Report

IRENA
International Renewable Energy Agency

Pacific Lighthouses

Hybrid power systems

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.
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Preface

In the Abu Dhabi Communiqué on accelerating renewable energy uptake for the Pacific Islands (of 13 January 2012), leaders from the Pacific Island Countries and Territories (PICTs) called on the International Renewable Energy Agency (IRENA) to "…map the Renewable Energy Readiness of the Pacific Islands Countries and Territories to ascertain the status of renewable energy opportunities and identify pathways to close gaps" and to integrate all IRENA activities in the region "…into a coherent roadmap for the Pacific Islands". In response, IRENA has carried out a wide range of activities of specific relevance and application to the PICTs as well as other Small Island Developing States (SIDS). This work has now been integrated into the IRENA report: ***Pacific Lighthouses: Renewable Energy Roadmapping for Islands***.

The report consists of an overview roadmap framework and 15 island-specific studies on the respective energy situations, and the challenges and opportunities for renewable energy deployment, around the region. These studies are available for the Cook Islands, the Federated States of Micronesia, the Republic of Fiji, Kiribati, the Republic of the Marshall Islands, the Republic of Nauru, Niue, the Republic of Palau, Papua New Guinea, Samoa, the Solomon Islands, the Kingdom of Tonga, Tokelau, Tuvalu and the Republic of Vanuatu. The IRENA Pacific Lighthouses report draws on those studies, as well as this additional study on a diesel-renewable energy hybrid power system, intended as a transition measure to a renewables-based energy future for the PICTs, which is also part of the series.

IRENA, in collaboration with its members and other key development partners, will continue to support the development national roadmaps and strategies aimed at enhanced deployment of renewables in the Pacific and other island states and territories.

Acronyms

GDP	Gross domestic product
GWh	Gigawatt-hours (Thousand Million kilowatt-hours)
kWh	Kilowatt-hours (1000 Watt-hours)
kV	Kilovolts
kVA	Kilovolt-ampere
ML	Megalitres
MW/ MWh	Megawatt (Million Watts)/ megawatt-hours
PV	Solar Photovoltaic
RPM	Revolutions per minute
USD	United States dollar (Currency)
Wp/kWp	Watts Peak/kilowatt-peak (Solar PV)

Summary

The use of diesel generators to power small and isolated electricity grids is especially prevalent in remote and rural areas in developing economies, especially in island states and communities where such generators are often the sole source of electricity generation. The remoteness of Pacific Islands and the related challenging and expensive logistics for fuel distribution result in high fuel costs and low security of supply. These issues threaten island energy and economic security and are of particular concern for the many least developed countries located in the area. Yet Pacific Islands possess a wide variety of abundant renewable energy resources that have the potential to greatly reduce or even eliminate their dependence on expensive imported fossil fuels.

The work reported herein focuses on identifying the key concepts, challenges and best practices needed to increase the uptake of renewables in Pacific Islands. In this context the report shows the results of a case study assessment and analysis of the potential for solar photovoltaic integration into the Tongatapu diesel-based power plant in Tonga. The study illustrates the role and levels that such hybrid systems could play towards a transition to a renewables-based energy future for islands of the Pacific region, where the power generation and transport sectors are mostly dependent on expensive imported refined oil products.

The key messages arising from this study are:

(i) In the medium and long terms, renewables-based power solutions would be the most sustainable and cost-effective solutions for Pacific Islands communities. In the transition to that stage, renewable power and diesel hybrid systems with high levels of renewables integration and energy efficiency measures can play a key role in the energy supply for island communities and are, indeed, a viable option for the Pacific Islands.

(ii) Successfully integrating solar power and/or wind power into a diesel generator-based power grid requires the use of a variety of enabling technologies to manage the variability of those sources of renewable energy.

(iii) Increasing the level of renewable power integration also increases the complexity of the systems needed to control variable power output to ensure grid stability, and could require investment in new diesel generators and improvement of grid infrastructure. It is therefore essential that local technical expertise is in place to ascertain sustainable operation and maintenance of the resulting complex grids.

(iv) Investment in smart meters and load control systems are needed if islands want to boost RE penetration through demand side management. The associated additional costs must be weighed against the money saved through reduced fuel consumption. Determining both the system cost and fuel savings requires a detailed knowledge of the final system configuration and power output. This requires islands to adopt a comprehensive power systems approach that takes into account all relevant information and generates a long term renewable power integration plan with clear and measurable goals.

(v) Planning efforts for renewable energy deployment need to identify the key skills and knowledge for successful system operation and maintenance and determine which skills are not present in the local labour force. Regional and local policy makers need to engage with Pacific universities and other institutions to develop local programs to start building these critical skills.

(vi) With relatively modest investments Pacific Islands could soon reach RE penetration levels that will eventually be required worldwide to mitigate climate change. Building strong local capacity in this area can transform the Pacific region into a center of expertise for decarbonising the power sector.

(vii) IRENA is already working with various partners in the regions, including the Pacific Power Association, to develop technical expertise for grid stability modelling and management.

1. Introduction

1.1 Energy challenges and opportunities for renewables in the Pacific islands

Islands present unique challenges and opportunities for the deployment of renewable energy (RE). Most Pacific islands are located far from major oil distribution hubs and depend on complex and lengthy fuel supply chains. Fuel delivery logistics are often further complicated by lack of modern port facilities, requiring the use of smaller, specialised boats. The small population sizes of many islands limit the level of fuel demand while the small geographic size constrains fuel storage. Both of these factors reduce the purchasing power of such island communities. As a result, islands in the Pacific region face some of the world's highest fuel costs and have greater exposure to price volatility and supply disruptions. In 2009 the region's utilities had consumer electricity tariffs that averaged USD 0.44/kWh and for some islands exceeded USD1.00/kWh. Electricity production costs are likely higher as many Pacific Islands provide subsidies to protect consumers from the full price of power generation.[1] High energy costs, price volatility and risks to fuel supply are of particular concern because most Pacific islands have small economies. High cost fuel imports can consume significant percentages of GDP, driving up prices on food and other essential items and limiting investments in education, infrastructure and other key services. In addition, climate change effects associated with oil consumption are major concerns for islands. Pacific islands face a significant threat from rising ocean levels, with some island having a maximum elevation of less than 5 meters above sea level.[2] Increased storm activity and weather disruptions associated with climate change threaten the many islands that are in the path of seasonal cyclones and typhoons.

Right from its inception, IRENA has acknowledged the exceptional status of islands and placed a special focus on assisting these communities. The opening declaration of the Agency's Statute specifically notes the "... the huge potential of renewable energy in providing ... access to energy for isolated and remote regions and islands[3]". Statute Article IV, which defines the activities that IRENA will engage in to support the uptake of renewables, mandates that the Agency bears "...in mind the special needs of the developing countries, and remote and isolated regions and islands."[4]

IRENA is demonstrating clear dedication to fulfilling its islands-specific mandate. One of the first activities of the Agency following its official launch in April of 2011 was a workshop on accelerated renewable energy development, with emphasis on the Pacific Islands region. This workshop took place in Sydney, Australia from the 26th to 28th of October 2011 and brought together leaders and key policy makers from a number of Pacific Islands Countries and Territories (PICTs). Discussions focused on identifying key technical, policy, economic and social barriers to the deployment of renewable energy and developing an understanding of how IRENA could assist the PICTs in overcoming those challenges. Grid stability was among the key issues identified for further support. Grid stability is very important if the share of renewables must be increased in existing grids.

This report focuses on identifying the key concepts, challenges and best practices needed to increase RE uptake on Pacific islands through hybrid RE and diesel-powered systems.

1.2 Energy use in the Pacific Islands region

Transportation and power generation dominate energy use in the pacific. Industry is mostly limited to mining on a few islands and more wide spread agricultural, forestry and fish processing facilities almost all of which rely directly on electricity. Traditional biomass use for cooking – although slowly declining in favour of LPG and kerosene – still accounts for the largest share of overall energy use in rural areas throughout the Pacific. With the exception of some notable contributions from hydropower energy use in the Pacific is dominated by fossil fuels. The lack of local oil resources and refining capacity in most of the PICTs means that refined oil products must be imported over great distances at high and volatile costs.

1 *Pacific Economic Monitor, Asian Development Bank, July 2010*

2 *https://www.cia.gov/library/publications/the-world-factbook/geos/kr.html*

3 *IRENA Statue, Opening Declaration, page 2*

4 *IRENA Statue, Article IV Activities, page 7*

1.2.1 Transpor sector

In the Pacific, transportation accounts for approximately 75% of energy demand and uses almost exclusively imported refined oil products. A lack of detailed data makes it difficult to determine the exact split of fuel usage between land, sea and air transport. However it can be generally stated that land transport is the largest sector and is dominated by a mix of diesel and gasoline passenger cars and light commercial vehicles. Sea and air transport can a play notable roles for Pacific states with a wide dispersion of populated islands. Generally sea transport is the larger of the two with varying contributions from interisland passenger and cargo services and fishing fleets. Local air transit is generally limit to a small number of light aircraft but can be significant on islands with developed tourist industries.

Currently cost and technical barriers impede a major shift in the transportation sector from the use of fossil fuels to renewables. However, given that the transportation sector dominates oil consumption in the Pacific Islands, it is essential that renewable energy-based options for transportation be thoroughly examined to determine when and how they can be deployed on a large scale.

1.2.2 Power generation

Power generation represents approximately 25% of energy demand in the Pacific Islands. Hydropower provides a major contribution to electricity generation on Fiji, PNG and Samoa. There is limited use of biomass to offset power consumption on islands with forestry and agricultural processing facilities. Solar PV systems, used widely for rural electrification are spread across the region. Utility scale wind parks are operational on Fiji and Vanuatu islands. However, the vast bulk of power generation capacity is based on internal combustion engines and generators utilising imported diesel, heavy fuel oil (HFO) and light fuel oil (LFO).

1.3 Overview of power generation in the Pacific Islands region

Table 1 presents the results of a review of the electricity generation systems of 15 PICTs. This review was performed using a variety of sources, including the Pacific Power Association (PPA) 2011 Benchmarking report and local utilities. The total generation capacity for the 15 PICTs is approximately 700 MW. In 2011 approximately

Table 1: 2010/2011 electricity generation statistics

PICT	Installed Capacity MW	Peak Demand1 MW	Annual Generation MW
Cook Islands	10.36	4.9	27,763
FSM-Chuuk	2.0	4.0	9,768
FSM-Kosrae	5.0	1.1	6,504
FSM-Pohnpei	7.6	6.9	38,920
FSM-Yap	6.6	2.3	13,000
Fiji	211.2	139.6	835,169
Kiribati	5.5	5.3	21,641
Marshall Islands-Majuro	28	8.9	75,749
Marshall Islands-Ebeye	3.6	2.0	14,183
Nauru	6.04	3.3	17,103
Niue	3.25	0.54	3,168
Palau	18.9	15.4	84,860
Papua New Guinea	292[2]	92.94	796,610 + 1,900,000[3]
Samoa	37.5	18.0	111,353
Solomon Islands	25.6	13.8	83,600
Tokelau[4]	0.927	0.20	34,000*
Tonga	15.3	7.7	52,609
Tuvalu	5.1	1.0	11,800
Vanuatu (UNELCO)	23.9	11.3	60,360
Vanuatu (VUI)[5]	4.1	1.71	3,350
Total	**712**	**349**	**4,201,510**

1: Peak demand main island nation grid only, excludes notable power systems on secondary / remote islands & private generation

2: Excludes substantial generation assets dedicated to private mining activities

3: First value: PNG public utility, second value: private mining operations

78% of the power generation on these islands came from generators fueled with diesel, HFO or LFO. The remaining 22% was primarily provided by hydropower. PNG and Fiji are significant outliers in terms of both total capacity and generation mix. Omitting PNG and Fiji, the total generation capacity is roughly 175MW and consists almost entirely of diesel generators. Because many PICTs are composed of numerous islands, the 175MW is divided among many smaller power plants. To determine the characteristics of these individual power plants IRENA reviewed the 2011 World Electric Power Plants (WEPP) Database. Table 2 gives an overall picture of the diesel generator fleets of the 15 Pacific islands. The database shows that the bulk of the region's generation capacity consists of power plants of less than 10 MW utilising several generators with capacities ranging from around 25 kilowatt (kW) to 10 MW.

Figures 1 shows a breakdown of the year-by-year and cumulative installation of the current diesel generator fleet. For this figure PNG and Fiji are excluded to give a better representation of the average conditions on the smaller Pacific islands.

The small and isolated nature of the majority of Pacific diesel power plants is a particular concern for the integration of high levels of variable RE. Large interconnected mainland grids have a wide variety of generation assets they can draw on to balance out variable RE power generation. Pacific grids are dependent on isolated diesel-powered stations and will have to augment their existing generation systems with new technology to compensate for variable RE.

Another key concern is the advanced age of the diesel generator fleet. The average generator in the Pacific is around 20 years old. Figure1 shows that the last major deployment of generators occurred over ten years ago. This means many generators in the Pacific are approaching or have exceeded the manufacturer's recommended lifespan. It should be noted that the WEPP database does not always include direct verification for remote areas such as in the Pacific Islands region. Some of the older generators in Table 2 may no longer be in operation. However, inquiries with the PPA identified generators that have been in continuous use since the early 1980s.

Table 2: WEPP Pacific island diesel generator statistics (2011)

PICTs	Capacity (MW)	Number of Units	Unit Size (MW)		Operational Year	
			Min	Max	Oldest	Newest
Cook Islands	11.04	24	0.025	2.1	1990	2009
FS of Micronesia	35.09	36	0.027	3.2	1974	2012
Fiji	67.03	39	0.06	10.15	1953	2011
Kiribati	8.90	9	0.6	1.4	1994	2005
Marshall Islands	41.90	33	0.06	6.4	1982	2003
Nauru	4.00	5	0.8		2002	2005
Niue	1.68	4	0.421		no data	
Palau	18.88	17	0.1	3.4	1997	2012
Papua New Guinea	141.34	28	0.14	15	2007	2011
Samoa	16.59	15	0.045	3.5	1979	2001
Solomon Islands	37.78	44	0.04	4.2	1971	2006
Tonga	14.44	19	0.056	1.729	1972	1998
Tokelau	no data					
Tuvalu	3.71	30	0.045	1	1982	2001
Vanuatu	15.46	14	0.1	4.23	1994	2010
Total	**418**	**317**				

The advanced age of the Pacific diesel fleet has significant implications when considering high levels of RE penetration into existing grids in the region. The older units may lack computer control systems and likely have slower ramp rates and reduced efficiencies versus modern diesels. A basic review of diesel generator function and the effects of RE integration are given in Section 2 to shed light on the particular challenges posed by the small capacity, isolation and advanced age of the Pacific islands' diesel fleet.

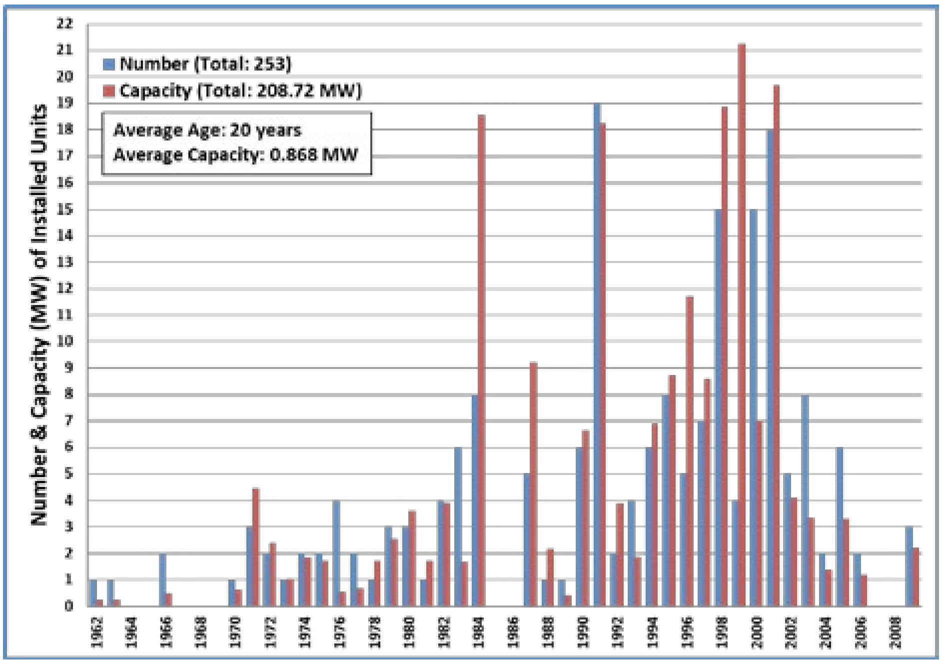

Figure 1: Year-by-year installation of current diesel fleet (Excludes Fiji & PNG)

2. Diesel power systems

Diesel generators are the most common generation technology used for power systems in remote areas such as Pacific Islands and often provide isolated communities with their first access to electricity. A number of factors make diesel generators well suited for island power generation. Diesel fuel has a high energy density which greatly reduces fuel storage requirements compared to other fossil fuels such as coal. The generators are relatively compact and available in a wide range of capacities allowing for power plants that can be closely matched to an island's demand. The majority of power plants in the Pacific use several diesel generators running in parallel. This gives operational flexibility as individual generators can be started up or shut down when demand changes. Multiple small generators also increase efficiency and security of supply versus a single large generator. Diesel generators have relatively quick start times and good flexibility in meeting daily and seasonal variations in demand. They provide fast response times and good power quality and are relatively simple to operate and maintain. The technology is robust and has a long track record of successful deployment.

A generator includes a small battery and electrical starter motor to bring the main engine online when there is a demand for electricity. Once the engine is running a small amount of power is used to keep the starter battery charged. The fuel system stores the diesel and delivers it to the engine. The engine burns this fuel, converting chemical energy into thermal energy (waste heat) and rotational kinetic energy. The engine is attached to an alternator that converts the rotational kinetic energy into electrical energy.

Utility scale generators in the Pacific Islands region produce three-phase alternating current (AC) electricity, the same type of power generated by traditional mainland power plants. Three-phase AC is composed of three separate flows of electricity which are equally spaced apart and oscillate in a sinusoidal fashion. Electricity grids have three separate sets of wires, one for each phase. Electrical loads with high power demand (e.g. industrial motors) often use all three phases while common household loads such as lights and appliances use only one phase. The AC frequency is 60Hz in U.S. Pacific territories and 50Hz on all other islands. The voltage of the AC electricity produced by generators varies depending on the model but voltage is usually stepped up by a transformer to a higher level for transmission across the island and then stepped back down to a standard level for distribution to the loads of individual customers.

2.1 Meeting demand: active power and frequency control

A key fact of power generation is that the supply from generating units must always match the demand from customer loads. Whenever a load is turned on additional power must be immediately generated. When the load is switched off generators must immediately reduce their power output. Demand is constantly changing as customers switch loads on and off at their convenience. This can lead to sudden spikes and drops in demand as major industrial equipment is powered up or shut down or when populations arrive at home after work and power on lights and appliances and then shut these loads off before going to sleep.

The power that does work on the grid, lighting a bulb or powering an oven, is called active power. The diesel generators monitor the frequency of the AC electricity being produced to sense and respond to changes in the demand for active power. Generators are designed to run at certain speed of rotation (rpm) regardless of their level of power output. A generator's alternator is designed such that this rpm is directly proportional to the frequency of the AC power being produced. As a generator is powered on and brought up to speed the moving components of the generator, the pistons, crankshaft and other components acquire a significant amount kinetic energy. These moving parts have a substantial inertia such that if fuel was suddenly cut off from the engine they would continue to spin and their kinetic energy would be transformed into electricity.

When a generator is running at steady power output and a load on the grid demands more power the load is able to extract this power instantaneously from the kinetic energy of the moving components in the generator. This loss of energy slows the speed of the generator and thereby reduces the frequency of AC power output. The controls on the generator sense this drop in frequency and compensate by increasing the fuel input to the engine. This raises the power output of the generator to match the increased demand from the load and returns the generator to its optimal rpm and AC frequency. The opposite is true when a load is switched off. In this case, the physical resistance to the generator's rotation drops when the demand from the load diminishes. This causes the generator to spin faster resulting in an increasing frequency. The controls sense this rise in frequency and reduce the fuel input to the engine dropping the power output to match the lower demand on the grid and returning the generator to its optimal rpm and frequency.

The frequency is not just a control parameter. Maintaining the frequency within certain limits is also required because the grid and associated loads have all been designed to operate within a narrow frequency band. Excursions outside this band will result in reduced efficiency and could damage grid infrastructure and attached equipment (loads).

2.2 Reactive power and voltage control

In addition to supplying the active power that performs work on the grid, generators must also provide reactive power. The amount of reactive power required is determined by the number of inductive and capacitive loads on the grid. Electric motors, transformers and other devices attached to the grid contain inductive coils and/or capacitors that need to be charged up with voltage before they can operate. This power to charge these components is not consumed but stored within the voltage built up across each component. As such this reactive power does no work on the grid. However, it must be supplied by the generator for the grid and certain loads to function. As loads requiring reactive power come on and off of the grid the generator must sense and provide this additional power.

While active power control is linked to frequency, reactive power control is linked voltage. Although voltage control is commonly supplied by a range of power electronics distributed across the grid, an active voltage regulator (AVR) on the generator plays a key role in maintaining a constant voltage on the grid. Alternators use the mechanical power from the attached engine to spin a magnet. This moving section is known as the armature. As the armature spins the field of the rotating magnet passes through stationary field coils on the outer wall of the alternator. Each pass of this magnetic field induces an electric current to flow in the field coil, first in one direction, then the other. This results in oscillating AC electricity that is fed from the field coils onto the grid. The voltage of this AC electricity is directly linked to the strength of the magnetic field passing through the field coils.

In a simpler alternator the armature uses a permanent magnet with a fixed strength. Advanced alternators in diesel generators use an electromagnet in the armature. The AVR is a set of electronic sensors and controls that is able to use small amount of power from the generator to adjust the strength of the armature magnet's field and thereby control the voltage output of the generator.

When a load requiring reactive power is connected to the grid it causes a drop in voltage as the inductive/capacitive components inside the load are charged up. The AVR senses this voltage drop and provides more power to the magnet in the alternator's armature. This boosts the strength of the magnetic field and brings the voltage back to the correct level. When a load consuming reactive power is removed from the grid the voltage will go up. The AVR senses this voltage rise and decrease the power to the armatures magnet, reducing its field strength and returning voltage the correct level.

Similar to frequency voltage is not just a control variable. Grid infrastructure and attached loads are designed to operate in a narrow band of voltages. Voltages on the grid outside of these limits reduce efficiency and could cause significant damage. Diesel generator control systems are designed to monitor and control both frequency and voltage to ensure safe and efficient grid operations. In this manner diesel generators are able to provide power quantity, matching supply to demand, and power quality, maintaining frequency and voltage.

2.3 Spinning reserves

Another key feature provided by diesel generators is spinning reserves. Spinning reserves represent generation capacity that is up and running but not providing power for the grid. This capacity is held in reserve in case there is a sudden increase in demand at which point it can be rapidly deployed to prevent any disruption to power supply or quality. Diesel generators are designed to operate at a nominal power output but can provide significantly higher levels of power output for short periods of time. This represents a short term spinning reserve that can be called on to stabilise the grid in case of sudden spikes in demand. In addition diesel power plants commonly keep one or more generators running in a standby mode with no power output. Although the fuel to keep this generators running is "wasted" because no electricity is being produced it means the full production capacity of the generator is available as spinning reserves that can be deployed if demand suddenly increase or in the case of an accident that damages one of the generators providing power to the grid.

2.4 Grid integration of renewable power and its impacts

Diesel based power plants face a number of challenges when viewed in the context of integrating high levels of RE. In order to better understand these challenges the WEPP data base was reviewed to identify the Original Equipment Manufacturers (OEMs) of diesel generators used on 15 PICTs. This data is given in Table 3. OEMs with substantial presence in the region were contacted regarding the effects of high RE penetration on generator operations. This process identified two main areas of attention: reduced generator power output ("generator load") and the variability of RE power generation.

The primary goal of RE integration is decreasing power output from diesel generators to reduce imported fuel consumption. High level RE integration can cause generator to run at low load and could even allow the generator to be shut down. Low generator loading and frequent stops, however, have important performance and safety implications.

Diesel generators operate most efficiently at a certain load, generally 65-80% of the maximum rated capac-

Table 3: WEPP database diesel generator statistics by OEM (2011)

Engine OEM	Capacity (MW)	Units No.	Unit Size (MW)			1st Operational Year		
			Min	Max	Average	Old	New	Average
CAT	40.74	46	0.06	3.25	0.886	1980	2006	1996
Mirlees	28.39	17	0.6	3.5	1.646	1972	2001	1987
Deutz	20.05	10	0.027	6.4	2.005	1995	2000	1999
Crossley	19.27	6	3.2	3.27	3.21	1982	1984	1982
MAN	15.60	12	0.25	4.2	1.300	1962	2001	1975
Cummins	15.49	30	0.103	1.1	0.514	1989	2009	2001
Daihatsu	15.45	8	1.25	2.5	1.931	1991	2004	1998
Wartsila	13.82	8	0.275	4.2	1.728	1988	2003	1995
Mitsubishi	11	3	3.8	4.2	3.6667	1998	1999	1998
Unknown	7.76	55	0.025	1	0.140	1982	2001	1996
Perkins/FG Wilson	6.86	16	0.088	1.5	0.4284	1991	2001	1996
Allen Power	6.60	4	1.2	3	1.65	1987		
Duvant	4.20	2	2.1			1991		
Enterprise	2.6	1	2.6			1987		
Ruston	2.25	3	0.75			1994	1997	1996
Yanmar	2.23	9	0.135	0.35	0.2478	1976	1979	1977
Niigata	1.85	1	1.85			1979		
Lister	1.64	9	0.042	0.6	0.183	No Data		
SDMO	1.52	2	0.52	1	0.760	1994	1996	1995
Volvo	1.20	4	0.3			1998		
White	0.80	1	0.8			1974		
Dorman	0.22	4	0.056			1983		
Gardner	0.16	2	0.08			No Data		

ity. Island power plants are generally designed to meet varying demand while keeping generators as close to this load as possible. This delivers higher efficiency and provides spinning reserves to meet demand increases. Operating below this load reduces generator efficiency, limiting the desired fuel savings. Operation below 30-40% of the rated load can result in engine over-fueling, which carbonises injection tips and disrupts the fuel spray pattern. The resulting poor combustion leads to soot formation and un-burnt fuel residue which clogs and gums piston rings.[5] As a result prolonged low load operation has numerous cost impacts. It further decreases generator efficiency, increases maintenance requirements and reduces a generator's lifespan.

Low load operation is also a concern for power quality. Many RE assets are capable of providing frequency and voltage control. However, their control systems are normally designed to monitor the frequency and voltage produced by the diesel generator and link their output to these "master control" levels. Below 30-40% of rated load most generators cannot support power quality on the grid. Technologies exist that will allow some RE resources to support power quality on the grid and will be discussed in detail below. However they are not commonly deployed in the Pacific.

The deployment of technologies such as centralised inverters will allow RE generation systems to supply the power quality needed to support grid stability. This will allow generators to be shut down permitting the grid to run on 100% RE and greatly increasing fuel savings. However, if RE production suddenly drops generators would need to be quickly restarted. Frequent stop-start operation reduces efficiency, increases wear and tear and reduces the useful lifespan of the system. Systems will need to be designed to limit start/stop operation.

Low load and start-stop operations are of particular concern for power systems in the Pacific Islands region owing to the advanced age of the region's generator fleet. Many of these generators have already exceeded the OEMs recommend running hours and as such non-standard operation could severely impact efficiency, maintenance costs and increases the risk of generator failures. Older control systems may simply not allow for prolonged low load operation or rapid shutdown and startup. There are low load generators that can operate safely and efficiently below 10% of rated load. However, the review of PICTs diesel generators indicates that low load generators are not currently deployed in significant quantities. In this context it is essential for islands considering high RE penetration to perform a detail inventory of their diesel generator assets and factor possible replacement of current diesel assets into the budgets for RE programs.

The variability of RE output is a challenge but it is not an insurmountable one. Modern generator control systems provide a great deal of operational flexibility and control systems on older generators can be upgraded. Advanced power electronics and supervisory control systems can greatly reduce the impacts of RE variability on diesel grids. The following section examines the technologies and control strategies that allow variable RE resources to work in harmony with or even completely supplant diesel power generation.

5 *http://www.generatorsolutions.org/#/gen-faqs/4534128446*

3. Modelling solar PV integration in the Tongatapu diesel-powered grid

3.1 Hybrid systems

Systems that combine RE and traditional power generation such as diesel generators are called hybrid power systems. These systems use a wide variety of enabling technologies to overcome the difficulties associated with RE resource variability and allow RE generation to be smoothly integrated into diesel power systems. The possible configurations of hybrid systems are numerous owing to the wide variety of RE sources and existing enabling technologies. However, hybrid systems can generally be classified – based on the level of RE integration they can support – as low, medium or high penetration. The U.S. National Renewable Energy Lab (NREL) has developed definitions for low, medium and high penetration hybrid systems based on its experience with wind and diesel hybrid systems. These definitions are detailed in Table 4.

Here it is important to distinguish between instantaneous and average RE penetration. Instantaneous penetration is the ratio of the RE power output (kW) to the current grid demand (kW). In order for diesel generators to be shut down instantaneous penetration must exceed 100% – i.e., there must be more than enough RE input to cover current demand. Average penetration is a ratio of the total RE output (kWh) to the total grid demand (kWh) summed over a given time period, normally a month or a year. Average penetration can also exceed 100% and would represent large surpluses of stored energy for example in a pumped hydro system. Instantaneous penetration relates to hybrid system complexity and the required level of control to maintain acceptable power quality. Average penetration gives an indication of the fuel savings and can be used to calculate the financial impact of the systems.[6]

The exact values for RE penetration will vary greatly depending on the type of RE resource and the individual system configuration but these basic definitions are useful for understanding the key challenges of integrating RE into diesel grids. In order to clearly demonstrate

6 *Technology, Performance, and Market Report of Wind-Diesel Applications for Remote and Island Communities, Conference Paper, NREL/CP-500-45810 May 2009*

Table 4: NREL guidelines for low, medium and high penetration hybrid systems[1]

Penetration Class	Operating Characteristics	Penetration: Peak Instantaeous	Penetration: Annual Average
Low	• Diesel(s) run full-time • Wind power reduces net load on diesel • All wind energy goes to primary load • No supervisory control system	<50%	<20%
Medium	• Diesel(s) run full-time • At high wind power levels, secondary loads dispatched to ensure sufficient diesel loading or wind generation is curtailed • Requires relatively simple control system	50%-100%	20%-50%
High	• Diesel(s) may be shut down during high wind availability • Auxiliary components required to regulate voltage and frequency • Requires sophisticated control system	100%-400%	50%-150%

1: http://www.akenergyauthority.org/wind/02_Wind-diesel_power_systems_basics_01-01-2008.pdf hybrid system function and how these systems can assist Pacific Islands in achieving high levels of RE integration, a step by step example is given below taking Tonga's main island of Tongatapu from low to medium to high levels of RE penetration.

3.2 Current power system of Tongatapu

The Tongatapu's power plant in 2012 consisted of seven diesel generators with a total maximum rated capacity of 11.28MW. Detailed statistics on the power plant are given in Table 5. Figure 2 shows a typical weekday demand curve for Tongatapu and demonstrates how the diesel generators are capable of easily matching their output to the grid's demand for power.

3.3 Low penetration system

Tongatapu Installed a 1MW PV system in July 2012 (Maama Mai solar farm). This level of RE integration represents a low penetration hybrid system as it requires no special control equipment. Figure 3 shows that the PV generation will have a limited impact on the diesel generators, although the Maama Mai solar farm will provide for only around 4% of Tongatapu's total electricity demand. The PV output is seen as a negative load by the generators, which continue to match their output to the changing demand profile and support power quality on the grid. The gap between the reduced diesel output and grid demand represents the fuel saved over one day of operation. Inverters on the PV system monitor the frequency and voltage on the grid and match the system's frequency and voltage to these values. Even a 100% drop of the PV system output at the noon peak represents less than 10% of generator capacity and

Table 5: Tongatapu power plant statistics (2011)

Generator Name	Engine Model	Engine Serial No.	Alternator Model	Alternator Serial No.	Frequency (Hz)	Base Voltage (kV)	Base kVA	Max Power (kW)	Speed (rpm)	Year in Service
UNIT 1	CAT 3516B	7RN00540	SR4HV Kato Engineering	8JS00812	50	11	1,525	1,400	1,500	1998
UNIT 2	CAT 3516B	7RN00541	SR4HV Kato Engineering	8JS00814	50	11	1,525	1,400	1,500	1998
UNIT 3	CAT 3516B	7RN00542	SR4HV Kato Engineering	8JS00809	50	11	1,525	1,400	1,500	1998
UNIT 4	CAT 3516B	7RN00543	SR4HV Kato Engineering	8JS00809	50	11	1,525	1,400	1,500	1998
UNIT 5	CAT 3516B	7RN00544	SR4HV Kato Engineering	8JS00813	50	11	1,525	1,400	1,500	1990
UNIT 6	CAT 3516B	7RN00989	SR4HV Kato Engineering	8JS00838	50	11	1,525	1,400	1,500	1998
UNIT 7	CAT MaK 6CM32C	38232	LSA56 B2 11-10P Leroy Somer	600374-1	50	11	3,456	2,880	600	2006
UNIT 8	CAT MaK 6CM32C	No data	No data	No data	No data	No data	No data	No data	No data	Q1 2012
Trailer Unit	CAT PM3516B	No data	No data	No data	No data	11	1,525	1,400	1,500	Out of service

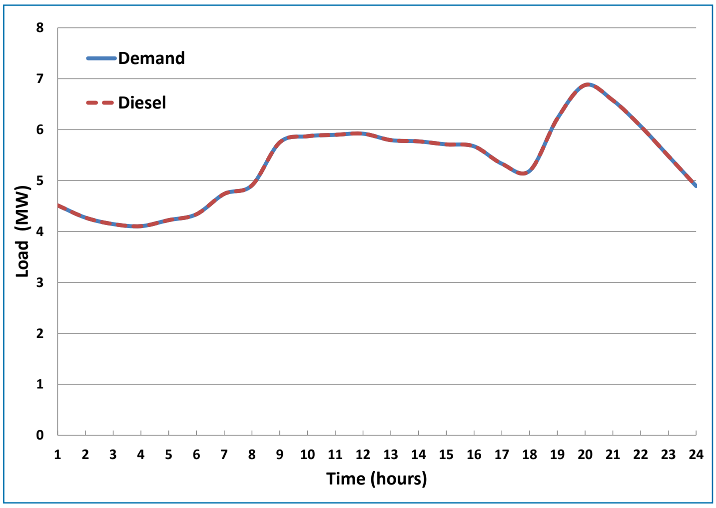

Figure 2: Tongatapu typical weekday demand and diesel power output

could be covered by diesel spinning reserves. This example helps to show that Pacific islands can commence with smaller RE projects without major effects on their current generation assets.

3.4 Medium penetration system

In order to achieve significant reduction in diesel fuel consumption it will be necessary for Tongatapu to install additional PV capacity. Figure 4 shows the notable drop in diesel generator load that could be achieved with the deployment of a 5MW PV system. This would be classified as a medium penetration system because it will require that additional control systems to work effectively with the existing diesel generators. There are two key reasons why additional control equipment are required – protecting the diesel generators from low loading and limiting generator cycling.

3.4.1 Low generator loading

As previously noted diesel generators have a lower load limit of approximately 30-40% of rated capacity. Below this limit the generator suffers from poor combustion that reduces efficiency, increases maintenance cost and can cause permanent damage that reduces the generator's usable life span. In addition, below this lower loading limit the generator can no longer support power quality on the grid and there is a risk of damaging grid infrastructure and attached loads, and even of causing a black out.

There are numerous strategies to prevent low generator loading, thus allowing higher levels of variable RE onto the grid. One common and easy to implement approach is power limiting. In this situation control equipment monitors generator load and when high PV output risks reducing generator load below the lower loading limit the control equipment has the inverter on the PV system reduce the power output. This prevents the generator from dropping below the lower limit protecting it from poor combustion and loss of power quality. Figure 5 shows the same 5MW system and demand profile with power limiting systems installed.

While power limiting protects diesel generators from low loading it wastes the additional PV power available at the noon peak and reducing the fuel saving delivered by the PV system. Even with power limiting, the 5MW system still delivers significantly more fuel savings than the 1MW system. However the additional fuel offsets require additional control systems that increase the cost of the PV system.

Additional options exist to deal with low loading. Installation of dump loads can turn RE overproduction into useful energy (e.g. heat). The limited heating demand in the Pacific constrains the value of this option. Therefore load dumping for ice making for cooling demand is an option for dealing with low loading. Specialised low load diesel generators that are designed to operate efficiently and provide power quality down to 10% of rated capacity are an attractive option for Pacific islands with older generators but would represent a substantial cost for islands where the generators still have usable lifespan. The cost of each of these options will have to

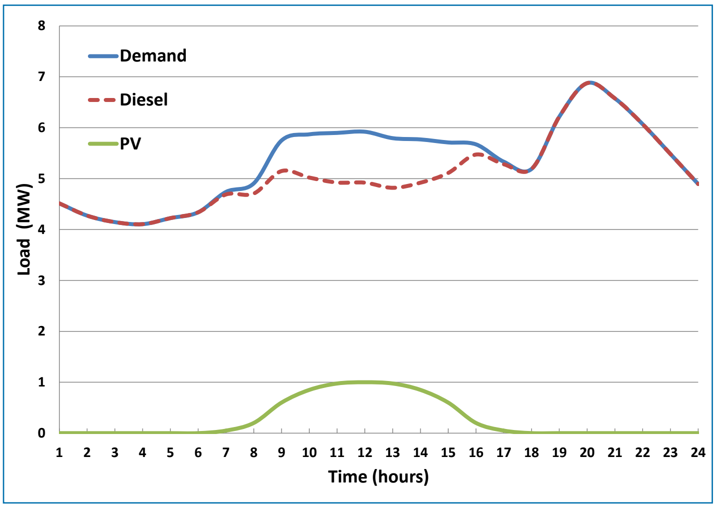

Figure 3: Tongatapu demand and diesel power output with 1MW PV

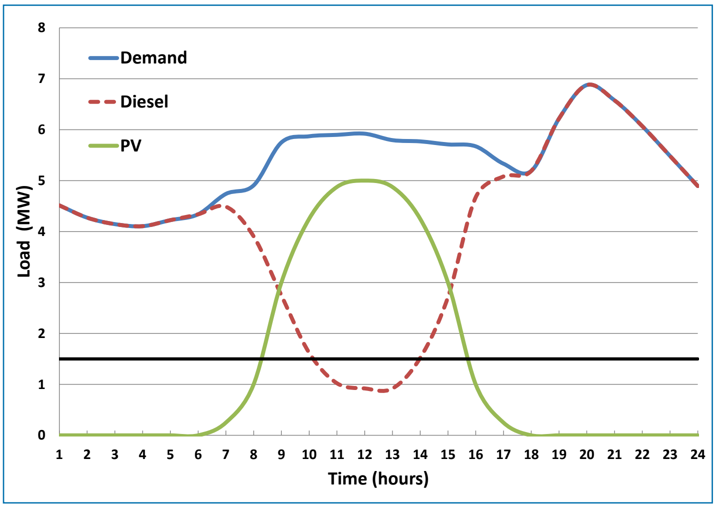

Figure 4: Tongatapu demand and diesel power output with 5MW PV

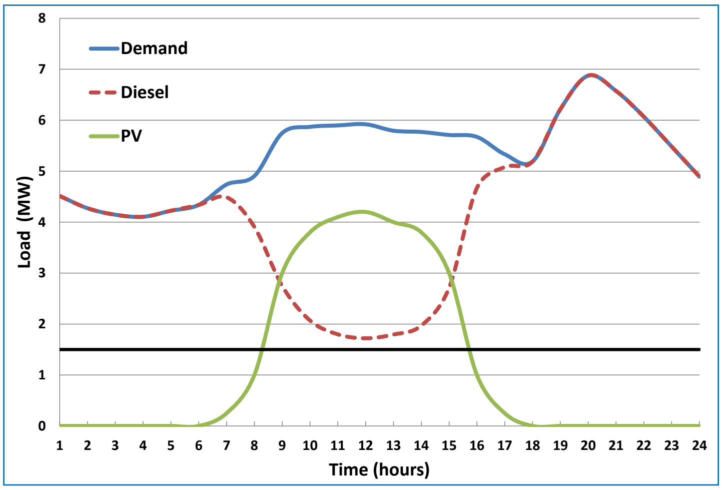

Figure 5: Power limiting of 5MW PV system to prevent low generator loading

be weighed on a case-by-case basis against the value of offset fuel consumption.

3.4.2 Variable renewable power output and generator cycling

An additional problem for medium penetration systems arises from the variable RE power output. Figure 6 shows 15 minutes of PV output near the noontime peak and demonstrates how typical RE output variations can cause rapid generator cycling even with a flat demand profile.

Generator cycling reduces efficiency and can cause damage that increases maintenance costs and reduces the usable lifespan of the generator. More significantly the RE variability can exceed the response ramp rate of the diesel engine leading to mismatches in power supply and demand that can destabilise the grid and cause a black out. As with low generator loading there are additional technologies that can be added to the power generation system to limit the effects of RE variability.

The primary technique utilised to limit generator cycling and protect grid stability in medium penetration hybrid systems is short-term energy storage. Figure 7 examines the same 15 minutes of noontime PV peak output to illustrate how short-term energy storage is used to reduce the impact of variable RE output and could reduce diesel costs by up to 50%. With short-term energy storage a control system uses a variety of factors to set a nominal output for the PV system and monitors the real time output to look for significant fluctuations that could exceed the response ramp rate of the generator. PV output above the set point is diverted from the grid into the energy storage system. This energy is stored until the control system detects drop in PV output at which time the stored energy is released into the grid. In this way the output from the PV can be maintained at a relatively constant rate greatly reducing generator cycling and the associated negative effects.

A variety of commercially available systems are capable of providing short-term energy storage. The most common are mechanical flywheels (which store RE overcapacity as kinetic energy in spinning mass that can be easily convert back to electricity) and certain batteries such as Li-ion that have rapid charge and discharge rates. Regardless of the technology chosen the energy storage and associated control equipment represent an additional cost. In addition, while these technologies are capable of stabilizing short-term low magnitude variations in RE output major drops in RE power will have to be covered by diesel spinning reserve. Maintaining the high level of spinning reserves needed to back up large drops in RE output reduces the fuel savings for medium penetration hybrid systems. All these cost must be balanced against the potential fuel savings to determine if the additional investment is worthwhile.

The additional control systems required for medium penetration hybrid systems are largely automated and the operation and maintenance (O&M) of these systems can likely be supported by the current skill set of Pacific utilities. Medium penetration systems have been successfully demonstrated on numerous systems throughout the world mostly to support wind energy systems although several PV systems have been deployed in Australia.[7]

The main consideration for medium penetration hybrid power systems is the tradeoff between the costs of the

7 http://www.apva.org.au/

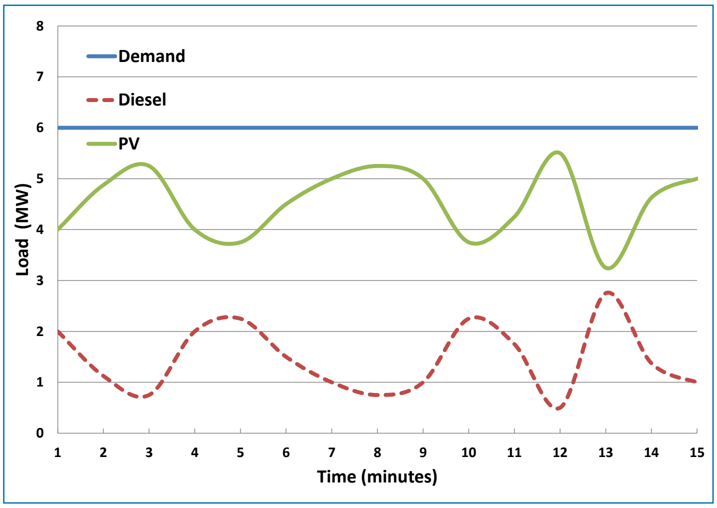

Figure 6: PV variability and diesel generator cycling

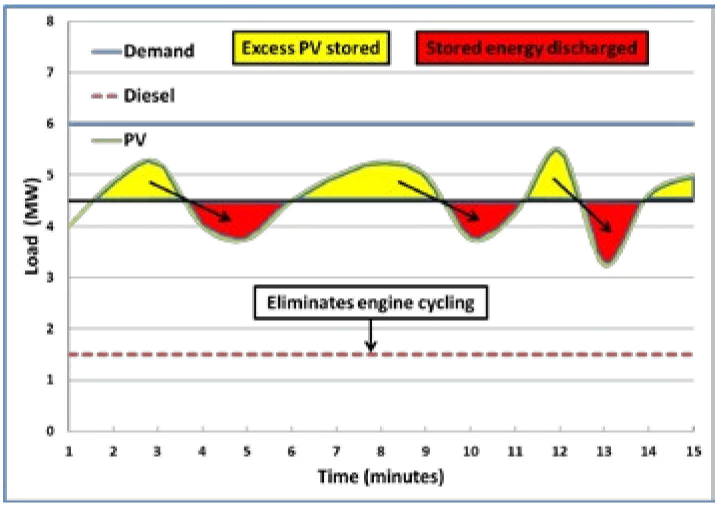

Figure 7: Short-term energy storage function & reduced generator cycling

additional systems needed to boost RE penetration and value of the associated fuel savings. The high cost of diesel fuel in the Pacific Islands means that medium penetration hybrid systems are likely to be cost effective. While system O&M is relatively simple, the system design process is quite complex and needs to be precisely executed to ensure that the full potential for fuel reductions are achieved. High quality site-specific RE resource data is essential for this design process and the lack of such data is a major impediment to widespread deployment of medium penetration systems in the Pacific Islands region.

3.5 High penetration system

While a successfully operating 5MW PV medium penetration hybrid system would considerably reduce diesel fuel consumption on Tongatapu it would most likely not achieve the 50% annual reduction outlined in Tonga's energy roadmap. This level of fuel saving will probably require a high penetration hybrid system that can provide sustained 100% instantaneous RE penetration allowing the diesel generators to be completely shut down for long periods during the day. To illustrate how such a system could function, Figure 8 shows the effect of an 8MW PV system on Tongatapu's diesel generators.

Figure 8 shows that the 8MW PV system can achieve over 100% instantaneous penetration for roughly 4 hours around the noontime peak. This could allow the diesel generators to be shut off. However, even with control systems for a medium penetration hybrid system in place the grid is still dependent on the diesel generator to match supply to demand and provide the frequency and voltage needed to stabilise the grid. In the scenario shown in Figure 8 the grid would become unstable as the generators dropped below their lower load limit and a black out would occur if the generators were shut off. Power limiting could be used to reduce PV input and keep the generators above their lower limit. While this would help to stabilise the grid, the wasted PV overcapacity would likely make it very difficult to achieve a positive return on the financial investment in the larger PV system. In order for high penetration systems to function additional technology must be installed on the grid that allow the available RE power output to be matched to demand and support power quality while the diesel generators are shut down.

A number of technologies including synchronous condensers, load banks, dispatchable loads, power converters and advanced system controls can be employed to support demand matching and power quality while the diesel generators are shut down. Additionally demand-side load management, including load-shedding schemes, can be utilised to support grid stability and reliability. However one of the most promising technologies to enable high penetration hybrids systems is long-term energy storage.

Long-term energy storage can be provided by a number of technologies. For most Pacific Islands large battery banks are the most likely form of long-term energy storage. While lead-acid batteries have been used successfully in small capacity high penetration hybrid systems their relatively low energy density and concern over toxic materials limit their potential deployment on islands. A number of advanced battery chemistries offer promising performance but NaS batteries are the only commercially available battery with the high energy density, rapid discharge rate and non-toxic composition suitable for high penetration hybrid island power systems.[8] Figures 9 and 10 give an illustration of how a battery based high penetration hybrid system could allow for 8MW of PV to be successfully operated on Tongatapu.

In Figure 9, when PV output reaches 100% instantaneous penetration the diesel engine is able to shut down. PV production exceeding the current demand is directed into a large capacity battery. Additional control equipment such as a multi-MW centralised inverter takes over the role of matching power supply (now coming exclusively from PV) to current demand and provides the appropriate frequency and voltage on the grid. If a major drop in PV output occurs the battery will act as a buffer providing the needed energy to the centralised inverter. If the drop in PV is sustained over a long period the battery and inverter will give the control system time to bring the diesel generator back online to support the grid. The sustained midday PV over production allows the battery to be charged to a high level. This energy can be used later in the day as shown in Figure 10.

Figure 10 shows how the energy stored in the battery can be deployed in several ways. By the end of the midday PV peak the battery has attained a high state of charge. As PV production drops off this energy can be deployed to keep the diesel engines shut down for a longer period of time. The remaining battery charge can be slowly depleted to keep the diesel running at a lower level. As the PV outputs drops to zero the centralised inverter can hand control over matching demand and power quality back to the diesel generator and save the remaining battery charge to offset most of the evening peak. In this manner large additional fuel reductions can be achieved.

8 *http://www.credp.org/Data/YounicosRES_EN.pdf*

PV-based high penetration hybrid systems have been successfully deployed on smaller Pacific islands such as Apolima in Samoa, where a 13.5 kW PV system with batteries has successfully provide 24-hour power since 2006, eliminating the use of diesel power generation and eliminating the importation of 2,460 liters of diesel per year. On the Japanese island of Hokkaido, a grid connected demonstration project with 5MW PV and 1.5MW of NaS batteries has been successfully operated for over four years.[9]

The example given in Figures 9 and 10 greatly simplifies the operation of high penetration hybrid systems, which require complex control systems to simultaneously monitor and operate a wide variety of technologies. Even in this case the diesel generator is still running for the majority of the day. Increasing the capacity of the PV system and battery to provide 24-hour power is financially prohibitive for larger islands like Tongatapu. As such further fuel savings will need to come from integrating other RE resources into this already complex system. Wind is an excellent complement to solar as it generally blows most strongly at night when PV output is zero. However, wind output is generally much more dynamic that PV, thus increasing the level of control required to stabilise high levels of integration. Detailed resource and power system modeling are required to confirm the profitable operation of the complex systems.

Successful deployment of high penetration hybrid systems is required to achieve many of the RE targets set by Pacific Islands but significant work needs to done on RE resource data collection and power system modeling before such systems can be widely deployed. In addition, proper O&M of the complex control systems and numerous enabling technologies will require significant training of the local workforce. All of these challenges can be overcome but they require Pacific Islands to take a comprehensive approach to power systems planning.

9 *http://www.fasid.or.jp/daigakuin/sien/kaisetsu/gaiyo21/pdf/15-4.pdf*

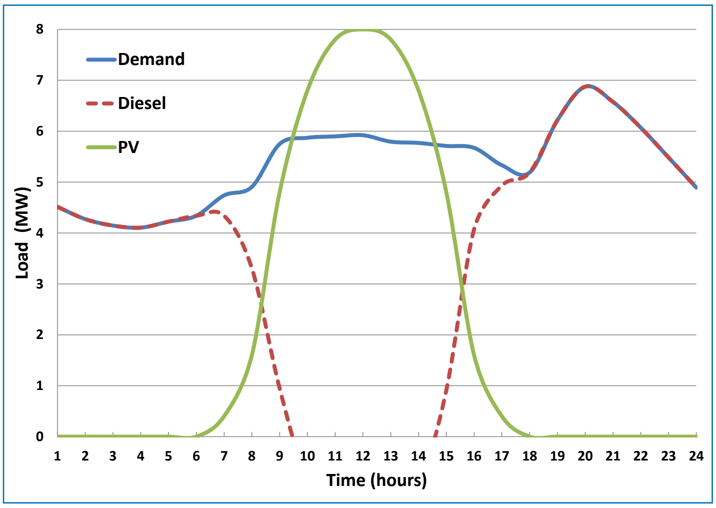

Figure 8: Tongatapu demand and diesel power output with 8MW PV

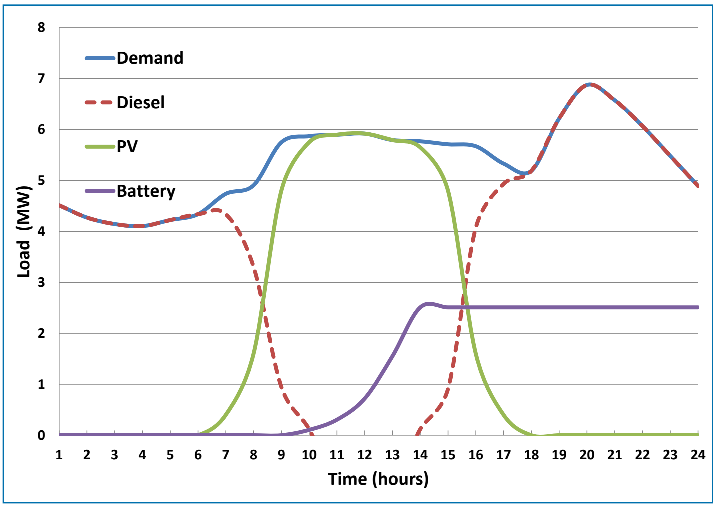

Figure 9: Long-term energy storage matching RE output to midday demand

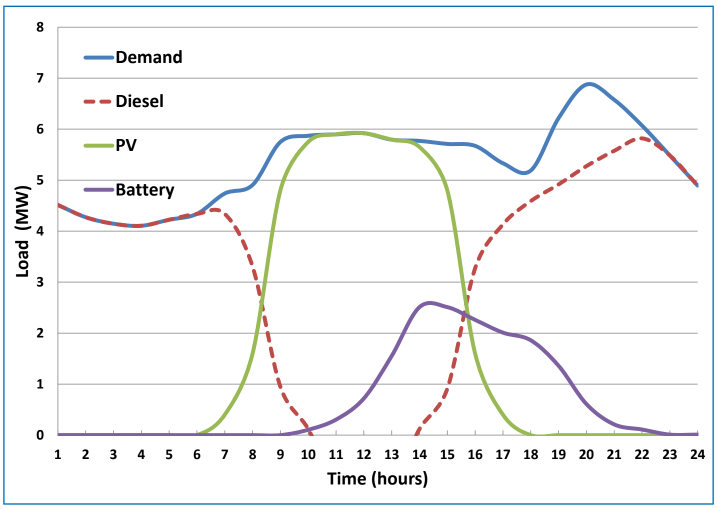

Figure 10: Long-term energy storage shifting PV overcapacity to supplying evening peak

4. Comprehensive power systems approach

4.1 Renewable energy resource data collection

The first step in a comprehensive power systems approach is a detailed review of locally available RE resources. The underlying RE resources are the key driver for the configuration and power output of the system and need to be understood in detail. Undoubtedly, a number of RE studies in the Pacific Islands region have been carried out by various development and other organisations. The data from these reports would provide a great resource if collated. As such island RE planning should start as soon as possible with an effort to identify key RE production sites and begin data collection to verify resource availability.

4.2 Grid modelling and verification

The need to integrate RE systems into existing grids and the notable impact this can have on diesel generators and grid stability requires that islands have a thorough understanding of current grid function. This entails a thorough examination of local demand characteristics and generation assets along with an assessment of the physical and electrical grid structure. Once this information has been collected, detailed static and dynamic modeling should be performed. Static modeling examines power system performance under a constant load and is used to locate grid losses and inefficiencies. If detected these issues will need to be corrected so that the full value of RE production can be delivered to customers. Dynamic modeling allows system designers to examine how possible disruptions from RE generation affects grid stability. In addition to detailed knowledge of the grid and attached loads, effective dynamic modeling requires knowledge of the RE resource. This allows identification of the key effects of potential RE technologies on grid stability and drives the selection of the additional technology best suited to allow RE integration.

A number of software packages exist that can perform static and dynamic modeling. However, more important than which package is chosen is the selection of a modeler who has intimate familiarity with the operation of smaller diesel based grids. All model results need to be directly verified with onsite measurement. Due to the highly dynamic nature of small island grids the equipment required for these measurement needs a have a very high sampling rate and represents a non-trivial expense.

4.3 Energy efficiency

Static modeling will help to identify grid related energy efficiency opportunities but all island RE planning efforts need to go beyond this and include a comprehensive examination of opportunities for increasing energy efficiency across the island. Energy efficiency efforts such as replacing inefficient electric heaters with solar thermal water heaters or eliminating the use of incandescent light bulbs can lead to notable reductions in demand thereby allowing a smaller and less expensive RE system to cover a higher percentage of island demand. Many energy efficiency efforts can be rapidly deployed leading to immediately reduced diesel consumption that frees up additional funding for RE projects.

4.4 Selecting partners with the right expertise

Detailed knowledge of RE resource availability and the results from grid modeling and verification will help to define the baseline options for an island's hybrid power system. However even with these details established the wide variety of RE technologies and diversity of associated power electronics, storage technologies and other equipment required to control RE power production results in a large number of possible system configurations.

Sorting out which system is most efficient, economical and best fits an island's power needs requires the expertise of a power system designer with established experience in field of hybrid systems. In addition, island-specific challenges such as limited infrastructure, high temperature, humidity, salinity, strong storms and other key factors need to be accounted for in the design and selection of components. This makes the selection of designers and system installers with island experience and knowledge of local conditions an important factor in successful system deployment.

Island RE project planners should place a high priority on identifying experienced project partners. Given the limited Pacific RE systems deployment, island RE project planners need to make sure off-island experts are accounting for island specific challenges.

4.5 Clear steps and measurable goals

The technical complexity and numerous processes required to deploy RE systems that can reduce island oil dependence can be overwhelming. RE planning efforts should take a long-term view and develop a detailed understanding of the specific steps required to achieve high levels of RE penetration. This step-by-step process needs to include clearly defined and measurable goals so that RE project planners can ascertain their progress, identify particular challenges and prepare for the upcoming phases of project implementation. This comprehensive approach can identify which project options have a positive return on investment and guards against costly mistakes that are a particular concern given high RE system cost and limited access to project funding in the Pacific Islands region.

A comprehensive power systems approach is essential to widespread RE deployment in the Pacific. However, IRENA's review of RE projects to date and consultations with local utilities and policymakers have identified a number of critical policy and financial challenges that will have to be addressed before RE power systems can be widely deployed in the Pacific. It is essential that the project planning process be expanded beyond the technical design realm and include local experts with knowledge of the Pacific's unique policy and financial environment. To assist in this process some of the key non-technical challenges identified by IRENA are detailed below.

5. Non-technical challenges of high integration of renewables in Pacific Islands diesel-powered grids

5.1 Wide range of affected stakeholders

High penetration RE projects have impacts on Pacific communities that extend beyond those associated with the small footprint of diesel based power systems. The high land use of many RE technologies is clearly a challenge for small islands where space is at a premium. Intricate land ownership regulations and numerous cultural sites can greatly complicate and delay landuse-intensive RE and power transmission projects. The visual impact of some RE technologies can create significant community resistance, especially in areas dependent on "pristine" tropical island environments to support tourist industries that often represent significant percentages of national GDP. These concerns and many others mean that a wide variety of people will be directly affected by large RE systems. As such, social acceptance of RE is key and it is essential that the planning process include a broad base of stakeholders and well-executed public information campaigns. Identifying and addressing key community concerns upfront prevents costly changes to projects and the creation of unnecessary opponents. Broad stakeholder participation is especially important given that off-island technical experts without direct knowledge of the communities concerns are likely to be the designers of many projects.

5.2 Local capacity building

IRENA's review of Pacific RE projects to date, primarily kW scale PV, revealed that the lack of proper maintenance was one of the major causes of underperformance and system failure. Pacific islands now have a much greater familiarity with these systems and have learned that well-trained technicians from local utilities should handle O&M. The current level of power systems expertise in the Pacific can most likely support a significant buildup of low to medium penetration PV and wind systems. However high penetration RE systems that greatly reduce or eliminate the importation of fossil fuels require the efficient operation of a wide range of advanced technologies which have different operation constraints and maintenance needs. RE planning efforts need to identify the key skills and knowledge for successful system O&M and determine which of these skills are not present in the local labour force. Regional and local policy makers need to engage with Pacific universities and other institutions to develop local programs to start building these critical skills.

A local high skills labour force will not only increase the capacity for O&M of high RE systems; it will also allow the Pacific communities to expand the benefits of these beyond energy security. Detailed knowledge of how to successfully operate high penetration RE systems is of incredible value across the globe. With relatively modest investments Pacific islands can soon reach RE penetration levels that will eventually be required worldwide to mitigate climate change. Building strong local capacity in this area can transform the Pacific into a center of expertise for decarbonising the power sector.

5.3 Legal and regulatory support of renewables

On most Pacific Islands power is provided by a single utility, typically state owned. However, a high incorporation of RE will likely requires numerous privately owned RE systems including distributed RE on private homes and larger systems built by investors and project developers for return on investment. The legal and regulatory structures on most islands have been designed to support a single utility and as result can pose notable challenges to incorporating RE. In some cases the state utility is the only entity that is legally allowed to generate power. More common is a lack of the legal frameworks needed to support the entry of independent power producers (IPP). For example it may be unclear if the law allows power-purchasing agreements with a private utility or defines who in government is responsible.

Another common issue is electricity subsidies. The subsidy structure on many islands is designed to protect customers from volatility and high prices of diesel. Significant uptake of RE will likely require a legal rework to allow some of the money to be dedicated to RE. Islands will have to decide what type of subsidy scheme to adopt, for example feed in tariffs versus RE production certificates and will have to write and enforce new regulations to supports these subsides. In addition the current codes and standards will likely need to be updated to allow RE generation technologies, associate power electronic and energy storage systems to be connected to the grid.

5.4 Island grouping for economies of scale and leveraging of private capital

Public funding from development banks, NGOs, multilateral institutions and mainland governments of territories currently dominate the financing of RE deployment in the Pacific Islands region. The considerable capital cost of RE systems will place a heavy burden on these limited resources. As such it is essential that all efforts be made to reduce RE project costs. A promising possibility is the creation of regional islands group based on common characteristics such as the type of RE resources available. These groups could collaborate to combine their RE project planning to create a large demand for design services, equipment installation and workforce training. This would create economies of scale and increase the chances of leveraging private capital.

5.5 Renewables market structure impacts

High penetration RE systems will likely result in a complex market structure; with power provided to the grid by public and private utilities, and consumers with small RE generation systems. The regulations controlling this market will need to ensure both affordable electricity prices and sufficient return on investment of RE projects.

6. Conclusion

This review of RE deployment potential in the Pacific uncovered several key messages. Despite the wide diversity among Pacific islands they share a common dependence on high cost imported oil. Consequently power generation from a variety RE resources are price competitive with diesel generators that currently dominate the region's power sector. A review of Pacific RE resources has determined that a wide variety of RE resources are available across the Pacific with the long-term potential to greatly reduce or even eliminate the region's oil dependence. However, in the near-term most of these RE resources are limited to niche roles. As such PV and wind are the RE technologies that can be most widely deployed in the near future. However, energy efficiency measures can play a key role in the energy supply for island communities and are, indeed, a viable quick-win option for the PICTs

The variable nature of PV and wind power generation and the dependence on diesel generators mean that high levels of RE utilisation will require complex hybrid powers systems. As such, island RE planners need to adopt a comprehensive energy systems planning approach that examines all the entire process for deploying high penetration RE systems and delivers a clear step-by-step process with well-defined measurable goals. The first step in the process, direct verification of site specific RE resource availability needs to be rapidly undertaken due to long data collection periods and the strong impact of RE resources on system performance and financing. IRENA is actively working to assist Pacific Islands in this task with the development of a global RE resource atlas.

The involvement of policy makers to support local capacity building is essential for project success, as high penetration RE systems will require training a local workforce with a wide variety of specialised technical skills. Building this local capacity also represents an opportunity for the Pacific to become a global center of expertise in hybrid power systems. IRENA is assisting the Pacific islands in local capacity building by working with the PPA to boost its ability to perform dynamic power systems modeling, a key skill required to deploy RE power generation.

A significant buildup of RE generation in the Pacific is inhibited by the limited financing in the region, which is primarily composed of public funding from various development partners. The creation of island groups with similar RE resource presents a potential opportunity to create the economies of scale required to bring down costs and provide the needed access to private financing. Working with NREL, IRENA is providing Pacific islands with information on island groupings and other options to increase access to private RE project financing. Furthermore, the United Arab Emirates has offered a commitment from the Abu Dhabi Fund for Development (ADFD) of up to USD 350 million to support financing of renewable energy projects in developing countries endorsed by IRENA. The IRENA/ADFD project facility is currently evaluating projects from various countries, including countries in the Pacific Islands region, for the first round of funding from the fund.

Finally it needs to be noted that although the focus of this report is on near term deployment of RE power generation this sector represents on average only 25% of Pacific island oil imports. Achieving reduced dependence on fuel imports will require regional RE planners to address the more challenging issue of wide spread RE use in the transport sector. Electric vehicles are the best technology currently available for RE based transport but require deployment of large RE power generation to offset fuel consumption.

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