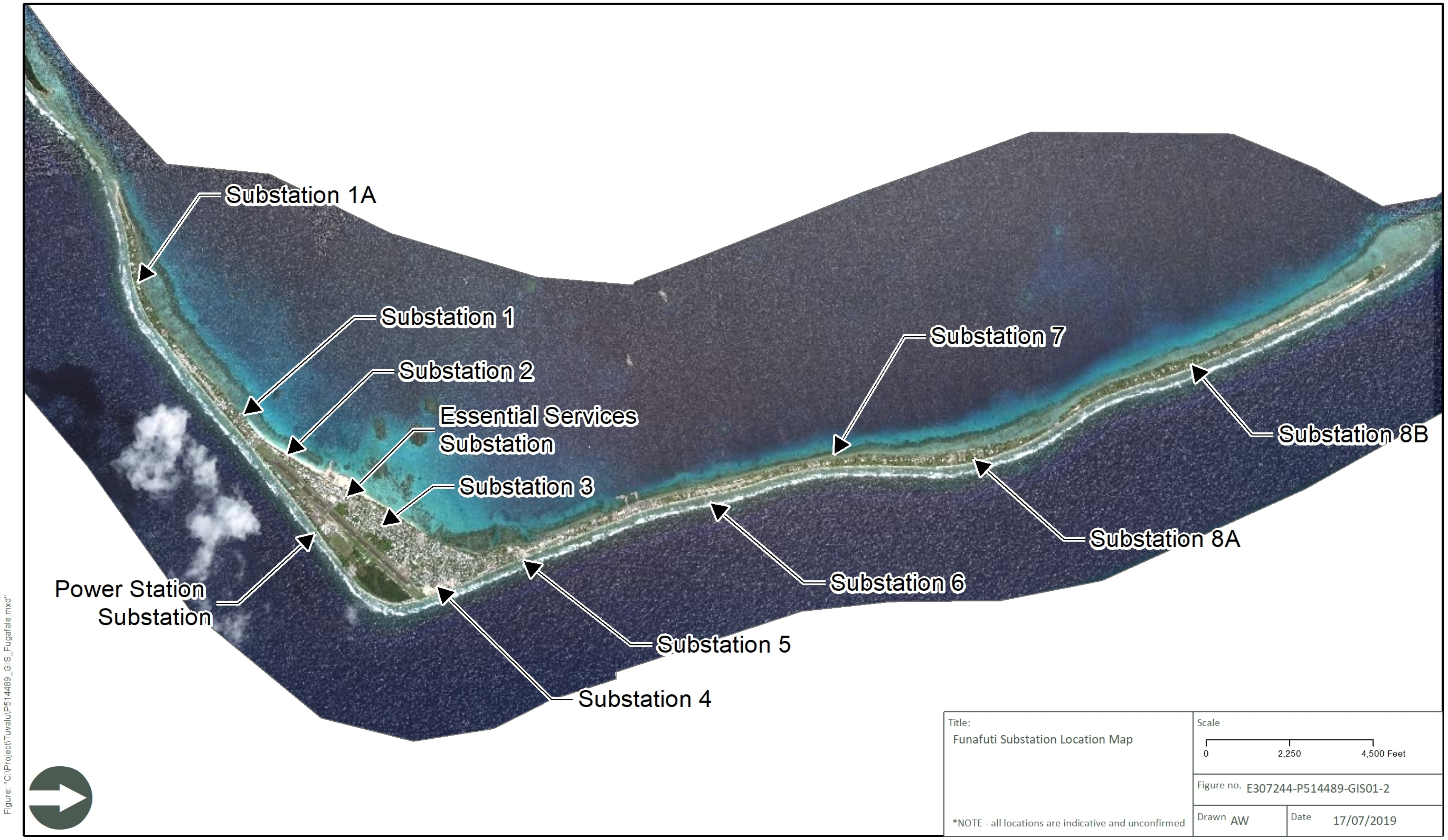
Data source(c): Building: Fieldsurvey; Basemap: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

A.5 World Bank project proposed solar sites on Funafuti

Title:	Scale
World Bank project proposed solar sites	0 250 500 750 Feet
	Figure no. E307244-P514489-GIS01-2
*NOTE - all locations are indicative and unconfirmed	Drawn AW / Date 17/07/2019

Data source(c): Building: Fieldsurvey; Basemap: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

A.6 Funafuti Substation Locations (rotated view of Fongafale islet on Funafuti Atoll, Tuvalu)



Data source(c): Building: Fieldsurvey; Basemap: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS

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B Funafuti solar PV assessments

To enable an assessment of solar PV capacity for Funafuti several assumptions have been made regarding proposed equipment configuration, and an updated approach to align with the technology used for existing systems. Some assessments are limited in their accuracy by low resolution imagery.

In the assessments it is assumed that 320W modules or greater will be selected as the cost effective module capacity. The capacity assessments for sites are based on currently available cost effective module power outputs. In the future it is highly likely that these will increase as technology improves and solar PV costs fall.

Standard array size configurations are utilised for the purposes of this assessment which for some sites is limited in resolution of the available imagery. Estimates given are conservative and it should be noted that limited high resolution site data may affect the accuracy. 200 mm offsets to ridges, edges and guttering are assumed. If skylights or other obstacles are present but not identified in this assessment there may be reductions in capacity for some buildings. Installations can be optimised and adjusted to suit any unidentified minor constraints or obstacles in detailed designs once screw hole/framing fixing locations are confirmed with onsite measurements of roof configurations. Some installations with low roof pitch angles may require additional inter-row spacing to allow for maintenance access which could result in less potential capacity.

A summary of the assessment considering the possible options is presented in Table 10.1. The Sports ground stadium and Fisheries buildings have been assessed for solar capacity however the World Bank or other projects may utilise these areas. Other options considered but assessed as unfeasible have been discarded. Areas or possible sites where assessments are incomplete or require further investigation are included for reference and discussion.

Uncertainties remain around the structural integrity of some of the older buildings in regard to their roofs ability to withstand the additional wind loading created by adding solar. These aspects will be considered further with structural engineering assessments to occur prior to procurement contract completion if warranted.

Table B.1: Solar expansion options for Funafuti

Option (appendix ref./building name)	Assessment completed	Assessment accuracy	Potential capacity (kWp)	Rooftop Structural Integrity [19]
QE II Park				
B.1 - QE II Park Rooftops	Yes	high	500	New, good.
B.2 - QE II Park walkway, roadway and carpark covers	Yes	high	1,220	N.A.
Government Building rooftops				
B.3 - Princess Margaret Hospital	Preliminary	medium	259	Assessed as satisfactory
B.4 - Fisheries office and sheds	Preliminary	medium	141	Unknown, not assessed
0 - Partnership house	Preliminary	high	67	Unknown, not assessed
B.6 - Prison rooftop	Preliminary	medium	22	Unknown, not assessed
B.7 - Waste sorting building	yes	medium	25	New, good.
B.8 - New Court house	Preliminary	low	50	Unknown, not assessed
B.9 - Civil Servant Buildings	yes	high	192	Unknown, not assessed
B.10 - Govt. office building carparks	Preliminary	high	30	Assessed as satisfactory
B.11 - Ministerial housing	Preliminary	medium	See below	Unknown, not assessed
B.11.1 - Governor General house	Yes	high	14	Unknown, not assessed
B.11.2 - Prime Ministers house	No	low	-	Unknown, not assessed
B.11.3 Ministerial house – 1 to 6	Preliminary	low	115	Unknown, not assessed
B.11.4 Ministerial house - 7	Preliminary	low	20	Unknown, not assessed
B.11.5 Ministerial house - 8	Preliminary	low	34	Unknown, not assessed
B.11.6 Navy House Compound	Preliminary	low	45	Unknown, not assessed
B.12 Airport Rooftop	Yes	low	168	New, good.
B.13 Sportsground / grandstands	Yes	medium	825+	Poor or N.A.
Local Government Buildings – Funafuti Kaupule				
B.14 Kaupule Hall – Tausda Lima	Preliminary	medium	84	Unknown, not assessed
B.15 Kaupule Church	Preliminary	medium	84	Unknown, not assessed
B.16 Kaupule Water cistern	Preliminary	high	147	N.A.
Other Government controlled land				
B.17 Road coverage or other public spaces	Preliminary	low	2000+	N.A.
B.18 Wetlands - solar option	Preliminary	low	1-2MW	N.A.
B.19 Funafuti Lagoon Floating Solar	Preliminary	low	1-4MW	N.A.
B.20 Piggeries roof cover	Preliminary	low	50	Poor or N.A.
B.21 Bank rooftop	Preliminary	low	12.8	Unknown, not assessed
B.23 Land at southern end of airstrip	Preliminary	medium	610	N.A.
B.24 land behind air controller building	Preliminary	low	120	N.A.

Option (appendix ref./building name)	**Assessment completed**	**Assessment accuracy**	**Potential capacity (kWp)**	**Rooftop Structural Integrity [19]**
Non-Government organisations and land				
B.25 Primary school	Preliminary	medium	183	Unknown, not assessed
B.26 Island community hall, (at airport)	Preliminary	low	34	Unknown, not assessed
B.26 Vaiavu Vaialofa Church	Preliminary	low	34	Unknown, not assessed
B.28 NGO - women's health	Partial	medium	20	Unknown, not assessed
B.29 Provident fund house	Preliminary	medium	12	Unknown, not assessed
B.30 Greenhouses adjacent to airstrip	Partial	medium	270	Unknown, not assessed

Note: Potential capacity values have been rounded from the below assessments. Preliminary rooftop assessments are likely to require structural assessments of roof weight and wind loading capabilities for final assessments.

B.1 QE II Park building rooftops

To enable an assessment of solar PV capacity for Funafuti several assumptions have been made regarding proposed equipment configuration, and an updated approach to align with the technology used for existing systems. In the assessments it is assumed that 320W modules or greater will be selected as the cost effective module capacity

Standard array size configurations are utilised for the purposes of this assessment with 200 mm offsets to ridges, edges and guttering are assumed. If skylights are present but not identified on the construction drawings in this assessment there may be reductions in capacity for some buildings. Installations can be optimised and adjusted to suit any unidentified minor constraints or obstacles in Contractor detailed designs once screw hole/framing fixing locations are confirmed with onsite measurements of roof configurations.

Assessments for further capacity on the QE II Park achievable through walkway covers, internal roadways and/or carpark covers is included in the separate road map report.

The QEII Park buildings remain under construction. Plans for the convention centre not been made available at the time of this assessment, drawings for the Falekaupule and Bungalows have been provided. A draft drawing version of the overall site plan is shown below in Figure B.8. Estimations of total roof area have been provided by the QE II Park site Project Director, as per the following Convention centre assessment. The assessments undertaken as detailed in this section have been used to define the ADB Stage 1 project scope and for modelling purposes, showing significant capacity of at least 500 kWp could be added on the roof tops of the new buildings once construction is complete. This project targets installing low cost rooftop solar in the QE II Park, raised walkway/roadway covering structures for solar PV are detailed for this area are detailed in this section for Stage 2 and the future roadmap. Completion of a more detailed assessment of the convention centre rooftop remains a high priority for this project and work is continuing to collect the design information.

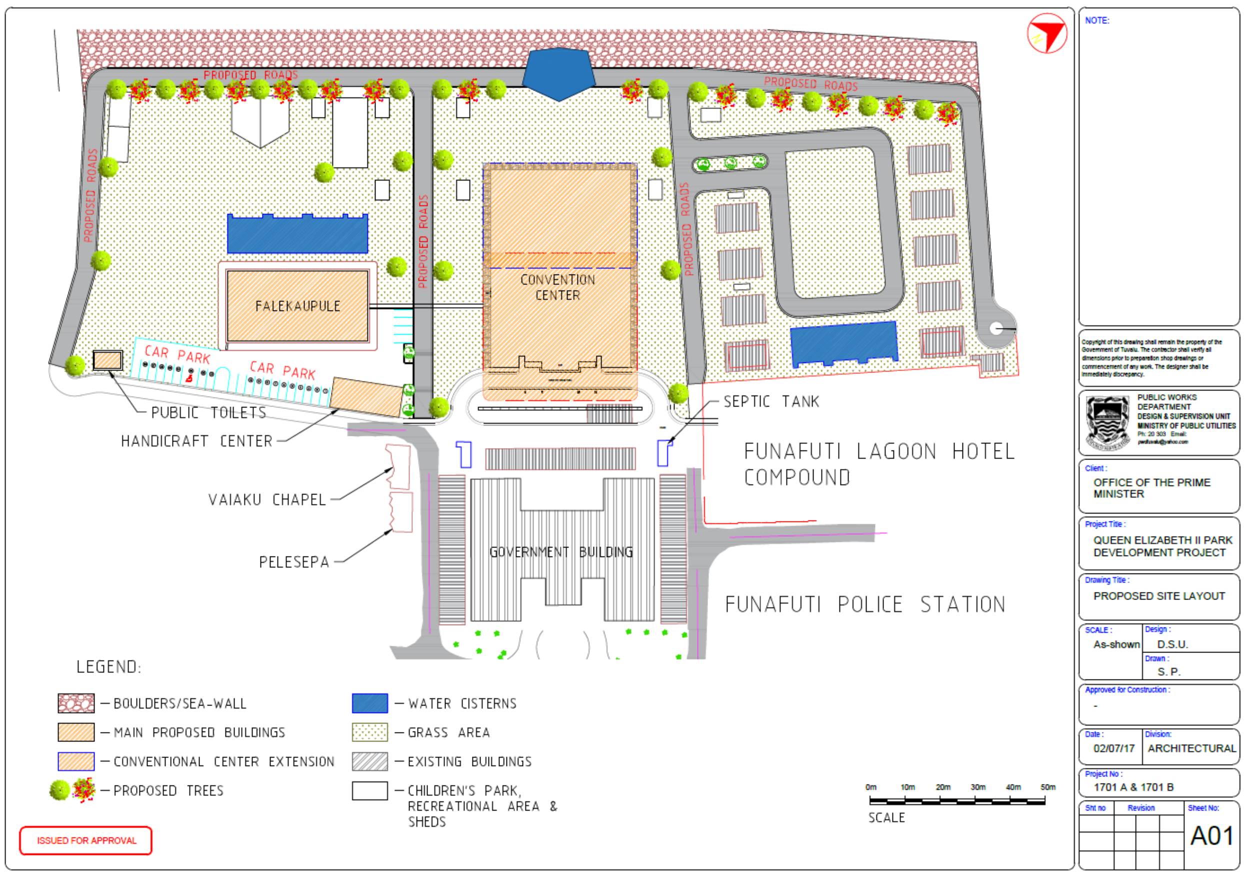


Figure B.1: Draft version of the overall QE II Park site plan.

B.1.1 QE II Park - Bungalows

Latitude	-8.523597
Longitude:	179.194042
number of modules (qty.)	588
Solar capacity (kWp)	188.6

These buildings are new and mostly complete with several out buildings still under construction. They sit on reclaimed land to the North West of the main Government office building. The As-Built drawing set has been provided for the bungalows, with rooftop dimensions shown below.

Ten bungalows in total are under construction as seen on site and in Figure C.9 and Figure C.10.

Figure B.2: QE II Park buildings viewed from the southern edge.

Figure B.3: QE II Park bungalows viewed from the eastern side at the Lagoon Hotel.

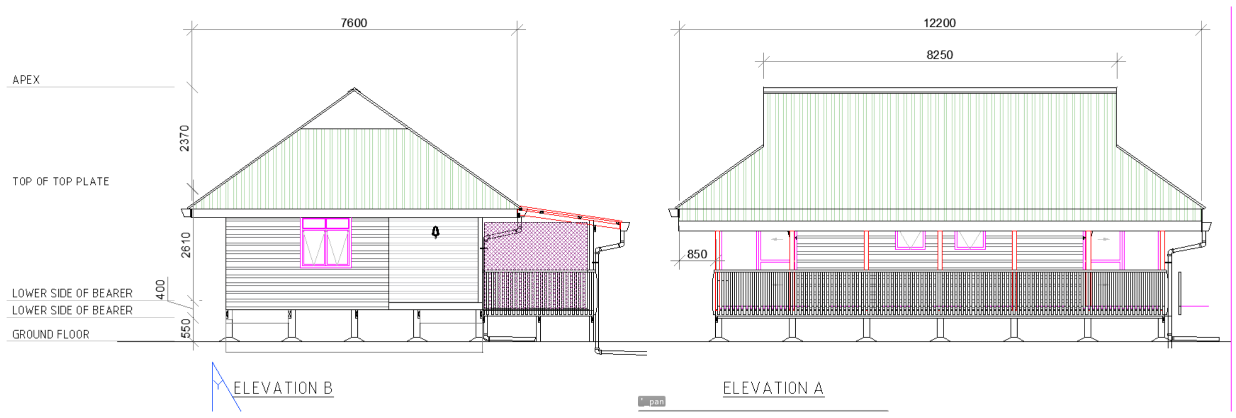


Figure B.4: QE II Park bungalows elevations

Each building is constructed in the same design with a two pitched gabled roof (North West & South East) and smaller pitches on the other edges. Due to the angle of elevation of the South West pitch it is assumed that solar installed on this area would be uneconomic due to the sub optimal orientation and shading from the apex/ridge above. Each East West pitch measures around 4.56 m wide by 8.25m long. Allowing 200mm room for edge clearance will still leave room for a 5 module long by 4 high array in Landscape (L) with vertical railing. The North pitch of each building will fit four modules in a 2 x 2L or a 4 x 1P configuration. Additionally each bungalow has a 12m, long veranda suitable for a single row of 10 modules in Portrait (P). In total per bungalow, 54 modules (17.28 kWp utilising 320W modules).

There are ten buildings leading to a total potential capacity of 172.8 kWp for the bungalows.

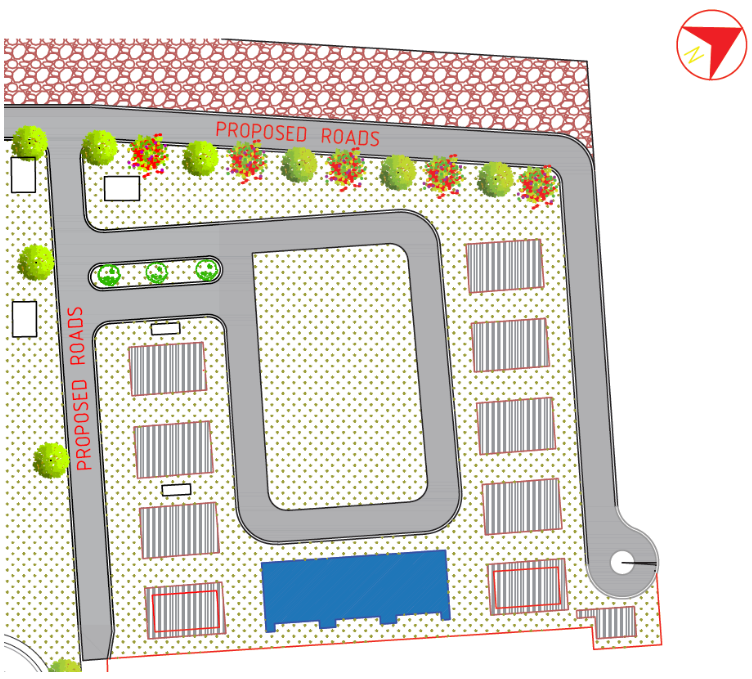


Figure B.5: Preliminary Bungalows area site layout, communal building shown in blue, nine buildings shown but ten buildings are confirmed under construction.

Within the area contained by the bungalows there is also a large central communal bar and dining area, shown blue in in Figure B.5 above, that has different roof pitch areas of which two are suitably constructed and orientated to accommodate solar. Each of these has two pitches suitable for rows of 6x2P arrays, leading to a total of 48 modules for the building (15.36 kWp utilising 320W modules).

Each building on the site has space besides its local switchboard for a string inverter per structure.

Overall the capacity assessment for the buildings in the bungalows area gives a total of 188.16 kWp. Significantly greater capacity can be achieved in this area through the construction of raised framing structures covering walkways and roadways. These are discussed separately for the whole of the QEII Park site and have a higher cost profile.

B.1.2 Convention centre

An estimation of the total rooftop area available for the Convention centre (2,669 m2) has been provided by the Project Director, Ampelosa Tehulu, enabling an estimate of the upper bounds of the rooftop space. Utilising standard module sizing, the typical module capacity selected (320W) and covering approximately 80% of the area, gives the following upper bound capacity:

Building	**Available area (m^2)**	**Modules (qty.)**	**Capacity (kWp)**
Convention centre	2,669	1420	454.4

B.1.3 Falekaupule - Stage

Drawings of the Falekauple building have been provided, showing a gabled roof construction with the apex ridge aligned from North East to South West.

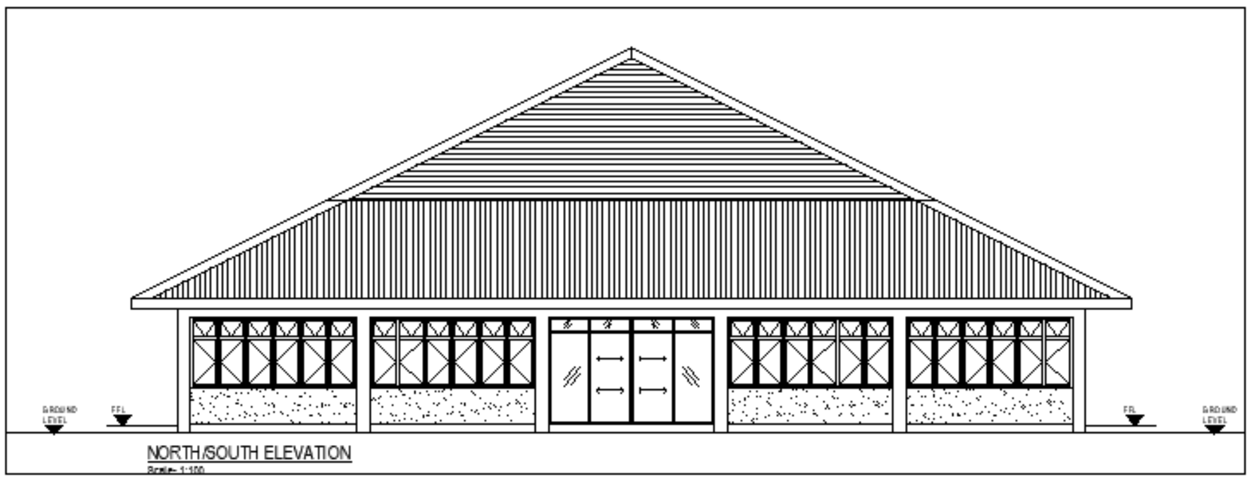


Figure B.6: Falekauple N/S building

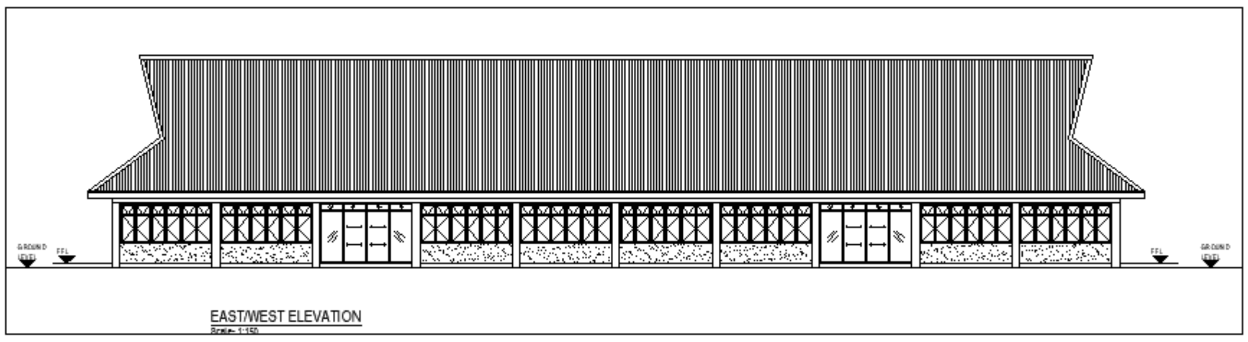


Figure B.7: Falekauple building E/W elevation

Each large pitch measures 12.47m vertically by 32m long of usable area. With a rooftop array of this size and vertical extent it is recommended to leave some inter-row spacing's for ease of access if maintenance testing or module replacement is required at a later stage. To this end, lengthways rows per pitch of 3 x 2P x 30 modules long are recommended. Hence for this building the assessed capacity is for 360 modules (115.2 kWp with 320W modules)

Building	**Modules (qty.)**	**Capacity (kWp)**
Stage	360	115.2

B.2 QE II Park Bungalow walkway, roadway and carpark covers

The QEII Park site remain under construction. The site plan drawing below is subject to further change. This section examines the potential site capacity for raised frame solar PV structures.

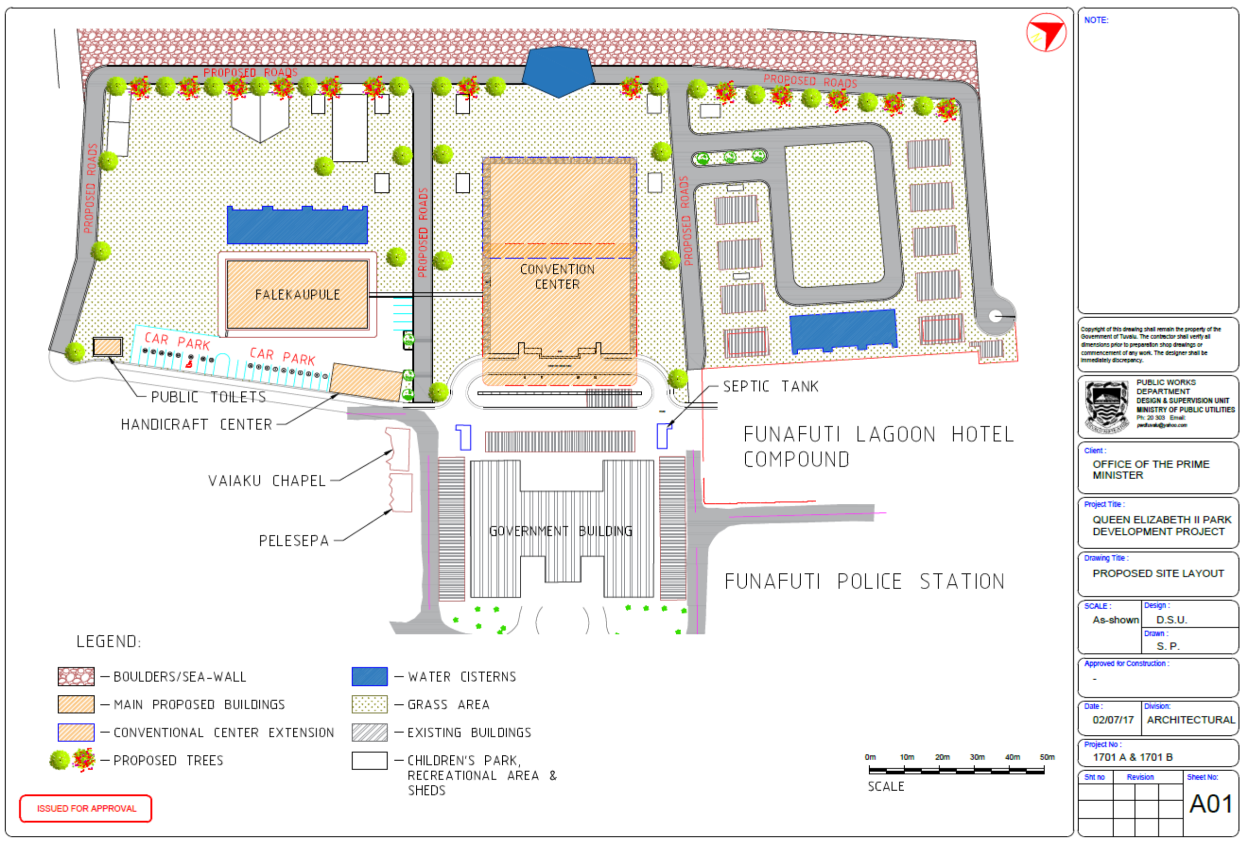


Figure B.8: Draft version of the overall QE II Park site plan.

Capacity of the various options on this site has been assessed using a combination of measurements from existing walkways on site and plan view measurements within the site plan drawing CAD file.

Walkways exist on site around the bungalow buildings. These are not shown on the drawings. Walkway covers of two module lengths wide can provide solar capacity in these areas at lower cost than roadway or carpark covers as their heights and framing structures would require less substantial framing systems. 6m wide road way covers are considered along with a 55m by 10.5m area for the carpark cover.

Area	Modules (qty.)	Capacity (kWp)
Roadways	2,868	917
Carpark	385	123
Bungalow Walkways	570	180
Totals	**3,823**	**1,220**

B.3 Princess Margaret Hospital rooftop

Latitude	8°30'54.10"S
Longitude:	179°11'57.71"E
number of modules (qty.)	925
Solar capacity (kWp)	259

Assessment of the Hospital rooftop via desktop with high resolution imagery has been undertaken. As seen in Figure C.7 the proposed solar has been overlayed on the image with care taken to provide edge clearance and space from obstacles. The proposed capacity includes 925 modules, leading to an overall capacity of 259 kWp.

The capacity of the existing AC switchboards and transformer at the connection point has not been fully assessed. The hospital transformer capacity listed on the Funafuti SLD is 300kVA, below the capacity of the combined existing and proposed PV, although the hospital would have a minimum load level which may offset the capacity shortfall through self-consumption. Spare capacity and suitability of the existing Hospital switchboard has not been confirmed on site. Regardless of the existing connection point capacity there are options to upgrade if required to facilitate the proposed capacity. This can be confirmed during procurement tender site visits or by the final installation contractor during the design process.

Figure B.9: The Hospital rooftop aerial view, with some existing solar visible (darker blue) and proposed solar over-laid (lighter blue).

B.4 Fisheries building and other Marine warehouses

Latitude	8°30'13.41"S
Longitude:	179°11'45.99"E
number of modules (qty.)	507
Solar capacity (kWp)	141.96

The capacity at the Fisheries site is spread over the main office building (88.76 kWp) and the two warehouse buildings to its south (53.2 kWp combined). The connection point capacity at this site requires confirmation and there is another building to the north of the main fisheries office where more capacity may be added. These details will be investigated during the next site visit.

Figure B.10: The Fisheries main office rooftop aerial view in the top centre of the image, with proposed solar over-layed (blue). The two separate marine warehouses are seen to the south.

B.5 Partnership house rooftop

Latitude	8°31'32.82"S
Longitude:	179°11'36.71"E
number of modules (qty.)	240
Solar capacity (kWp)	67.2

Figure B.11: Partnership House roof, showing roof space available from low resolution 2016 satellite imagery. (Image courtesy of GoogleMaps)

Measurements from satellite imagery indicate a gabled roof with two pitches (North West & South East), each 7.5m wide and 32m long. Conservatively, using both pitches this would allow for six 10 kWac array blocks arranged in 6 x 10m format (a 4 portrait arrangement per pitch), leading to 67.2 kWp in total. Some shading may impact the North Eastern edge from a coconut tree, this could be replaced with a lower growing species.

B.6 Prison rooftop

Latitude	8°31'37.52"S
Longitude:	179°11'41.57"E
number of modules (qty.)	80
Solar capacity (kWp)	22.4

The best resolution image available for assessing the prison rooftop is from June in 2016 via google earth. While it may be possible to fit up to 30% more on the rooftop, the uncertainty in measurements from the available data have led to an estimated capacity of 22.4 kWp for this site.

The suitability and capacity of this building will be assessed in more detail during the next site visit to confirm the pitch and available area. Ground mount structures may also be possible on this site if they do not conflict with future management or development plans.

Figure B.12: Prison roof top, showing roof space available from low resolution 2016 satellite imagery. (Image courtesy of GoogleMaps)

B.7 Waste sorting building

Latitude	8°31'24.10"S
Longitude:	179°12'1.28"E
number of modules (qty.)	90
Solar capacity (kWp)	25.2

This new building has been recently completed on the Eastern side of Funafuti to the North East of the Sports Field. The existing vents significantly limit solar PV capacity, it could be three times higher without the vents in their current location. Options exist to relocate the vents but this is likely a cost prohibitive exercise when there is available space on other buildings under assessment. The vents are visible in the figures below.

Figure B.13: the newly constructed Waste Sorting Building viewed from the south.

Figure B.14: the newly constructed Waste Sorting Building viewed from the South West, with vents visible.

B.8 New Court house

Latitude	8°31'30.53"S
Longitude:	179°11'38.10"E
number of modules (qty.)	90
Solar capacity (kWp)	25.2

Latitude: -8.524310,

Longitude: 179.198749

This two storey building is currently under construction and the scale of the available roof space is unknown at the time of writing this report. Building plans have been requested. Based on the footprint of the foundations the capacity has been estimated at 50 kWp, yet this is highly uncertain and further investigation is required when information becomes available.

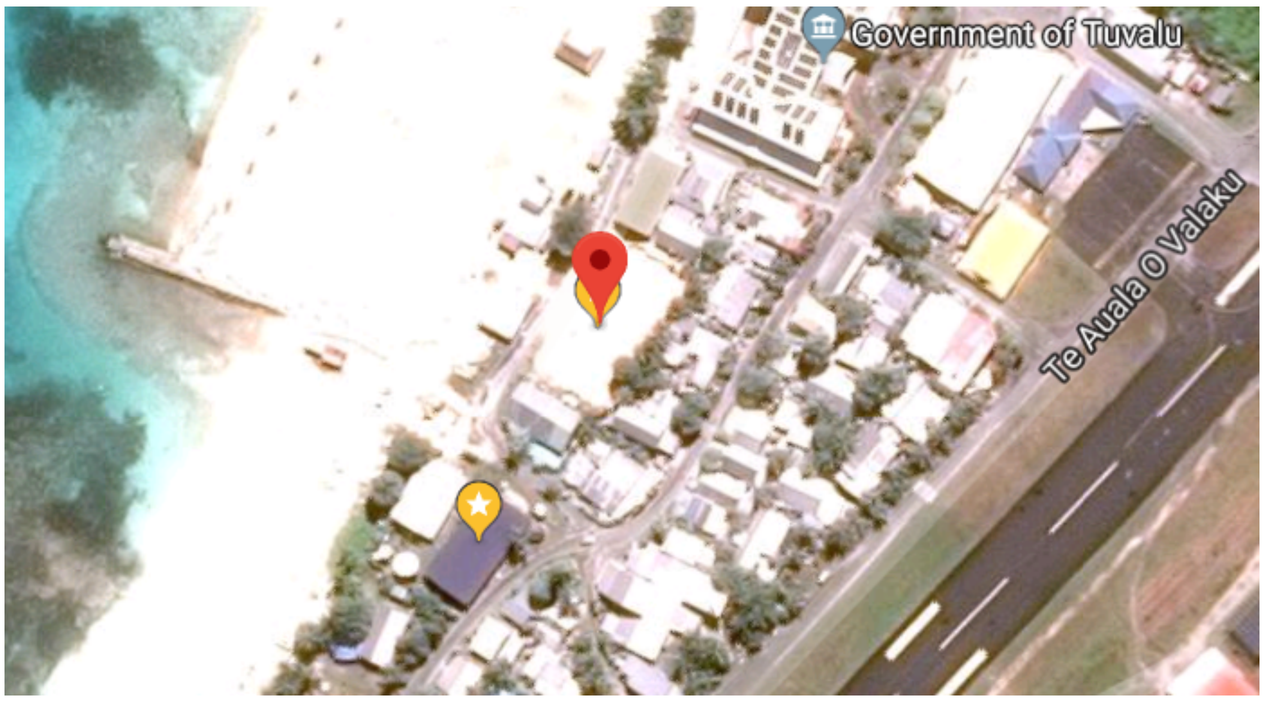


Figure B.15: The Court house location, under construction. (Image courtesy of GoogleMaps)

B.9 Civil Servant Buildings (Disaster relief houses)

Latitude	8°31'22.49"S
Longitude:	179°11'43.58"E
number of modules (qty.)	600
Solar capacity (kWp)	168

From observations during Entura's site visit to Funafuti these buildings appear half way through construction. With four out of fifteen buildings completed as seen in Figure C.8.

Figure B.16: Civil Servant houses, four are visible in this image, with another eight nearing completion immediately adjacent on the Sothern side (not shown). (Image courtesy of GoogleMaps)

Each building is constructed in a very similar design patern with a two pitched gabled roof (North West & South East aspects). Each pitch measures 4 m wide by 12 m long however image resolution is low. Allowing room for edge clearance would still provide space for a 3 m by 10 m, 6.4 kWp array block on each pitch.

Fifteen buildings in total with two pitches per building holding 6.4 kWp each, leads to a total potential capacity of 192 kWp.

Management of these buildings is currently through the central government. Informal comments indicate that these buildings (along with the ministerial housing) may be transferred to the local Kaupule in the near future.

Figure B.17: Civil Servant houses, eight nearing completion, viewed from the North East.

B.10 Govt. office building carparks

Latitude	8°31'27.75"S
Longitude:	179°11'39.99"E
number of modules (qty.)	108
Solar capacity (kWp)	30.24

The carpark rooftops have a gabled construction type as per the 2014 image below. This, and the aerial view measurements leads to a likelihood that only one row of modules in portrait will be reasonably practicable. The construction type of the newer western side carpark roof is unclear from the more recent 2017 imagery as per XXX. The Sothern side carpark roof appears likely to be severely affected by shade and is considered unviable at this time. The total estimated capacity of 30.24 kWp is conservative at this time and may be increased if warranted by further site inspections.

Figure B.18: a gabled construction type visible on the Northern carpark rooftop. (Image courtesy of GoogleMaps)

Figure B.19: low resolution 2017 imagery leading to a conservative capacity estimate. (Image courtesy of GoogleMaps)

B.11 Ministerial housing

B.11.1 Governor Generals house (temp.)

Latitude	8°31'36.22"S
Longitude:	179°11'35.85"E
number of modules (qty.)	52
Solar capacity (kWp)	14.56

The Site photo (Figure C.6) shows a two pitched gabled roof (North West & South East). Measurements from the aerial view (Figure C.6) indicate a 4m wide by 14m long pitch on each side. There is significant uncertainty in this measurement due to the image resolution.

For each pitch, 2 modules in portrait by 13 in length would well utilise the space, with allowance for the required edge clearances. This leads to a total of 52 modules or around 14.56 kWp.

Figure B.20: Aerial view of the Governor General house rooftop. (Image courtesy of GoogleMaps)

Figure B.21: The Governor Generals residence as viewed from the roadway to the North West.

B.11.2 Prime Ministers house rooftop

The Prime Minister's residence is currently being rebuilt. The rooftop design has not been made available for this assessment, hence the assessment is incomplete at this time.

B.11.3 Ministerial Housing (buildings 1 to 6)

Latitude	8°31'33.63"S
Longitude:	179°11'35.81"E
number of modules (qty.)	60/360
Solar capacity (kWp)	19.2/115.2

Figure B.22: Ministerial House No.1 viewed from the front roadway.

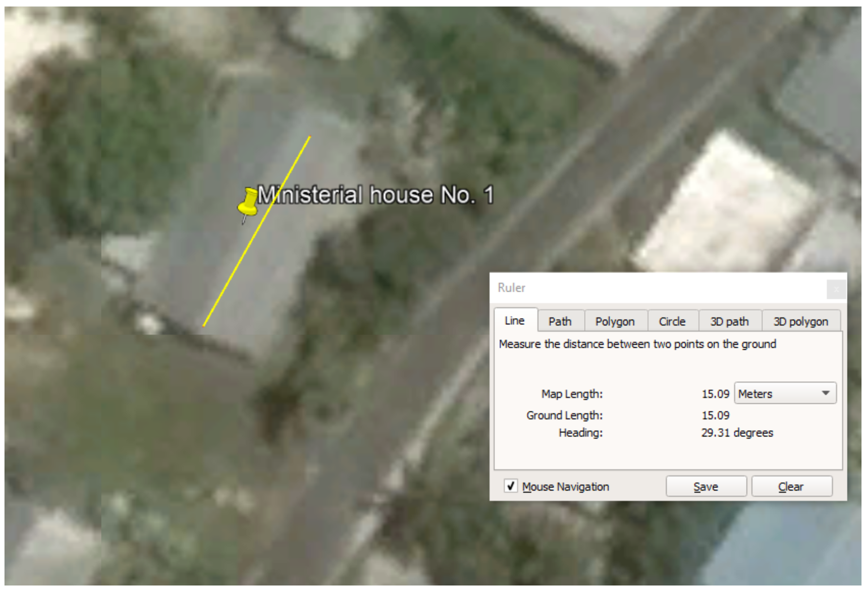


Figure B.23: Ministerial House No.1 plan view (Image courtesy of GoogleMaps)

These buildings are all of similar design with various small outbuildings. Conservative plan view measurements for each of these buildings show that each pitch has space for 2P x 15 module rows, a total of 60 modules, at 320W each leads to 19.2 KW per building. The southernmost two buildings have recently been upgraded and their current rooftop space is not visible on the older available imagery. It is believed that their roof space provided by the upgrades is slightly larger than the measurements for the other four structures, hence, this assessment is conservative.

B.11.4 Ministerial House No.7

Latitude	8°31'39.40"S
Longitude:	179°11'32.48"E
number of modules (qty.)	62
Solar capacity (kWp)	19.84

Aerial view measurements indicate that each of the upper pitches of this building are likely to support 2 Portrait x 19 modules rows. There is also a gabled roof section running to the south where another 24 modules may be located, leading to a total of at least 62 modules for the building (at 320W each gives 19.84 kW. There are other smaller roof areas which may be utilised but these cannot be confirmed without detailed measurements on site.

Figure B.24: Ministerial House No.7 viewed from the roadway to the south east.

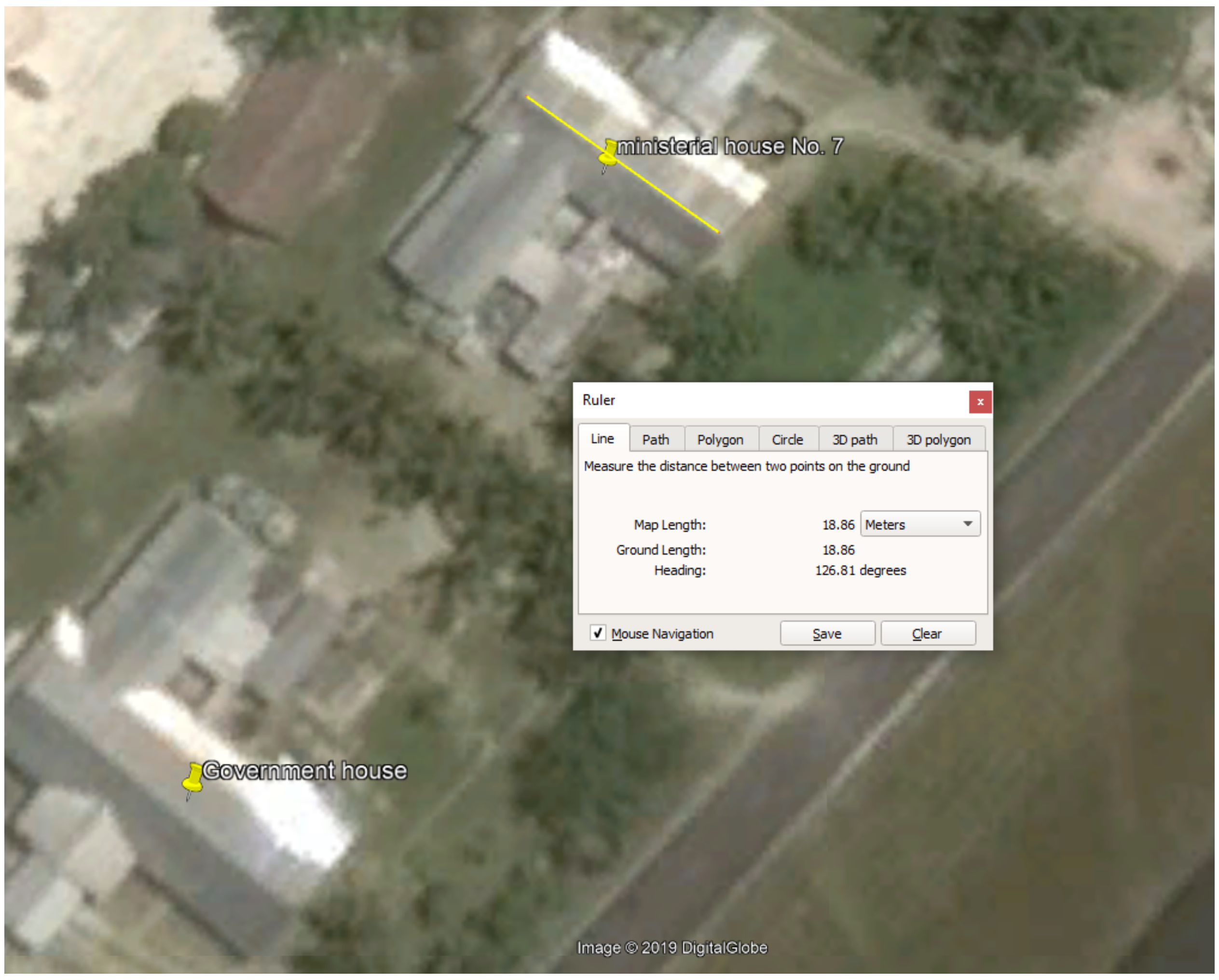


Figure B.25: aerial imagery of Ministerial house No. 7 (Image courtesy of GoogleMaps)

B.11.5 Ministerial House No.8

Latitude	8°31'43.01"S
Longitude:	179°11'29.89"E
number of modules (qty.)	105
Solar capacity (kWp)	33.6

Aerial imagery of this building indicates that 3 rows in portrait will fit on each of the main gabled roof pitches and one below on the lower space visible in the image below. The roof length measures just over 15 meters, leading to a total of 105 modules, at 320w each, 33.6kW

Figure B.26: Ministerial House No.8 viewed from the roadway to the south east.

B.11.6 Navy House Compound

Latitude	8°31'43.73"S
Longitude:	179°11'29.26"E
number of modules (qty.)	140
Solar capacity (kWp)	44.8

This building consists of two gabled roof sections; running from West to East, joining in a L-shape and then running N/S. The four available roof sections each provide sufficient vertical space for 2 Portrait module rows, with a total row length of 70m (140 modules, @320W each, 44.8 kW).

Figure B.27: Navy House Compound colloquially known as Australia House.

B.12 Airport rooftop

Latitude	-8.524495
Longitude:	179.195064
number of modules (qty.)	560
Solar capacity (kWp)	168.96

The Airport building rooftop has been designed with some internal allowance for cabling with ducting installed. The current available imagery does not show the newly completed building however several photos are available from the inception trip to undertake an approximate assessment of the achievable capacity on the given roof space.

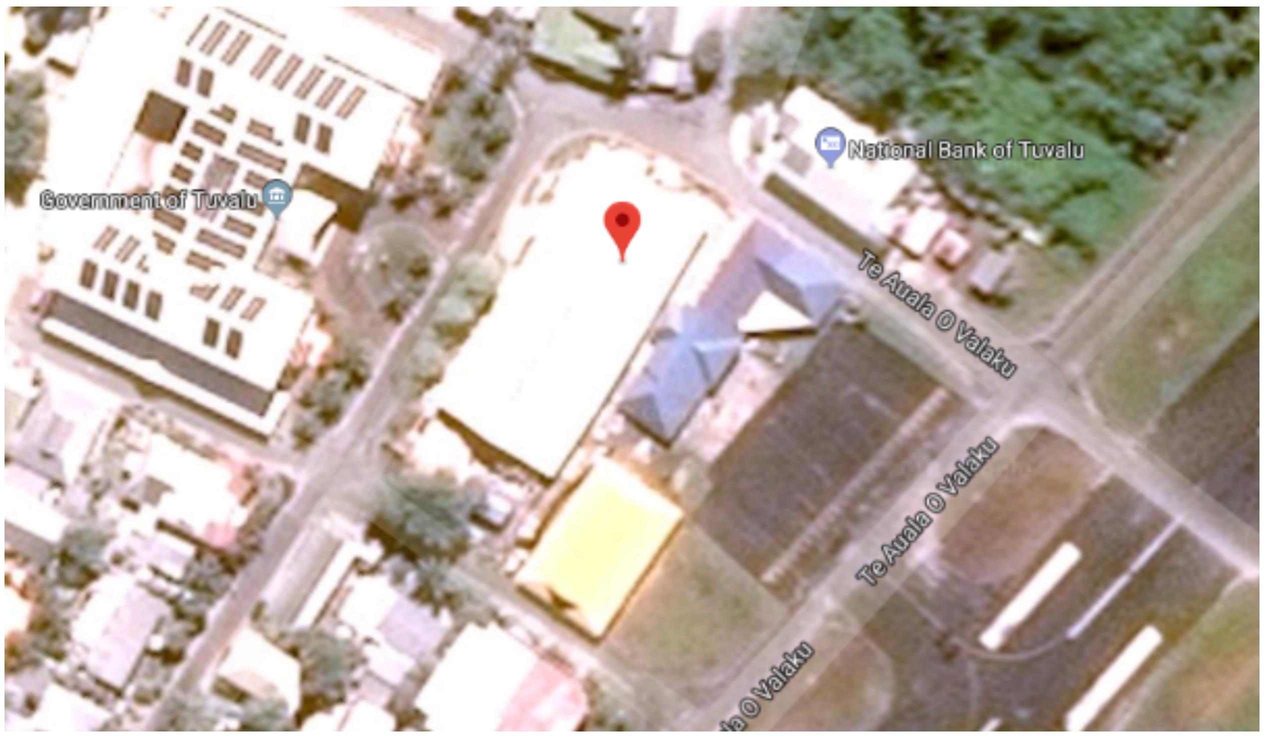


Figure B.28: Airport arrivals/departure lounge roof via Google maps Imagery, showing new roof space with poor definition for assessment of available area. (Image courtesy of GoogleMaps)

Google Earth measurements indicate each pitch (North West & South East) measures approximately 11m wide and 50 m long. On each pitch 6 rows in portrait by 48 modules should fit comfortably with spacing every second row for maintenance, however some interference is likely from the ridge skylights reducing this estimate to 5.5 rows by 48 modules. Utilising 320W modules leads to approximately 84.48kW capacity available per pitch. Leading to an upper estimate of capacity being 168.96 kWp. Additional photos confirming this assessment are shown below where the ridge skylight is visible. Rooftop measurements are required to confirm capacity and designs in more detail.

Figure B.29: The airport roof North West pitch with the skylights visible on the top centre right.

Figure B.30: The airport roof North West pitch with the skylights visible on the top.

B.13 Sports park structures

Latitude	-8.524310
Longitude:	179.198749
number of modules (qty.)	2,580
Solar capacity (kWp)	825

The sports park has an existing 40 kW array which is out of service and is likely at the end of its useful life. The existing modules are heavily delaminated, with junction boxes hanging loose and damaged wiring.

Entura understands that government plans include replacement of the older grandstand and installation of a new change room/amenities building on the opposite side of the sports ground where there is currently a wooden view stand shelter in place. The existing structures can be seen from the aerial imagery in Figure B.33.

Figure B.31: The grandstand solar project nameplate from 2007.

Figure B.32: The grandstand solar project module condition after 11 years of operation. Delamination, discolouring, loose junction boxes and damaged wiring is visible.

Figure B.33: the existing grandstand structure seen in the bottom right, the wooden view stand shelter can be seen marked with a star in the top left. (Image courtesy of GoogleMaps)

Building plans for the replacement of the grandstand and the new amenities building were unavailable at the time of writing this assessment. For estimation purposes it has been assumed that the new structures will occupy a similar or slightly larger footprint as the existing infrastructure. It is also assumed that new roof pitches will be of negligible elevation angle and can be fully utilised for solar modules. It is also assumed that additional raised fixed structures to the north and south of the sports ground would be acceptable.

Replacement structures for the wooden view stand shelter to the west and the existing grandstand to the south east could be built with the following features; measuring 9m wide by 100m long, each suiting 600 modules.

Additional raised fixed structures to the north and south of the sports ground could be constructed in a similar form to those at the TEC power station. If constructed 9m wide by 115m long, each could house 690 modules.

Efficiencies of scale would be realised on this site which reduce cost although additional structures would be required in a form similar to those at the power station or larger grandstands. The costs of grandstand seating and other facilities has not been examined in detail in this assessment. The above estimate leads to a potential capacity of 2,580 modules at 320W each, leading to a total of around 825 kW for this site. This capacity could be further increased by up to 30% by increasing the width of the structures to the north and south of the sportsground.

It has been reported that the World Bank Project now plans to utilise this site. Indications are that their array footprint is outside of the proposed layout discussed above, however it is likely that it would lead to a reduction of this assessment. The proposed layout in this assessment will remain as preliminary until the World Bank Project plans are completed as any further additions would need to be coherent, integrated and considered for astetics.

B.14 Kaupule Hall – Tausda Lima

Latitude	8°31'5.32"S
Longitude:	179°11'52.04"E
number of modules (qty.)	262
Solar capacity (kWp)	83.84

Figure B.34: Kaupule Hall – Tausda Lima, viewed from the northern end looking south. A side view is available below in Figure B.37.

This building is of a gabled roof construction, with each main East/West face consisting of two pitches, each of increasing inclination angle which increase ascending towards the ridge.

The upper pitches each measure 4m vertically in plan view by 24m long, suitable 2 Portrait module rows for a combined total of 96 modules. The lower East/West pitches would hold a similar capacity. There is a shorter north eastern pitch suitable for around another 20 modules and a newer western roof area which may support an additional modules. This leads to a total of 262 modules, at 320W each, leading to a total of 83.84 kW for this site.

B.15 Kaupule Church

Latitude	8°31'6.17"S
Longitude:	179°11'53.50"E
number of modules (qty.)	264
Solar capacity (kWp)	84.48

Figure B.35: Kaupule Church building on the left.

Figure B.36: Kaupule Church building viewed from the west with the water cistern visible down low in front.

This building, similar to the Kaupule Hall, is of a gabled roof construction, with each main East/West face consisting of three pitches, each of increasing inclination angle which increase ascending towards the ridge. The highest pitch has a very high inclination >50%, hence considered unsuitable for solar at this latitude.

Each of the lowest E/W pitches measures 4.5m x 36m and would likely fit rows of modules in 3 protrait, with 105 modules per pitch. The central pitches appear suitable for 2 protrait rows by 27m long, giving 54 modules. In total for this building the potential capacity is 264 modules, at 320W each, leading to a total of 84.48 kW

B.16 Kaupule water storage cistern

Latitude	8°31'5.82"S
Longitude:	179°11'52.76"E
number of modules (qty.)	460
Solar capacity (kWp)	147.2

Figure B.37: Kaupule water storage cistern and hall in the background.

This large water cistern is located in the clear courtyard area between the Kaupule Hall and Church. The cistern is concrete and slightly raised above the surrounding road/pathway. A raised fixed framing structure on this site could have multiple benefits; providing significant solar PV capacity in close proximity to the two other potential buildings on this site, and rain covering of the cistern (providing a sheltered area, possibly for sports, and potential for additional rainfall catchment from the solar PV structure). The cistern area measures 21 x 33m, all of which could be covered by a raised PV structure. This equates to around 460 modules, at 320W each, leading to a total of 147.2 kW for this site.

B.17 Road coverage or other public spaces

Options for increased solar generation capacity include new solar module mounting structures covering roadways or public spaces, similar to the raised PV framing structures at the power station (see Figure C.19). Very large additional capacity could be added to the system by covering roadways.

There are numerous road lengths to explore, subject to community acceptance. Generally, public roadway coverings are likely to be more complex in implementation than other sites identified in this assessment, due to varying/multiple lease conditions & greater framing span widths and more complex detailed designs.

There are pros and cons regarding this approach;

- Higher cost than rooftop solar.
- Risks of impact leading to failure to gain approvals.
- The cost of implementation is higher than using existing rooftops due to the additional framing infrastructure.
- The framing cost would be higher than the power station array due to the span requirements without central supporting posts.
- Shade from the sun is provided to pedestrians and motorists.
- Detailed designs may be complex due to varying road widths and the need to avoid existing infrastructure.
- Land ownership and lease agreements may be complex.
- Land use is not impacted.
- A high profile approach that may provide international project exposure opportunities.

Figure B.38: the existing raised PV framing structures at the Funafuti power station

B.18 Wetlands – solar options

Latitude	8°31'14.25"S
Longitude:	179°12'6.62"E
number of modules (qty.)	8,659
Solar capacity (kWp)	1-2 MW

The wetland area North East of the airstrip has been identified as a potential area for an additional solar development in the future. The area is sufficient for a large raised fixed framed structure similar to the above example. To consider this up to a feasibility standard, further field investigations would be required at cost to confirm viability beyond the scope of this project. Floating solar options would have to be considered in regard to their suitability for the saline environment and possible cyclonic weather. Framing structures would also require similar investigations regarding water depth, construction methods and geotechnical design.

A 100 kWp solar pilot program is reportedly planned by Fastnet to be established in the northern end of this site.

At this time options for expansion of solar generation in the Wetlands have been ruled out as the local government now plans to rehabilitate the area. Capacity estimates for a raised fixed structure type installation are 2MW and for floating solar is 1MW

B.19 Funafuti Lagoon floating solar option

Latitude	8°31'14.44"S
Longitude:	179°11'30.60"E
number of modules (qty.)	3000
Solar capacity (kWp)	1095 (expandable to large scale)

A floating solar installation inside the Funafuti atoll lagoon is considered in this section. The sizing selected is presented to convey the anticipated footprint of a selected technology, it is easily expandable, with other solutions requiring different footprints. To consider this up to a feasibility standard, further field investigations would be required at cost to confirm viability beyond the scope of this project. Floating solar options would have to be considered in regard to their suitability for the saline environment and possible cyclonic weather. At this time this area is still considered as a possibility in the Funafuti Road Map, however Entura believe it is likely a higher cost option which should be left towards the end of the Road Map implementation. This preliminary assessment considers utilising the Ciel & Terre solution, although after more product development has occurred for the Ocean Sun solution that may be preferred due to its suggested ability to withstand cyclonic events.

For the floating solar array capacity sizing, larger modules with increased capacity have been assumed in-line with the capabilities of modular floating systems available from Ciel & Terre. The basic system specifications are outlined in the following tables.

PV Modules	**Unit**	**Inputs**
Supplier		Canadian Solar
Type		CS3U-365MS
Voc	V	47.2
Vmpp	V	39.4
Isc	A	9.77
Impp	A	9.27
Power STC	W	365
V Max	V	1500
µPmax	%/°C	-0.37
µVoc	%/°C	-0.29
µIsc	%/°C	0.05
NOCT	°C	
Width	mm	992
Length	mm	2000

Sub array	Unit	Inputs
Tilt (module inclination angle)	deg.	12
string length	qty.	30
string quantity	qty.	10
floating frame 'unit' length (East/West)	m	2
floating frame 'unit' length (North South)	m	1.26792242
area per module floating frame 'unit'	m^2	2.53584484
modules per 'sub array'	qty.	300
area per 'sub array'	m^2	760.753452
sub array length (East/West)	m	60
sub array length (North South)	m	12.6792242
sub array power	kWp (DC)	109.5

1 MWac array	Unit	Inputs
Sub Array quantity	qty.	10
floating solar power rating	kWp (DC)	1095
farm length (East/West)	m	125
farm length (North South)	m	68.396121

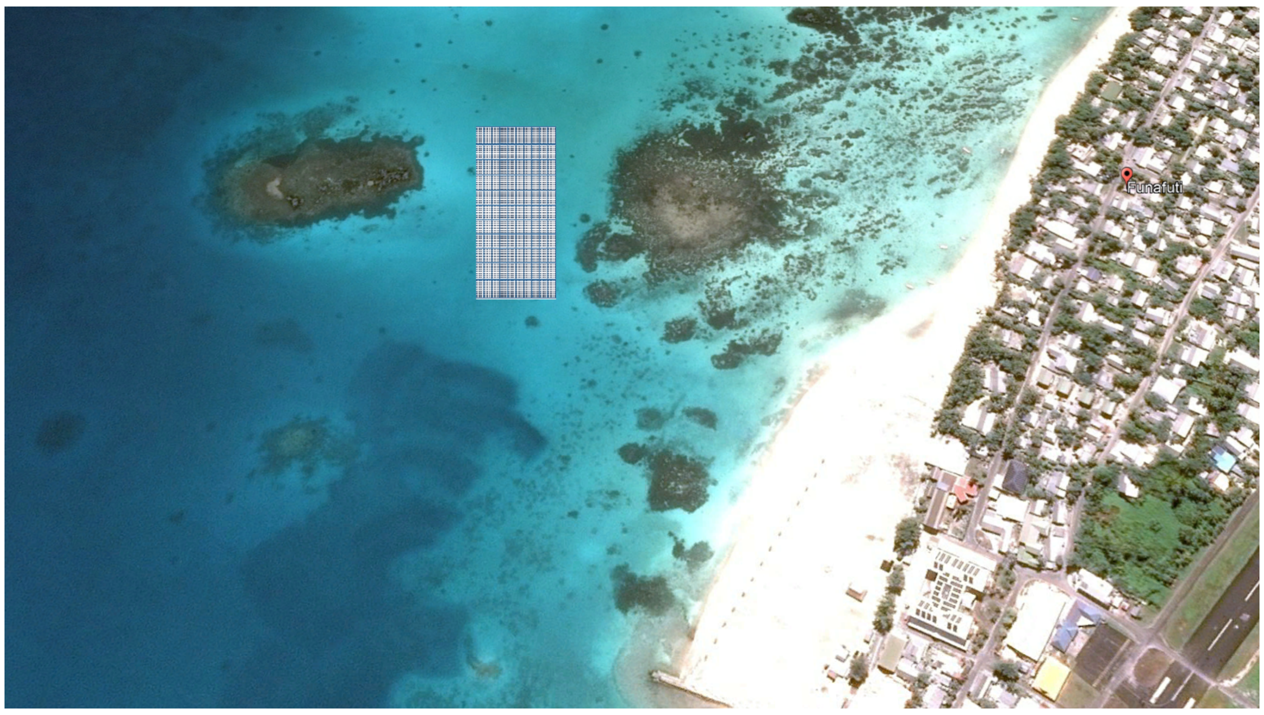


Figure B.39: Above, a 1 MWac simple floating solar layout option for the Funafuti Lagoon, to the north of the new QE II Park. (Image courtesy of GoogleMaps)

B.20 Piggeries roof cover

Latitude	8°31'14.15"S
Longitude:	179°12'2.62"E
number of modules (qty.)	156
Solar capacity (kWp)	50

A structure has been proposed as upgraded roofing for the existing piggeries that run along the North Easternmost edge of the runway. Unfortunately the majority of this site lies within the 61m standard clearance required for the runway, otherwise the site could house a substantial solar facility.

B.21 Bank rooftop

Available imagery of this site is poor resolution, limiting the accuracy of this assessment. Observations from site indicate that this rooftop is in poor condition and may require replacement prior to installing solar PV. Detailed assessment through rooftop measurements are recommended prior to proceeding with this site. This assessment requires further consultation with stakeholders.

Latitude	8°31'27.57"S
Longitude:	179°11'43.41"E
number of modules (qty.)	40
Solar capacity (kWp)	12.8

Figure B.40: Above, The Bank rooftop located adjacent to the airport terminal building (Image courtesy of GoogleMaps)

B.22 Further land reclamation in lagoon

The costs associated with this option are likely too high unless it is a secondary outcome realised by another project.

B.23 Land at southern end of airstrip

This assessment requires further consultation with stakeholders. The array is proposed to consist of low profile and tilt modules up to a height of around a meter. At this time the aviation clearance requirements for this space and offset limits are unclear.

Latitude	8°31'48.38"S
Longitude:	179°11'28.07"E
number of modules (qty.)	2180
Solar capacity (kWp)	610

Figure B.41: Land at southern end of airstrip (Image courtesy of GoogleMaps)

B.24 Space behind new air controller building

This assessment requires further consultation with stakeholders to determine if there are any future plans for the area. Plan view aerial measurements indicate the site may accommodate around 120kWp.

B.25 Primary school

Use of the primary school rooftops will require lease agreement with local Kaupule if and other stakeholder negotiations. They are likely to be favourable but would require compensation. This desktop study has been unable to clearly identify and confirm all buildings to be considered for installation of solar generation. Further assessments will continue during the next site visit.

Latitude	8°30'57.99"S
Longitude:	179°11'56.17"E
number of modules (qty.)	526
Solar capacity (kWp)	182.56

This initial assessment assumes all of the four larger buildings to the left of the roadway in Figure B.42 can be utilised. Roof pitch angles need to be confirmed onsite and structural assessments of roof framing wind loading capacity are likely to be required. These issues may reduce the solar capacity assessment.

Figure B.42: primary school No 1, usable rooftops to be confirmed. (Image courtesy of GoogleMaps)

B.26 Island community hall

Latitude	8°31'29.74"S
Longitude:	179°11'42.15"E
number of modules (qty.)	90
Solar capacity (kWp)	25.2

The Island community hall by the airport terminal has some useful roof space for solar although the capacity is constrained by the multiple. From available imagery it appears that there are four useful separate pitches suitable for single or double portrait module rows of at least 15m in length. Pitch angles and dimensions require site confirmation which may increase the capacity assessment for this site.

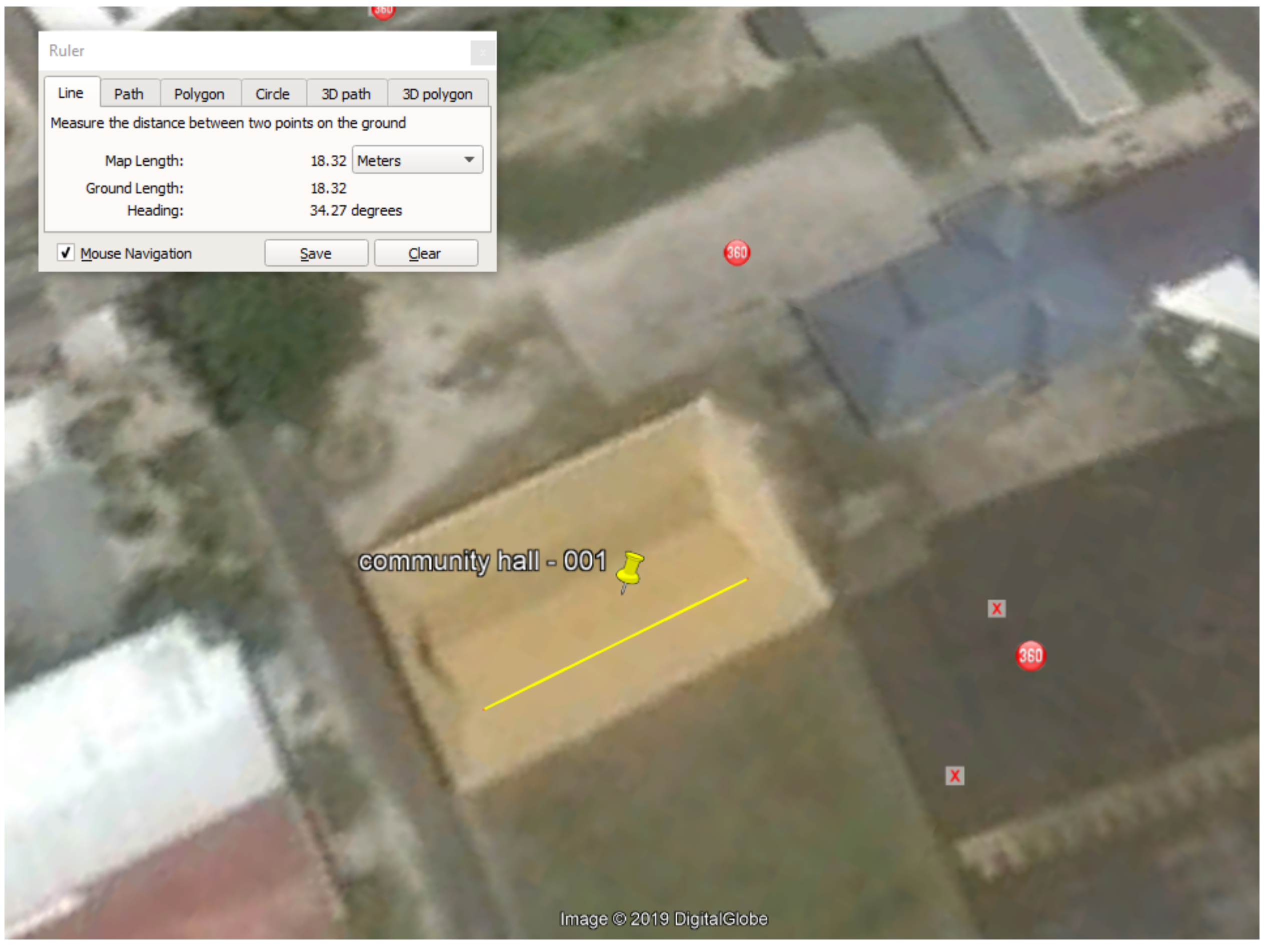


Figure B.43: community hall initial assessment with low resolution imagery. (Image courtesy of GoogleMaps)

B.27 Vaiavu Vaialofa Church

From available imagery it appears that there are two useful separate pitches suitable for rows of three modules in portrait of at least 20m in length. Pitch angles and dimensions require site confirmation which may change the capacity assessment for this site.

Latitude	8°31'29.23"S
Longitude:	179°11'38.52"E
number of modules (qty.)	120
Solar capacity (kWp)	33.6

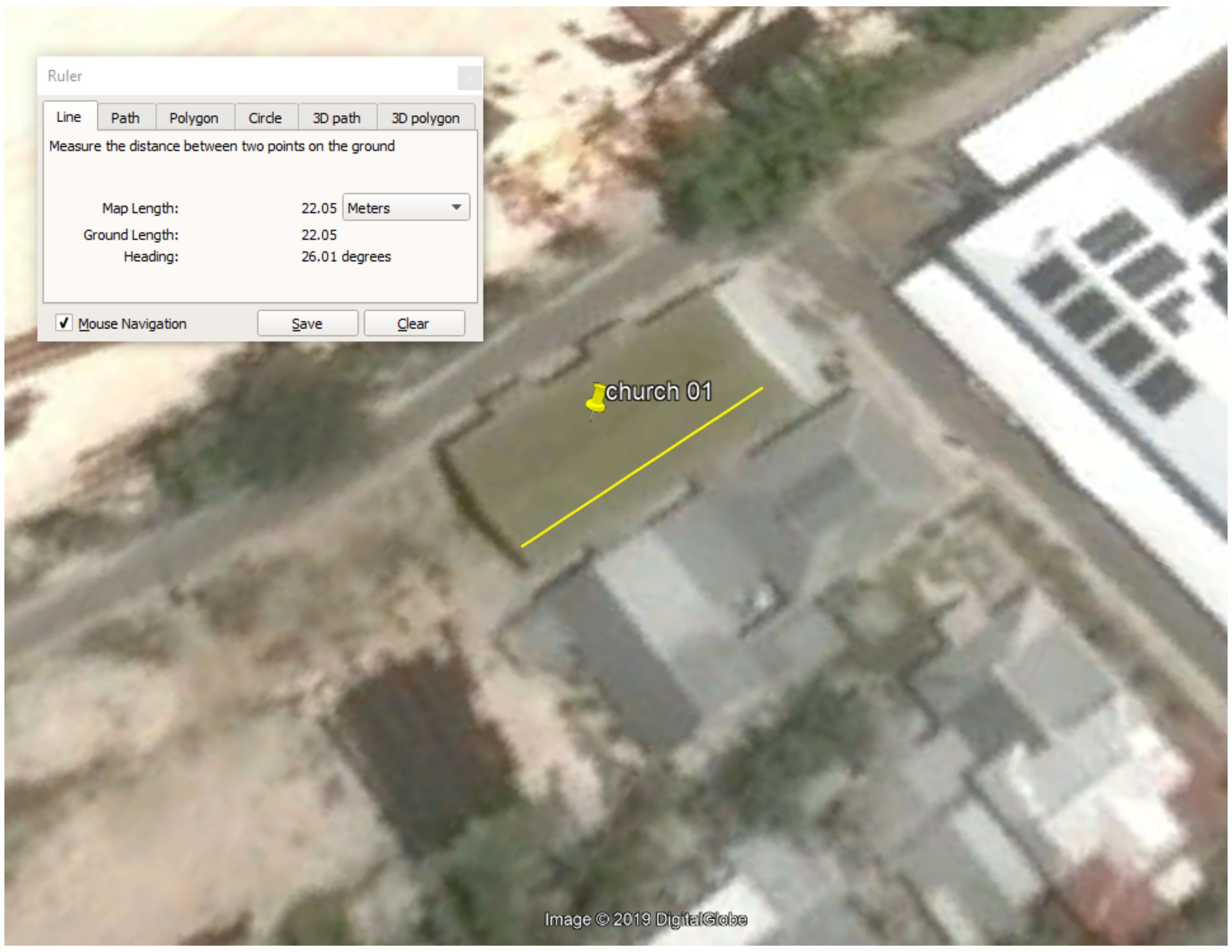


Figure B.44: Church No.1 initial assessment with low resolution imagery. (Image courtesy of GoogleMaps)

B.28 NGO – women's health - 2 buildings

From available imagery of the two buildings it appears that there are two useful separate pitches suitable for rows of two modules in portrait totalling at least 35m in length. Pitch angles and dimensions require site confirmation which may change the capacity assessment for this site.

Latitude	8°31'34.40"S
Longitude:	179°11'44.28"E
number of modules (qty.)	70
Solar capacity (kWp)	19.6

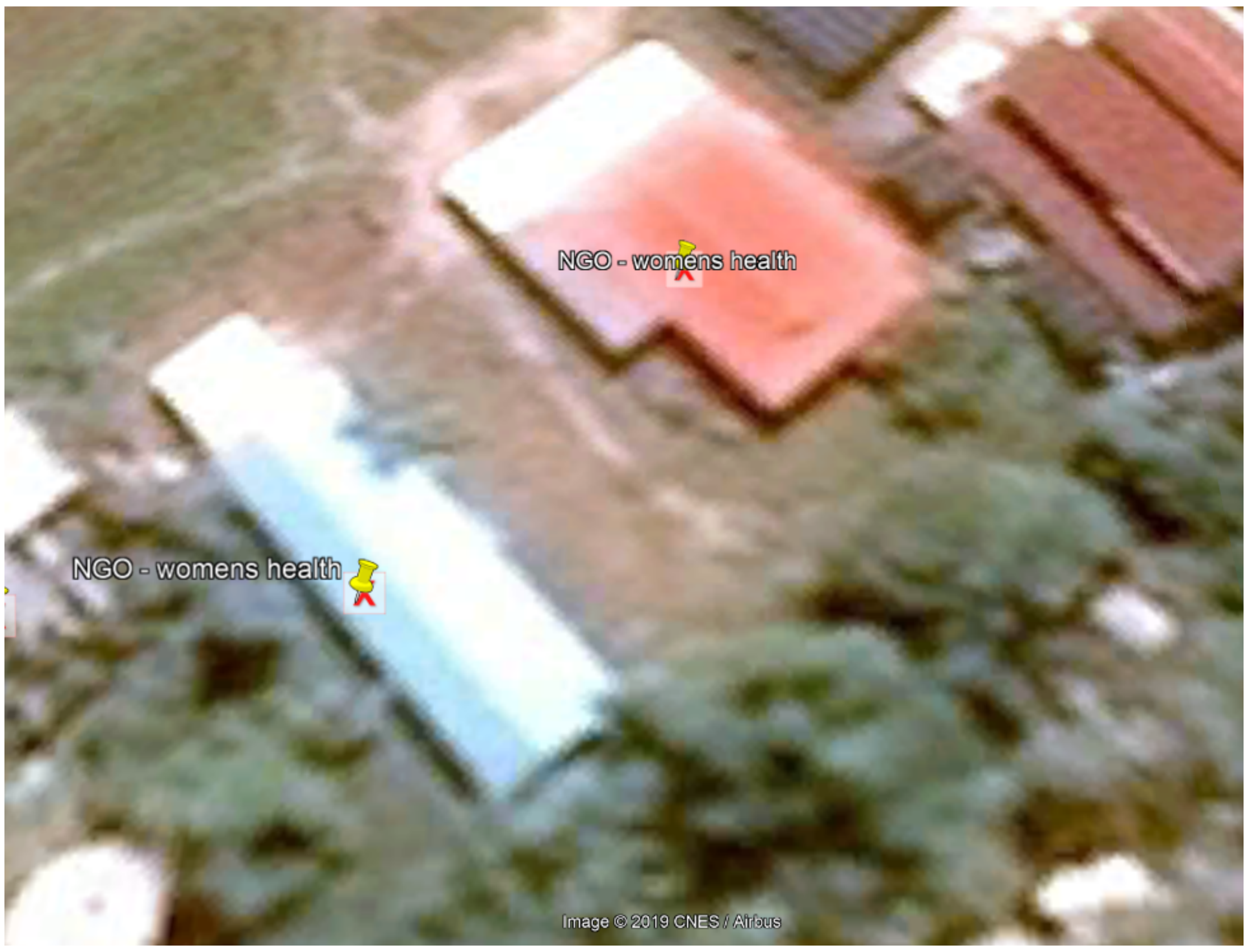


Figure B.45: The two Womens health buildings, with useful pitches on their North Eastern sides. (Image courtesy of GoogleMaps)

B.29 Provident fund house

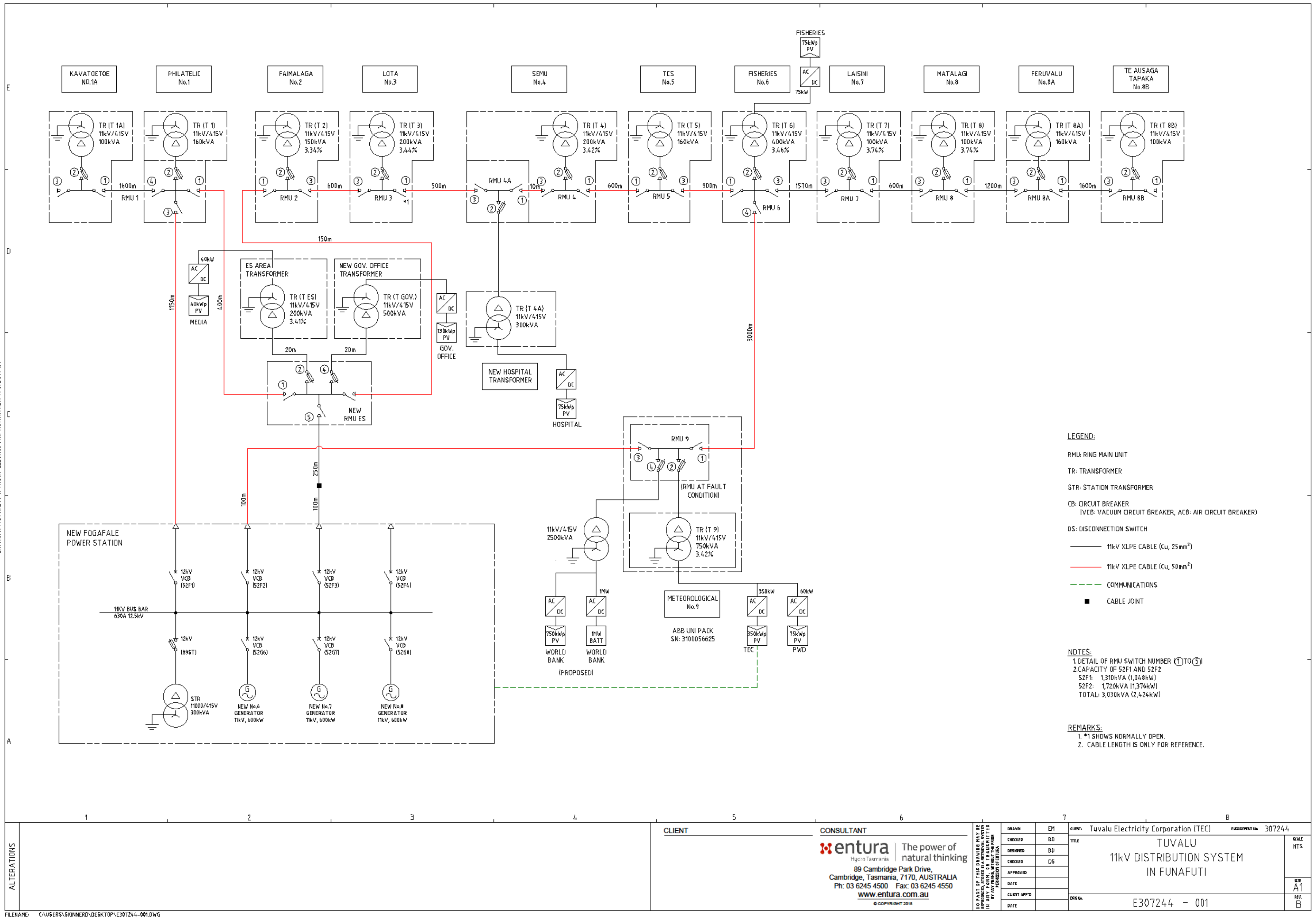
This assessment is incomplete due to low resolution imagery and limited site detail. The estimate of 12kW is based on brief site visit observations.

B.30 Greenhouses adjacent to airstrip on eastern side

This assessment is limited to aerial view measurements based on covering the entire area with raised fixed structures. The site area free from structures measures 85m by 25m, however almost half the site is within the 61m clearance required from the centre of the runway, reducing the width available down to 15m. This leads to available space for around 850 modules, or 270kW.

C Revised Electrical System Drawings

C.1 Funafuti Distribution Single Line Diagram – Existing System



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