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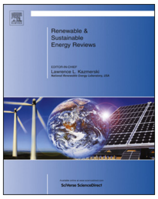

Grid-connected PV systems in the Pacific Island Countries

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ABSTRACT

Grid connected solar photovoltaic (GCPV) systems are fast becoming a regular feature of electricity power networks in urban and peri-urban areas within most Pacific Island Countries. A number of systems have been installed with many in the pipeline. This relatively new technology, utilizing the intermittent solar energy resource has presented new challenges to small island utilities that were hitherto almost completely dependent on diesel generators and hydropower. The present paper describes the current status of GCPV systems in the Pacific region and reviews some of the issues that arise in the deployment of this technology. It also reports a case study involving a 45 kW_p GCPV system located at the University of the South Pacific (USP) marine campus in Fiji. One of the first two GCPV systems established in Fiji, this system has an annual production of ~54,000 kW h and supplies about 10% of the electricity requirements of the campus. The actual system performance agreed well with the simulated results. This system also reduces USP's annual carbon footprint by more than 27,000 kg CO_{2e}.

Contents

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1. Introduction

In the past few years there has been a dramatic rise in renewable energy (RE) development and deployment on global scale. According to the recent REN 21 report [1], the global RE capacity was approximately 1560 GW in 2013 which was around 8.3% increase from 2012. Excluding hydropower, global RE installed capacity was 560 GW in 2013 with China leading followed by United States, Germany, Spain, Italy and then India. At the end of 2013, renewable energy based systems generated 22.1% of the global electricity [1]. Between 2000 and 2013, global renewable energy based electricity capacity more than doubled in size reaching 27% of the total capacity [2]. However, development of RE projects requires a lot of consideration as the cost of renewables (solar, wind, biomass geothermal and small hydro) is very site specific due to the uneven distribution of resources throughout regions, countries and even within a country [3].

Globally, solar PV industry has made significant progress in the recent years, which is mostly attributed to the decreasing cost of solar PV per kilowatt. Singh [4] provides a detailed review on the research and development that has been done in solar power generation since its commencement. The solar PV capacity reached 139 GW with 39 GW added in 2013 alone [1]. Most of the new PV capacity is in the form of grid-connected systems. China is the leader in global PV market followed by Japan and United States [5]. Raugei and Frankl [6] in their long-term scenarios for PV development predicted that there will be a huge increase in global cumulative PV capacity in the next few decades. Their preliminary results of life cycle analysis indicated that due to the current advancement in PV technology and emerging technology will lead marked lower cost per-kW h over the next few decades. IEA's solar technology roadmap envisions 4600 GW of solar PV by 2050 which would contribute to 16% of global electricity [5]. It stresses that appropriate regulatory framework and well-designed electricity market would be needed to achieve this vision.

A GCPV system allows the consumer to sell PV electrical energy at an agreed rate to the utility during production of excess electricity and to buy electricity from the grid during night. Since GCPV systems deal with large voltages and networks, their performance and interaction with the grid needs to be thoroughly investigated in each case especially for the larger systems. The experimental results during a performance analysis of a 2.7 kW_p GCPV at a university in Italy provided evidence that solar radiation and cell temperature affected the module efficiency [7]. Performance results of four 3 kW_p GCPV systems in Korea were obtained for one year to investigate operational characteristics of the system [8]. Other researchers [9–17] have also carried out performance analysis of small ($<1000\ kW_p$) GCPV systems using different methods to estimate energy output from PV systems and have also investigated their socio-economic impacts.

Bernal-Agustin and Dufo-Lopez [18] studied the environmental and economic performance of GCPV systems in Spain where environmental benefits were determined using Life Cycle Analysis (LCA) theory of the systems, calculating the recuperation time of the invested energy, the emissions avoided and the externality costs. LCA have been carried out by Bayod-Rujula et al. [19] for GCPV with 2-axis tracking and fixed modules systems. A knowledge of reliability of GCPV systems is paramount since it has a high capital investment and a sound business plan demand a long system life. Zini et al. [20] present a method based on fault tree and probability analysis to analyse and quantify the reliability of large-scale grid-connected PV systems.

1.1. *GCPV systems: technical issues*

Passey et al. [21] have reviewed the impacts on electricity grids when distributed generators (DG) employing renewable energy sources, especially PV, are connected. A number of effects viz. grid-derived voltage fluctuations, voltage imbalance, voltage rise and reverse power flow, power output fluctuations, frequency variation, harmonics and unintentional islanding can appear as a result of this interconnection Low penetration of DG can be tolerated by the grid provided they are within a minimum threshold. However, to accommodate increased levels of DG penetration, changes to the network have to be made such as minimizing reactive power flows, power factor correction, increased voltage regulation in the network and careful consideration of protection issues [21]. Extensive literature has been reviewed by Shah et al. [22] which showed that impacts of high levels of PV penetration on the power system are influenced by size, nature and location of PV installations, availability of adequate reserve in the system, reactive power compensation method among other factors. They suggest that dispatching strategy and spinning reserve should be studied for grid stability. Tarroja et al. [23] developed an array of metrics to evaluate the impact of intermittent renewable generation (such as wind and solar) on the electric load demand which allowed high penetration level of DG to be examined. Alsayegh et al. [24] proposed a two supervisory hierarchy scheme where local autonomous supervisory system (LSC) was configured to examine the performance of renewable energy source systems (RESs) by preventing negative influences by the RESs on the national grid, optimizing the usage of RESs and monitoring and controlling access to national and regional control centres.

ElNozahy and Salama [25] discussed that PV arrays providing electrical energy at the load side of the distribution network reduce the feeder active power loading which improved the voltage profile. Eltawil and Zhao [26] reviewed the challenges posed by high penetration of PV into the grid. Based on an extensive literature survey discussing the potential problems associated with high penetration of grid-tied PV, they recommend that GCPV inverters should operate at unity power factor since variable power factor would increase the probability of islanding during high penetration levels. The impact of large scale PV ($>500\ kW_p$) on transmission/sub-transmission networks is discussed in a study by Paatero and Lund [27]. There is an increasing requirement of ancillary services due to the variable output of GCPV (when PV production reduces due to cloud cover). This would mean that utilities need to provide fast ramping power generation to compensate for the variable power output from PV to maintain the voltage and frequency of the grid within allowable limits. It is

Nomenclature

DG	Distributed generation
FiT	Feed-in tariff
GCPV	Grid connected photovoltaic systems
GHG	Green house gases
IPP	Independent Power Producers
kW_p	Kilowatt peak
OPVI	Oil price vulnerability index
PICs	Pacific Island Countries
TERM	Tonga Energy Road Map
TERP	Tokelau Renewable Energy Project
USP	The University of the South Pacific

further noted [25,26] that there are stability and voltage problems in electrical network since GCPV systems cannot provide a dispatchable supply that is able to accommodate varying demand. On the other hand, for GCPV systems of less than 500 kW_p, there can be excessive reverse power flow (from low voltage side to medium voltage side) during mid-day (when supply form PV is more that the local demand) which can lead to overloading of the distribution feeders and excessive power loss [25].

1.2. Policies for market development of GCPV

The market for GCPV depends on technological advances, regulatory support and financial and economic criteria [28]. Yang argued in [29] that reduction in PV module prices alone was not enough to increase PV penetration and there must be enhanced political support such as financial incentives and policy mandates. A detailed literature survey has been provided by Antonelli and Desideri [30] on feed-in tariff (FiT) and its success in various countries. Ahmad et al. [31] reasoned that FiT was one factor which led to increase in solar PV global capacity by reducing the risk for investors through fixed prices and long contractual periods. In this work, they used systems dynamic approach to evaluate FiT policy in Malaysia to promote solar PV investments. Based on their studies on FiT regulations in Greece, Papadopoulos and Karteris [32] and Tsilingiridis and Ikonomopoulos [33] concluded that high FiTs and subsidies remained a necessity and useful tool for increasing PV penetration. Martin and Rice [34] studied the solar bonus scheme (SBS) for New South Wales in Australia which increased investor participation rate, installed capacity and quantity of electricity exported. However, this scheme placed tremendous burden on the local government by increasing the public costs. They recommended that (i) FiT scheme must have strict cost-management, (ii) policy control mechanism such as placing cap on installed capacity, total expenditure and system size, (iii) FiT rate should be suitable in long-term by considering current and future electricity costs, (iv) state level FiT must be harmonized with federal RE policies and (v) FiT designs must be integrated into electricity distributor and retailer business strategies [34]. Antonelli and Desideri [30] after studying the FiT scheme in Italy recommended that FiT schemes should be different for different macro-regions within a country depending on the solar radiation availability.

Once FiT has worked for some years, then countries could look into Solar Grid Parity. Biondi and Moretto defined grid parity as the time when the electricity price (purchased from the grid) equals the levelised cost of PV energy generation [35]. They used Real Option approach to determine the optimal time for investing in PV in Italy. These results were then compared to calibrating standard Grid-Parity model. Rigter and Vidican [36] developed a closed form equation for the cost of PV and used forecasts on prices on solar systems to derive an optimal FiT for regions in China. They concluded that reaching grid parity depended on grid prices and it could take another decade to achieve this. Ayompe and Duffy [37] presented a methodology that used smart metering data to design a targeted and efficient FiT for domestic scale GCPV in Ireland. They concluded that continuous FiTs were more efficient (compared to single or multiple FiTs) since they were designed for each household and resulted in no overcompensation.

Krasko and Doris [38] in their qualitative analysis for development of PV markets found that effective policy ordering started with improvement in interconnection standards, followed by improvement in net-metering standards and finally by enactment of a Renewable Portfolio Standard (RPS).

2. Status of GCPV systems in the PICs

PV systems are gaining much attention in the Pacific region where governments, development agencies and private investors are promoting the use of PV for electricity generation. Stand-alone solar PV systems are extensively used to provide electricity in dispersed islands and rural areas throughout the region. Now, GCPV systems are slowly being introduced across the cities and towns in many PICs and a number of feasibility studies are underway for potential installations.

PICs are highly dependent on the imported fossil fuels for their energy needs and hence their economies are highly vulnerable to the impacts of fluctuating world oil price. The oil price vulnerability index (OPVI) for some PICs, as developed by ADB and UNDP, are shown in Table 1 [39]. Kiribati is the most vulnerable among the 39 developing countries studied and all seven PICs are in the top 10. This index considers the economic growth, GDP, budget balance and oil intensity among other parameters to assess the vulnerability of a country. Dornan and Jotzo [40] noted that renewable energy based electricity generation has the potential to reduce the vulnerability to oil price. They studied financial risk of renewable technologies using portfolio theory in Fiji Islands and concluded that investment in low-cost, low-risk renewable technologies such as geothermal, biomass, bagasse and energy efficiency would reduce generation costs as well as financial risk in the electricity grid.

The average electricity tariffs for various PICs are given in Table 2. These prices are a reflection of diesel-based electricity generation costs and are unaffordable for most of the PICs population. In addition; the whole Pacific Islands region is at the forefront to the negative effects of climate change. Even though, PICs contribute very little to global GHG emissions, there is a strong desire among the PICs to show the global community that they are also investing and promoting renewable energy and energy

Table 1
Oil price vulnerability index for PICs [39].

Country	OPVI	Rank/39
Kiribati	1.00	1
Tonga	0.80	2
Fiji	0.79	3
Vanuatu	0.76	4
Solomon Islands	0.74	5
Samoa	0.73	6
PNG	0.66	7

Table 2
Electricity tariff for PICs in 2010 [41].

Country	Average electricity prices (US cents/kW$_p$ h)
Fiji	20.1
Australia	23.3
Palau	23.7
New Zealand	26.1
Samoa	32.31
PNG	33.1
New Caledonia	33.4
Kiribati	33.9
American Samoa	36.9
Tuvalu	37.9
Niue	46.1
Tonga	49.2
Vanuatu	51.3
Cook Islands	51.5
Solomon Islands	81.3

efficiency to mitigate their GHG emissions while securing their energy future.

For an energy secure Pacific region, development and deployment of local renewable energy based solutions are important. Solar and biomass resources are available in all PICs with hydro and geothermal in the larger countries like PNG, Vanuatu and Fiji. Wind power is site specific and there are some potential locations scattered around the region.

Due to the decreasing cost of solar PV modules and abundant solar energy, PV has emerged as one of the most economically attractive options leading to a remarkable growth in both standalone and GCPV system numbers in the recent years. The present work deals mainly with the GCPV systems and the following section describes the current status of GCPV systems for various countries in the region.

2.1. Cook Islands

Cook Islands has a net metering policy which allows customers to import and export energy on a ‘unit for unit’ basis for installations up to 2 kW$_p$ [42]. This has allowed over 90 private GCPV systems to be installed of which 60% are residential and 40% commercial. In 2012, there was a total of 667.68 kW$_p$ private GCPV systems installed [43]. A 950 kW$_p$ GCPV system is currently being installed at the Raratonga airport and the ADB is supporting a feasibility study to establish a 6 MW$_p$ GCPV system [44]. A recent study on PV and wind integration into the Rarotonga electrical network has determined an upper PV limit of 1500–2000 kW without any storage and up to 4480 kW with storage [45]. These systems would be distributed over many locations across the entire island which has a peak load of 4830 kW. The study recommended measures like fast-acting control that can keep the grid voltage fluctuations at a minimum and maintain power quality in case of passing clouds.

2.2. Fiji

Tourism plays a very important role in Fiji's economy and this sector is leading Fiji's push for GCPV and mini-grid solar PV systems. A 122 kW$_p$ GCPV roof mounted system on Port Denarau Marina building was commissioned in December 2012. It had an annual generating capacity of 0.19 GW h [46] with another 41 kW$_p$ added in January 2014. A 72.5 kW$_p$ system is installed at the nearby Sheraton resort. Recently, the Turtle island resort has installed the first large-sized mini-grid PV system in Fiji. This 240 kW$_p$ photovoltaic system was commissioned in February 2013 and on average produces 1.2 MW h a day. This system has reduced the resort's annual fuel consumption by 85,000 l [47] and has cut its carbon emissions by 220 ton [48]. The Tokiriki Island resort is also installing a 600 kW$_p$ PV based mini-grid, the largest resort based PV system in the South pacific. Other recent installations include a 125 kW$_p$ GCPV system on a supermarket roof in Nadi, a 250 kW$_p$ system for a poultry farm in Ba and a 273 kW$_p$ system for a clothing manufacturer in Suva [49,50].

2.3. Federated states of Micronesia (FSM)

Under the EU REP 5 programme (a European Union funded project), FSM installed five grid connected systems (totalling 52.5 kW$_p$), all in the single island state of Kosrae.

2.4. Kiribati

Kiribati has only one power grid, the South Tarawa power grid, which is entirely powered by imported diesel. On the Kiritimati Island, there is an 18 kW$_p$ GCPV installed privately [51]. With the support of World Bank, a feasibility study has found that maximum of 900 kW$_p$ of GCPV can be installed without any enhancement to the grid systems [52]. This study has identified 5 sites where installations are technically feasible and leased by government under long term lease arrangements. Pacific Environment Community (PEC) Fund of Japan has also approved finance for 400 kW$_p$ of GCPV which will reduce Kiribati's annual GHG emissions by approximately 36,2514 kg$_e$ CO$_2$ [53].

2.5. Republic of Marshal Islands (RMI)

The RMI has approximately 279 kW$_p$ GCPV installed at Majuro Island. It consists of 3 separate GCPV systems: a 57 kW$_p$ system mounted on a roof at the College of Marshall Islands, a 209 kW$_p$ system installed at Majuro Hospital and a 12.54 kW$_p$ system installed at the University of South Pacific campus [43].

2.6. Nauru

Under the EU REP 5 Programme, a 40 kW$_p$ grid connected PV system was installed on the roof the Nauru College. The system generates about 4500 kW h of electricity per month on average. Another 30 kW$_p$ GCPV system is installed at the government office building financed by Chinese Taipei institutions [43]. Through Japanese PEC funding, a 132 kW$_p$ GCPV is in the pipeline [53].

2.7. Niue

Three grid connected systems were installed in Niue under the EU's REP 5 programme. A 30 kW$_p$ system for the hospital, a 20 kW$_p$ system for the High school and 2 kW$_p$ for the Niue Power Company office building. A 70 kW$_p$ roof-mounted GCPV system is being funded by the EU. The Japanese PEC funded project has installed a 200 kW$_p$ of GCPV system coupled with a battery bank. The system was commissioned in February 2014 and will help reduce Niue's annual GHG emissions by 327 ton [53].

2.8. Palau

Electricity services in Palau are provided by the Palau Public Utilities Corporation (PPUC). From 2008 to 2012, PPUC installed a total of 550 kW$_p$ of GCPV at 6 different locations [43]. Through Japanese PEC funding, 6.5 kW$_p$ of GCPV was installed on the roof of island's solid waste segregation facility. In 2011, 42.3 kW$_p$ GCPV was installed on the roof of Military community service camp and 8.5 kW$_p$ GCPV is installed at a Bank. In addition, a total of 6.8 kW$_p$ GCPV is installed at the residences around the island.

These projects were supported by United Nations Development programme, European Investment Bank and an Italian Fund [43]. Under the EU REP 5 programme, a 100 kW_p GCPV system was installed on top of a car park shading at the Capitol complex, the government headquarters. The system is designed to generate 120,000 kW h of electricity annually on average.

2.9. Samoa

Samoa recently installed a 2 MW GCPV system and is in the process of establishing another 2.2 MW system which will be the largest in the Pacific. This project is being commissioned under the European Union-New Zealand Energy Access Partnership and financed via support from the Asia Development Bank [54]. The Electric Power Corporation (EPC) of Samoa has also obtained funding from Japanese government's PEC funds for installing 400 kW_p GCPV systems [55]. Another 546 kW_p system spread over three sites was commissioned in April 2014 [56].

For the Savaii Island, a study using steady state analysis found out that a maximum of 810 kW of PV can be added to the existing grid [57]. A dynamic analysis further showed that installing 900 kW of PV on the grid could lead to grid shutdown during daytime off peak case. One of the solutions suggested was to cross-trip PV generation. For Upolu Island, steady state analysis restricted PV penetration to a maximum of 7985 kW in order to keep system voltage and frequency within typical operating limits [58].

2.10. Tokelau

Under the Tokelau Renewable Energy Project (TREP), 10 kW_p GCPV was installed in 2005 on one of the atolls to evaluate the performance of such systems. Apart from a few problems with the inverter, the project was considered successful [43]. Since 2012, each of the three atolls has a large mini-grid where clusters of PV modules with battery storage have been installed. A total of 891 kW_p of PV in multiple clusters generate more than 90% of electricity requirements [59]. This together with generators running on coconut biofuel has given Tokelau the title of “first fully renewable energy powered nation”.

2.11. Tonga

Tonga has embarked upon a 10 year (2010–2020) initiative named the Tonga Energy Road Map (TERM) to “ reduce Tonga's vulnerability to oil price shocks and achieve an increase in quality access to modern energy services in an environmentally sustainable manner”. Among many activities envisaged, a grid connected PV system for the main island of Tongatapu has already been realized in 2012 which was funded by NZAID, European Investment Bank and Meridian Energy Ltd. of New Zealand. This 1.3 MW system is expected to generate an average of 1880 MW h annually reducing 1100 ton of CO_2 emission. Another 1 MW GCPV is being supported by JICA and a 500 kW_p GCPV is under construction funded by Abu Dhabi fund for Development [43]. ADB and Australia are funding an outer islands RE project that will see installation of a total of 1.25 MW GCPV systems spread over nine outer islands [60].

2.12. Tuvalu

The capital Funafuti was first introduced to GCPV in 2008 when a 40 kW_p system funded by Japan was installed [43]. Tuvalu also has a mini grid comprising 46 kW_p PV with battery bank in an outer island. This system, established in collaboration with the International Union of Conservation of Nature (IUCN) and the governments of Italy and Austria, saves about 43,800 l of diesel per annum [61]. GCPV systems totalling 300 kW_p are planned on three outer islands using financial support from the European Union [43]. Another 62.5 kW_p of GCPV systems are being established in Funafuti and in outer islands grid under the Japan PEC funding [53]. A recent study based on steady state analysis determined that a maximum of 400 kW_p of PV can be added to the 3 feeders in Funafuti without overloading the feeders [62].

2.13. Vanuatu

A 40 kW_p GCPV project funded through the Asian Development Bank was completed in 2012. Three systems, two 10 kW_p each and one 20 kW_p, are mounted on the roofs of public buildings including a hospital and a school in Lugaville on the island of Espiritu Santo [63].

3. USP/KOICA 45 kW_p GCPV system: a case study

As mentioned above, Photovoltaic (PV) solar power is increasingly gaining popularity in Fiji, an archipelago of 330 small islands of which about one third are inhabited. The dispersed nature of population within the group makes it difficult for the only power utility to provide unified grid based electricity to the whole population. While three islands (Viti levu,Vanua levu and Ovalau) have access to grid-connected power, people on other islands almost exclusively rely on standalone solar systems or micro/mini-grids based on diesel generators.

In April, 2012, The University of South Pacific (USP) in collaboration with the government of Republic of Korea established a 45 kW_p GCPV system at its Laucala campus in Suva, Fiji. This system was the largest of its kind in Fiji at that time and operates as a demonstration/training site for GCPV professionals while reducing USP's carbon footprint. The long term study of this system will help explore the behaviour of GCPV systems in an island climate setting while connected to a largely diesel/hydro powered grid.

This case study gives a description of the system and compares simulated results with the actual performance of the system.

3.1. GCPV system configuration

The 44.46 kW_p GCPV system at the USP Marine campus is connected to one of the main load distribution boards on campus to ensure that bulk of the PV power produced is consumed with minimal export to the grid.

The system consists of the following major components:

- 234 × BP4190T solar panels
- 6 × SMA8000TL GC Inverters
- Unirac U-LA ground mount structure
- SMA SunnyWebBox and SensorBox

The 3-phase power system layout is shown in Fig. 1.

3.2. System equipment

3.2.1. Solar panels

The BP4190T solar panel manufactured by BP Solar consists of 72 monocrystalline silicon cells. The specifications of the solar panel are described in Table 3.

The solar array is configured in strings of 13 panels each with 3 strings connected to each of the 6 SMA 8000TL GC inverters, giving the system a peak PV array power of 44.46 kW_p.

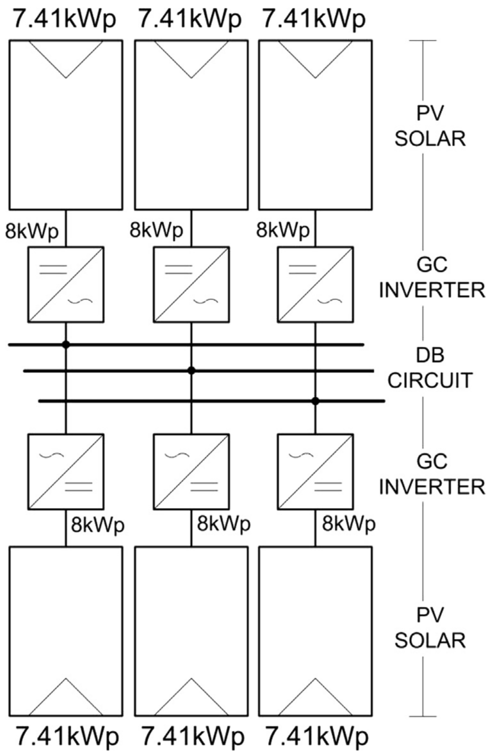


Fig. 1. The GCPV system layout.

Table 3
BP4190T PV solar panel specifications [64].

Solar Panel Manufacturer	BP Solar
Solar Panel Model	BP 4190 T
Maximum Power (P_{max})	190 W @ STC 1000 W/m^2
Voltage at P_{max} (V_{mpp})	37.1 V
Current at P_{max} (I_{mpp})	5.12 A
Short Circuit Current (I_{sc})	5.56 A
Open Circuit Voltage (V_{oc})	45.3 V
Nominal Voltage	24 V

Table 4
SMC8000TL technical specifications [65].

Input (DC)	
Max. DC input power	8250 W
Max. DC voltage	700 V
PV voltage range (Mppt)	333–500 V
Maximum input current	25 A
Output (AC)	
Nominal AC output	8000 W
Maximum output current	35 A
AC grid frequency range	50 Hz (± 4.5 Hz)
General data	
Noise emission	≤ 40 dB
Topology	Transformerless
Outdoor protection rating	IP65

3.2.2. *Grid connect inverters*

The inverters in this system are of the transformer-less type with specifications as shown in Table 4.

The inverters feature stacking capabilities and two inverters are connected to each of the three phase distribution circuits. These inverters have an efficiency of 98% that decreases slightly with increasing operating DC voltage [65]. With a maximum of 13 panels connected in series, the optimal maximum power point operating voltage of the inverter is 482.3 V and the inverter operates at around 97% efficiency as per the product datasheet.

3.2.3. *Mounting structure*

The solar panels are ground mounted and separated as two sub-arrays due to space constraints. Unirac U-LA series of ground mounting structures were utilized with the rail specifications as shown in Fig. 2.

As the system location is frequented by tropical cyclones on annual basis, special care was taken in designing the support system. The structure and foundation were sized to withstand a wind loading of 1.013×10^3 N m^{-2}.

3.2.4. *Monitoring equipment and data acquisition*

The system is remotely monitored using SMA SensorBox^{TM} and WebBox^{TM}. The system data is continuously collected and system monitoring, remote diagnosis, data storage and visualization are facilitated by the Sunny Web box which continuously collects all data from the inverters on the system side.

A SMA SensorBox is also integrated into the system to monitor the solar irradiance, ambient temperature and solar panel temperature. The irradiance and temperature data have been utilized to study the effects of these environmental aspects on the system output (yield) performance. Data can be accessed from the device via the following means:

- Flashview – Flash based software that displays (in real time) the system generation capacity and PV panel and ambient temperatures.
- Sunny Portal – An online database hosted by SMA that logs data and provides various forms of visualizing incoming data. The Sunny Portal is also programmed to pick up yield deviation alarms between the six inverters.
- SD card slot – All data can be logged onto an SD card in CSV form for analysis.
- Webserver – Integrated webserver on the WebBox that allows remote access over a TCP/IP link for system control and power generation data.

3.3. *System simulation and results*

The system was first simulated in PVSyst software. The main results from the simulation exercise are as follows:

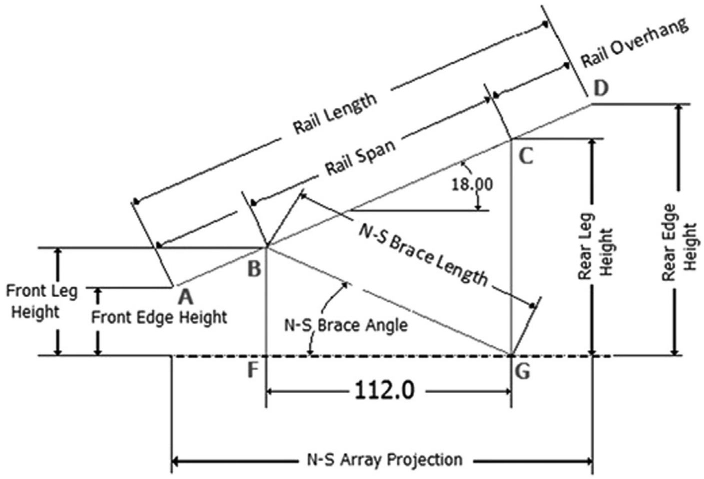
System production	57,310 kW h/year
Normalized production	3.53 kW h/kW$_p$/day
Specific production:	1289 kW h/kW$_p$/year
Performance ratio:	0.768
Array and System losses:	1.07 kW h/kW$_p$/day

In the year 2013, the actual production from this system was 54,195 kW h, about 9.5% less than the simulated value (Fig. 3). This could be attributed to a small shadowing by nearby trees in the mornings and also due to the inaccuracy in the synthetic radiation data employed in the simulation.

Fig. 4 shows the module temperature and ambient temperature on a typical sunny day. The module has an NOCT of 47 ± 2 °C and it can be seen that the module reaches its NOCT value for a very short time around noon. According to the product datasheet, the module produces 138 W$_p$ at NOCT and 800 W m^{-2}.

Fig. 5 shows the simulated results for energy production as a function of global radiation at the module plane. This relationship is also shown in Fig. 6 where actual daily specific yield (kW h/kW$_p$) is plotted along with average daily radiation for the month of April 2014.

Considering an emission factor of 0.5 ton CO_{2e}/MW h [66], this GCPV system has helped USP reduce its GHG emissions by approximately 27,500 kg CO_{2e}/year. Being one of the first



Member Description	Variables	Value	Units
Rail length	AD	196	in
Tilt angle	θ	18	degrees
Rail Span	117.77	BC	in
Rail Overhang	AB,CD	39.12	in
Front Leg Length	BF	36.09	in
Rear Leg Length	CG	72.49	in
N-S Cross Brace Length	BG	117.67	in
N-S Cross Brace Angle	β	17.86	degrees
NS Leg Spacing	FG	112	in

Fig. 2. Unirac ground-mount rail specifications.

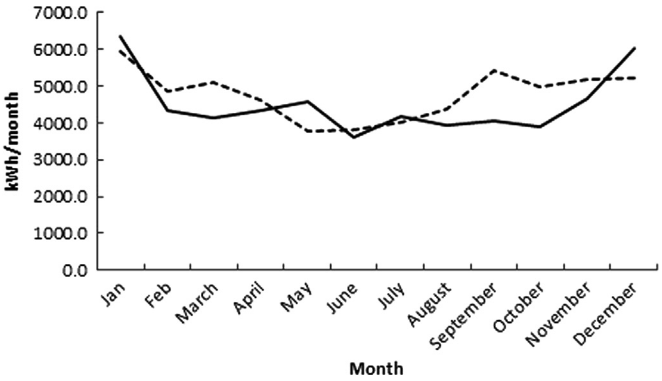


Fig. 3. Monthly production: actual (solid line), simulated (dashed line).

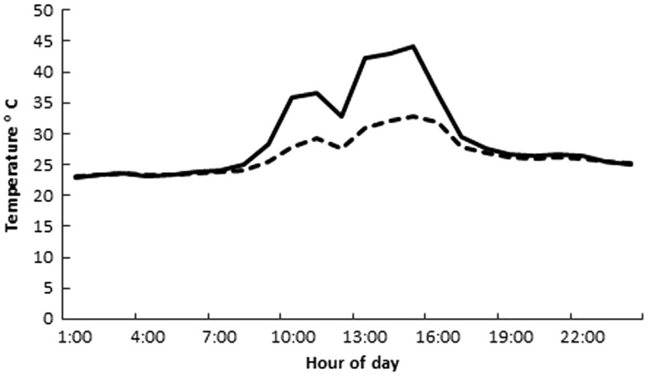


Fig. 4. Module temperature (solid line) and ambient temperature (dashed line).

such systems in Fiji, it has also played an important part in capacity building and general RE awareness among various stakeholders.

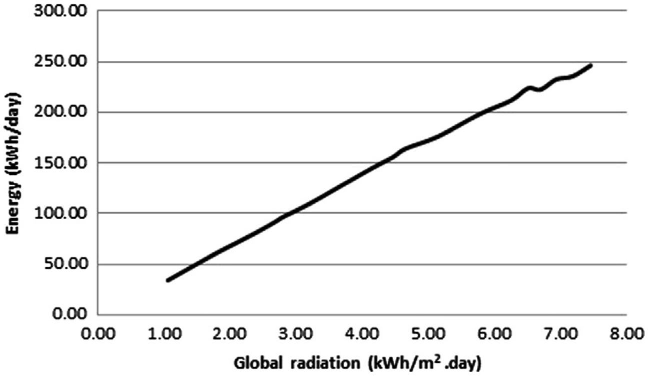


Fig. 5. Energy produced vs. global radiation (simulated).

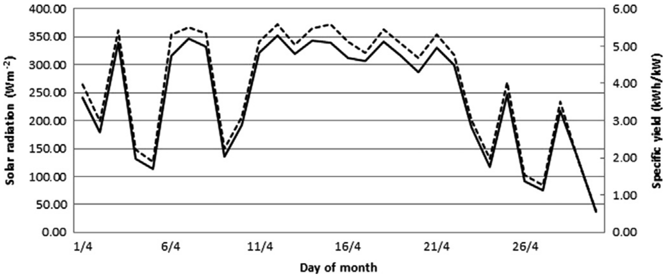


Fig. 6. Specific yield (Solid line) and solar radiation (Dashed line) for April 2014.

4. GCPV in the PICs: challenges

Yao et al. [67] reported that all utilities in the PICs are government owned and most countries do not have independent regulators. Only 5 out of the 19 utilities in PICs have external regulation [68] while some have plans for independent regulators.

This means that there is not much competition in terms of the distributed generation (i.e. IPPs may not be encouraged) and utilities look at their interests first before embarking on any distributed generation project. Following are some of the issues that need to be carefully considered to help GCPV systems proliferate in the Pacific region.

4.1. Variability of the solar resource and grid stability

Fig. 7 shows the average hourly output from the USP 45 kW_p system on two different days. The impact of solar radiation fluctuations over the course of the day on the daily production is significant and put the base load system under stress especially in the case of a large GCPV system. This intermittent nature becomes pronounced under tropical conditions.

The impact of cloud movement on an isolated grid in Australia is reported in [69]. A 1.1 MW distributed GCPV capacity is connected to 11.5 MW gas/diesel grid. In the year 2011, peak penetration during summer months was 13% with an annual average penetration of 3%. There were pronounced fluctuations at localized levels due to cloud movement but no system-wide impacts were detected. The cloud effect is much more pronounced in the case of centralized PV systems such as the two 12 MW GCPV systems connected to a 78 MW grid at the Kauai island in Hawaii [70]. A drifting cloud over the solar farm can cut the power output by 70–80% and drastically reduce the frequency. This is being tackled by using Lithium-ion battery storage that can provide enough power to keep the frequency stable during the passage of a cloud.

In most of the PICs the grids are built around generators that are more than 20 years old and have an average of 12.8% power losses [71]. While it is possible to introduce RE contribution at lower levels without much problem, increasing penetration contribution will require the island utilities to install new efficient diesel generators and upgrade their grid infrastructure [43]. A recent World Bank feasibility study on a distributed GCPV system for South Tarawa in Kiribati found that 900 kW_p (26% of peak demand on weekdays) of solar PV can be connected to the grid without any interventions if each individual installation does not exceed 300 kW_p and are spaced 2–3 km apart. However, there should be provisions for cutting back solar input during the weekends and public holidays when the demand is reduced [72]. IRENA is supporting grid stability assessment for PIC grids and a pilot grid modelling study was conducted for Palau in 2013 [73]. The study, carried out by DIgSILENT Gmbh, Germany, found that up to 30% PV penetration from dispersed systems, no special requirements such as storage, change in dispatch strategy etc. were needed and the frequency remained stable despite short-term (1 s–10 min) fluctuations in the PV output. However, significant changes in the grid infrastructure and introduction of storage will be essential if higher penetration is desired.

4.2. Policy and financing

Although most PICs have a National Energy Policy that supports renewable energy development, they are still a long way from developing concrete frameworks that clearly map the way forward and establish guidelines for RE inclusion. This is especially true for grid-connected RE systems. Some countries (Cook Islands and Palau) already have net-metering regulation in place while others are in the process of choosing between net-metering and feed-in-tariff (FiT) for their proposed Independent Power Producers (IPPs).

Although most of the current systems in the Pacific region are donor funded, there is a push for commercially operated systems. A new company in Fiji called Sunergise [50] offers solar PV power to commercial customers with no upfront cost. GCPV systems are designed to cater for 100% daytime requirements and electricity tariffs are guaranteed for long term. A number of corporate customers have installed systems under this scheme. To expand this effort in the whole Pacific region, it is important that the GCPV systems are shown to compete favourably or cheaper than the fossil-fuel based electricity generation. With average diesel generation costs between 0.35 and 0.55 USD/kW h [74] and solar modules getting cheaper, regional stakeholders are showing great interest in solar electricity. For example, in Fiji the cost of roof-mounted GCPV systems has come down to about USD 1700/kW_p from more than USD 5000/kW_p in 2010. The rates for Independent Power Producers have recently been revised in Fiji resulting in a flurry of potential investors [75] and there are plans to divest government shares in the Fiji Electricity Authority [76].

4.3. Human capacity

The SREEN report of IPCC has identified lack of relevant education and training as one of the major barriers to renewable energy development [77]. Passey et al. [21] also noted that lack of technical capacity within government departments and utility restricts the uptake of best practices increasing penetration level of DG in the grid. The availability of competent and certified professionals to carry out installation and maintenance of RE systems cannot be overstated. Traditionally, most of the renewable energy training has been project-based with hardly any pathways to sustainability. This problem has been acutely realized by all stakeholders and now there are concerted efforts underway to establish a regional centre of excellence in renewable energy and energy efficiency.

To attract PV investments in new and emerging markets, IEA solar technology roadmap suggested medium to long-term targets for PV deployment, facilitation of investment in distributed generation through FiTs or net-metering, identification of cost-structure of current projects and implementation of specific actions to reduce anomalous soft costs and finally, working with

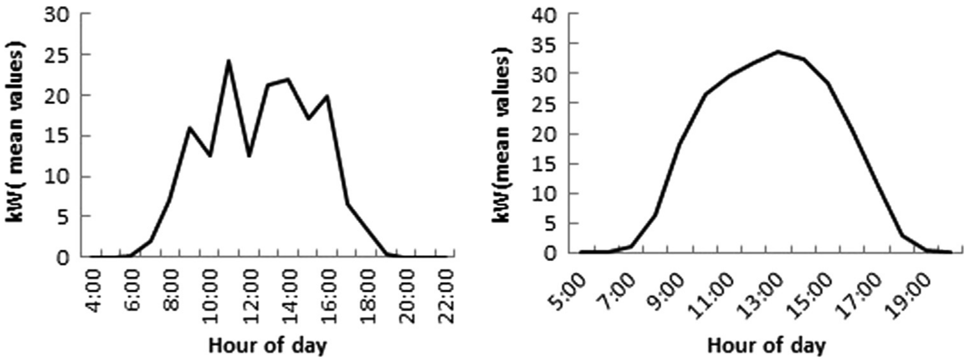


Fig. 7. Hourly production (Left: 6th December 2013 – A typical day in Suva, Right: 12th December 2013-A sunny day in Suva).

financial institutions to reduce PV deployment costs [5]. An IRENA report on renewable energy in islands [78] pointed out that successful investment in cost-effective renewable technologies can happen through (i) political priority to attract investment – governments should be committed and these commitment should be reflected in legislations, (ii) market framework for investment – the electricity market should be open to include IPPs and building owners and that the regulations should encourage utilities to invest in renewable generation, (iii) technical planning for investment – integrated planning must be done so that reliability of the service is not affected and environment, social and health costs are minimized and (iv) capacity to implement investment – skilled personnel are required plan, finance, manage, operate and maintain electricity generation.

In summary, a multidimensional approach dealing with various technological, human capital and economic policy issues is essential in order to mainstream GCPV into a country's electrical power system.

5. Conclusions

GCPV systems are going to play a crucial role as the global electricity networks slowly but surely reduce their dependence on fossil fuels. This is especially true in the case of developing countries including PICs. As the PICs continue their struggle with the challenges of climate change and imported fossil fuels, renewable energy becomes increasingly relevant in this region. Solar PV systems, both grid-connected and standalone present economically attractive opportunities to tackle these challenges. With decreasing module costs, grid-connected PV systems are emerging as important part of the PIC power systems. However, increasing penetration levels have to be planned and designed carefully with adequate safeguards in place. The policy landscape will also need to be modified in order to accommodate and encourage IPPs. Availability of adequate human capacity at all levels and sectors is also crucial.

The case study represents a typical GCPV system in the PICs and its performance matches well with the simulated indicators. In the year 2013, this system produced an average of 148.5 kWh/day corresponding to an average daily specific yield of 3.3 kW h/kW/day. The yield was highest in the month of January (4.6 kW h/kW/day) while the lowest value was recorded in June (2.72 kW h/kW/day).This system is also helping the USP marine campus to reduce its carbon footprint by almost 27,500 kg CO_{2e} per annum while generating 10% of campus electricity requirements. It should be noted that Suva is not the sunniest location in Fiji and a system in the western part would have a much higher yield.

References

[1] REN21, Renewables 2014 Global Status Report. Paris: REN21 Secretariat, 2014.

[2] International Energy Agency (IEA). Deploying renewables 2011: best and future policy practice. France: OECD/IEA; 2011.

[3] IRENA Report. Renewable power generation costs in 2012: an overview-executive summary; 2013.

[4] Singh GK. Solar power generation by PV (photovoltaic) technology: a review. Energy 2013;53:1–13.

[5] International Energy Agency (IEA). Technology roadmap: solar photovoltaic energy. Paris: OECD/IEA , ⟨http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf⟩; 2014 [accessed 08.05.15].

[6] Raugei M, Frankl P. Life cycle impacts and costs of photovoltaic systems: current state of the art and future outlooks. Energy 2009;34:392–9.

[7] Cucumo M, De Rosa A, Ferraro V, Kaliakatos D, Marinelli V. Performance analysis of a 3 kW_p grid-connected photovoltaic plant. Renew Energy 2006;31:1129–38.

[8] So JH, Jung YS, Yu GJ, Choi JY, Choi JH. Performance results and analysis of 3 kW_p grid-connected PV systems. Renew Energy 2007;32:1858–72.

[9] Sharma V, Chandel SS. Performance analysis of a 190 kW_p grid interactive solar photovoltaic power plant in India. Energy 2013;55:476–85.

[10] Acquaviva V, Poggi P, Muselli M, Louche A. Grid-connected rooftop PV systems for reducing voltage drops at the end of the feeder – a case study in Corsica Island. Energy 2000;25:741–56.

[11] Hong T, Koo C, Park J, Park HSA. GIS (geographic information system)-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system. Energy 2014;65:190–9.

[12] Aste N, Pero CD, Leonforte F, Manfren M. A simplified model for the estimation of energy production of PV systems. Energy 2013;59:503–12.

[13] Cansino JM, Cardenete MA, Gonzalez-Limon JM, Roman R. The economic influence of photovoltaic technology on electricity generation: a CGE (computable general equilibrium) approach for the Andalusian case. Energy 2014;73:70–9.

[14] Papadopoulos AM, Karteris MM. An assessment of the Greek incentive scheme for photovoltaics. Energy Policy 2009;37:1945–52.

[15] Ayompe LM, Duffy A, McCormack SJ, Conlon M. Projected costs of grid-connected domestic PV system under different scenarios in Ireland, using measured data from a trial installation. Energy Policy 2010;38:3731–43.

[16] Mitscher M, Ruther R. Economic performance and policies for grid-connected residential solar photovoltaic systems in Brazil. Energy Policy 2012;49:688–94.

[17] Spiegel RJ, Dl Greenberg, Kern EC, House DE. Emissions reduction data for grid-connected photovoltaic power systems. Sol Energy 2000;68:475–85.

[18] Bernal-Agustin J, Dufo-Lopez R. Economical and environmental analysis of grid connected photovoltaic systems in Spain. Renew Energy 2006;31:1107–28.

[19] Bayod-Rujula AA, Lorente-Lafuente AM, Cirez-Oto F. Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems. Energy 2011;36:3148–58.

[20] Zini G, Mangeant C, Merten J. Reliability of large-scale grid-connected photovoltaic systems. Renew Energy 2011;36:2334–40.

[21] Passey R, Spooner T, MacGill I, Watt M, Syngellakis K. The potential impacts of grid-connected distributed generation and how to address them: a review of technical and non-technical factors. Energy Policy 2011;39:6280–90.

[22] Shah R, Mithulananthan N, Bansal RC, Ramachandaramurthy VK. A review of key power stability challenges for large-scale PV integration. Renew Sustain Energy Rev 2015;41:1423–36.

[23] Tarroja B, Mueller F, Eichman JD, Samuelsen S. Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing. Energy 2012;42:546–62.

[24] Alsayegh O, Alhajraf S, Albusairi H. Grid-connected renewable energy source systems: challenges and proposed management schemes. Energy Convers and Manag 2010;51:1690–3.

[25] ElNozahy MS, Salama MMA. Technical impacts of grid-connected photovoltaic on electrical networks – a review. J Renew Sustain Energy 2013;5:1–12. http://dx.doi.org/10.1063/1.4808264.

[26] Eltawil MA, Zhao Z. Grid-connected photovoltaic power systems: technical and potential problems – a review. Renew Sustain Energy Rev 2010;14:112–29.

[27] Paatero JV, Lund PD. Effects of large-scale photovoltaic power integration on electricity distribution networks. Renew Energy 2007;32:216–34.

[28] Audenaert A, De Boeck L, De Cleyn S, Lizin S, Adam JF. An economic evaluation of photovoltaic grid connected systems (PVGCS) in Flanders for companies: a generic model. Renew Energy 2010;35:2674–82.

[29] Yang C-J. Reconsidering solar grid parity. Energy Policy 2010;38:3270–3.

[30] Antonelli M, Desideri U. The doping effect of Italian feed-in tariffs on the PV market. Energy Policy 2014;67:583–94.

[31] Ahmad S, Tahar RZ, Muhammad-Sukki F, Munir AB, Rahim RA. Role of feed-in tariff policy in promoting solar photovoltaic investments in Malaysia: a systems dynamics approach. Energy 2015;84:808–15.

[32] Papadopoulos AM, Karteris MM. An assessment of the Greek incentive scheme for photovoltaics. Energy Policy 2009;37:1945–52.

[33] Tsilingiridis G, Ikonomopoulos A. First results of incentives policy on grid interconnected photovoltaic systems development in Greece. Energy Policy 2013;58:303–11.

[34] Martin N, Rice J. The solar photovoltaic feed-in tariff scheme in New South Wales, Australia. Energy Policy 2013;61:697–706.

[35] Biondi T, Moretto M. Solar grid parity dynamic in italy: a real option approach. Energy 2015;80:293–302.

[36] Rigter J, Vidican G. Cost and optimal feed-in tariff for small scale photovoltaic systems in China. Energy Policy 2010;38:6989–7000.

[37] Ayompe LM, Dufffy A. Feed-in tariff design for domestic scale grid-connected PV systems using high resolution household electricity demand data. Energy Policy 2013;61:619–27.

[38] Krasko VA, Doris E. State distributed PV policies: can low cost (to government) policies have a market impact. Energy Policy 2013;59:172–81.

[39] Taking ADB. Control of oil: managing dependence on petroleum fuels in the Pacific. Manila: Asian Development Bank; 2009.

[40] Dornan M, Jotzo F. Renewable technologies and risk mitigation in small island developing states: Fiji's electricity sector. Renew Sustain Energy Rev 2015;48:35–48.

[41] Fiji Commerce Commission. Final determination of electricity tariff rates. Fiji Electricity Authority, ⟨http://www.commcomm.gov.fj/⟩; Date Issue 11 December 2012 [accessed 02.09.14].

[42] ⟨www.teaponga.com⟩; [accessed 10.05.14].

[43] IRENA Report. Pacific lighthouses: renewable energy opportunities and challenges in the Pacific region, ⟨www.irena.org⟩; August 2013 [accessed 05.02.14].

[44] ⟨http://reneweconomy.com.au/2014/netcon-ja-solar-build-1mw-solar-plant-cook-islands-72943⟩; [accessed 21.05.14].

[45] PES Cook Islands KEMA grid study – final report: integrating PV solar and wind generation with the TAU electric system. Te Aponga Uira O Tumu-Te_Varovaro, ⟨http://grein.irena.org/UserFiles/casestudies/Cook_Islands_Network_Analysis_Report.pdf⟩; January 2013 [accessed 08.05.15].

[46] Solar powered marina – Port Denarau goes Green! ⟨http://fijimarinas.com/solar-powered-marina-port-denarau-goes-green/⟩; [accessed 18.11.14].

[47] Nasiko R. More for solar. The Fiji Times Online, ⟨http://www.fijitimes.com/story.aspx?id=246083⟩; Friday September 20, 2013 [accessed 18.11.14].

[48] Turtle Island Resort solar power system, ⟨http://www.clayenergy.com.fj/news/turtle-island-resort-solar-power-system⟩; [accessed 28.11.14].

[49] Fiji Sun Online. Turtle Island Resort installs 968 solar panels, ⟨http://www.fijisun.com.fj/2013/03/19/turtle-island-resort-installs-968-solar-panels/⟩; March 19, 2013 [accessed 28.11.13].

[50] ⟨http://www.sunergisegroup.com/customers/⟩; [accessed 10.05.15].

[51] ⟨http://www.irena.org/DocumentDownloads/Publications/IRENA%20Kiribati%20RRA.pdf⟩.

[52] World Bank. Pacific islands – grid connected solar PV central station project. Washington D.C.: World Bank, ⟨http://documents.worldbank.org/curated/en/2012/04/16544687/pacific-islands-grid-connected-solar-pv-central-station-project⟩; 2012 [accessed 10.05.15].

[53] ⟨http://www.forumsec.org/pages.cfm/strategic-partnerships-coordination/pacific-environment-community-pec-fund.html⟩; [accessed 29.05.14].

[54] ⟨http://www.pv-magazine.com/news/details/beitrag/samoa-sets-sights-on-largest-solar-array-in-the-pacific_100014877/#axzz334FIpnUW⟩; [accessed 29.05.14].

[55] Pacific Islands Forum Secretariat. Secretary General inspects Samoa's largest solar photovoltaic system, ⟨http://www.forumsec.org/pages.cfm/newsroom/announcements-activity-updates/2013-4/secretary-general-inspects-samoas-largest-solar-photovoltaic-pv-system.html⟩; [accessed 21.02.14].

[56] ⟨http://www.photon.info/photon_news_detail_en.photon?id=85542⟩; [accessed 29.5.14].

[57] PES Savaii KEMA grid study – final report: integrating PV solar and wind generation with the EPC electric system. Electric Power Corporation. Version 2.0, ⟨http://grein.irena.org/UserFiles/casestudies/Samoa_Network_Analysis_Report_Savaii.pdf⟩; January 2013 [accessed 08.05.15].

[58] PES Upolu KEMA grid study: integrating PV solar and wind generation with the EPC electric system. Electric Power Corporation, ⟨http://grein.irena.org/UserFiles/casestudies/Samoa_Network_Analysis_Report_Upolu.pdf⟩; January 2013 [accessed 08.05.15].

[59] ⟨http://tokelau.org.nz/Solar+Project.html⟩; [accessed 29.05.14].

[60] ⟨http://www.adb.org/news/tonga/adb-australia-fund-solar-systems-help-tonga-cut-fuel-bill-power-costs⟩; [accessed 29.05.14].

[61] IUCN. Powering the Pacific – launch of Tuvalu solar project, ⟨http://www.iucn.org/news_homepage/news_by_date/?5080/Tuvalu-solar-project-commissioned⟩; [accessed 20.02.14].

[62] Funafuti Atoll. Tuvalu distributed renewable generation study: integrating PV solar and wind generation with TEC electric system. New Zealand Ministry of Foreign Affairs and Trade, ⟨http://grein.irena.org/UserFiles/casestudies/Tuvalu_Distributed_Renewable_Generation_Study.pdf⟩; 2013 [accessed 08.05.15].

[63] ⟨http://www.greenstage.co.nz/PDFs/CaseStudy_PicoGrid_Active_Power_Limitation.pdf⟩; [accessed 25.05.14].

[64] ⟨http://greenenergysolutions.com.au/assets/Datasheet_BP_4190T.pdf⟩; [accessed 18.05.14].

[65] ⟨http://files.sma.de/dl/5695/SMC8000TL-DEN102330.pdf⟩; [accessed 20.05.14].

[66] ⟨http://cdmloanscheme.org/sites/default/files/pdd-fiji.pdf⟩; [accessed 15.05.15].

[67] Yao X, Guild R, Trainor JM. Energy security and sustainable development opportunities in Pacific Island Countries. In: Yan J, editor. Handbook of clean energy systems. John Wiley & Sons Ltd.; 2015. p. 1–12 ISBN: 978-1-118-38858-7, (Published online: 16 July 2015).

[68] Pacific Power Association. Performance benchmarking for Pacific power utilities, ⟨http://www.ppa.org.fj/wp-content/uploads/2013/03/Power-Benchmarking-Main-Report-5-Feb.pdf⟩; December 2011 [accessed 08.05.15].

[69] ⟨http://www.irena.org/documentdownloads/events/VanuatuJuly2012/5_Geoff_Stapleton.pdf⟩; [accessed 10.05.15].

[70] ⟨http://www.technologyreview.com/news/534266/hawaiis-solar-push-strains-the-grid/⟩; [accessed 10.05.15].

[71] ⟨https://www.climateinvestmentfunds.org/cif/sites/climateinvestmentfunds.org/files/Kiribati_EOI.pdf⟩; [accessed 10.05.15].

[72] IRENA. Japan-IRENA joint workshop: accelerating renewable energy deployment in the pacific region – meeting the challenges. Okinawa, Japan; 26 May 2012.

[73] ⟨http://www.irena.org/documentdownloads/events/2013/march/palau/01_pilotproject_palau.pdf⟩; [accessed 09.05.15].

[74] IRENA. Renewable energy costs in 2012 – an overview, ⟨https://www.irena.org/DocumentDownloads/Publications/Overview_Renewable%20Power%20Generation%20Costs%20in%202012.pdf⟩.

[75] ⟨http://www.fijisun.com.fj/2014/05/28/energy-commcomm-reviews-ipp-rate-at-33-08-cents-to-attract-investors-now/⟩; [accessed 10.05.15].

[76] ⟨http://pidp.eastwestcenter.org/pireport/2015/April/04-21-08.htm⟩; [accessed 10.05.15].

[77] IPCC. IPCC special report on renewable energy sources and climate change mitigation. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, von Stechow C, editors. Prepared by working group III of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2011. p. 1075.

[78] GREIN and IRENA. Renewable islands: settings for success. IRENA, ⟨http://grein.irena.org/UserFiles/casestudies/Settings_For_Success_brochure_web.pdf⟩; 2014 [accessed 08.05.15].