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Research Paper

A Study on a Hybrid Energy System to Reduce CO_2 Emission In Mavuva Island, Fiji

Tae Yong Jung† · Jung Hee Hyun · Seul Lee · Minkyung Huh
Graduate School of International Studies, Yonsei University

마부바섬의 이산화탄소 감축을 위한 복합 에너지 시스템에 대한 연구

정태용† · 현정희 · 이 슬 · 허민경
연세대학교 국제학대학원

Abstract : Although the effects of climate change are universal, Small Island Developing States (SIDS) are considered to be most vulnerable. SIDS heavily rely on imported oil and fossil fuels for electricity generation and transportation, which makes them economically vulnerable and exposed to fluctuating oil price. Among the reasons SIDS highly depend on diesel fuel is due to the dispersed population living in remote islands which means, providing electricity through on on-grid system is difficult. Fiji as one of the SIDS, has actively promoted renewable sourced energy through a national plan to mitigate the impacts of climate change. In order to determine how feasible implementing a renewable energy (RE) system will be in Fiji, this study chose a remote island called Mavuva Island to test application of a hybrid RE system using HOMER. A combination of energy storage system (ESS), solar photovoltaic (PV) and diesel generator turns out to be the most cost effective and optimal configuration, resulting in effective greenhouse gas reduction for the given region.

Keywords : Renewable Energy, Hybrid Energy System, Off-grid System, Climate Change Effects

요 약 : 오늘날 대부분의 국가는 기후변화 문제에 직면해 있으며, 특히 군소도서개발국들(SIDS: Small Island Developing States)은 기후변화의 영향에 가장 취약하다. 이들은 전력생산 및 교통부문에 있어 수입된 석유와 화석 연료에 크게 의존하고 있으므로 유가 변동에 따라 경제적으로 매우 영향을 받는다. 군소도서개발국들(SIDS)이 디젤 연료에 의존하는 이유 중 하나는 외딴 섬에 인구가 분산되어 있어서 계통

First and Corresponding author: Tae Yong Jung, Graduate School of International Studies, Yonsei University, 50 Yonsei-Ro, Seodaemun-gu, Seoul, Korea, Tel: +82-2-2123-3594, E-mail: tyjung00@yonsei.ac.kr
Co-Authors: Jung Hee Hyun, Graduate School of International Studies, Yonsei University, 50 Yonsei-Ro, Seodaemun-gu, Seoul, Korea, Tel: +82-2-2123-3594, E-mail: hyunjunghee@gmail.com
Seul Lee, Graduate School of International Studies, Yonsei University, 50 Yonsei-Ro, Seodaemun-gu, Seoul, Korea, Tel: +82-2-2123-3594, E-mail: successeul@gmail.com
Minkyung Huh, Graduate School of International Studies, Yonsei University, 50 Yonsei-Ro, Seodaemun-gu, Seoul, Korea, Tel: +82-2-2123-3594, E-mail: bellamk89@gmail.com
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연결을 통한 전력공급이 어렵기 때문이다. 군소도서개발국들 중 피지(Fiji)는 기후변화의 심각성을 인식하고 기후 변화의 영향을 줄이기 위한 '국가계획'을 통해 신재생에너지 사용을 적극 장려하고 있다. 본 연구에서는 피지의 마부바 섬(Mavuva Island)을 대상으로 HOMER 프로그램을 사용하여 태양광, 에너지저장장치 및 디젤 발전의 조합을 통하여 최적의 에너지 시스템을 시뮬레이션하고 분석한다. 태양광과 디젤 발전을 합친 하이브리드 에너지시스템이 이 지역의 실행가능성 및 가격 측면에서 가장 효과적이고, 온실가스 감축효과도 큰 것으로 파악되었다.

주요어 : 신재생에너지, 하이브리드 에너지 시스템, 비계통 연계시스템, 기후변화영향

I. Introduction

The unique situation of Small Island Developing States (SIDS) was acknowledged at the United Nations Conference on Environment and Development in Rio de Janeiro in 1992. Fiji is one of the most developed economies in the SIDS and classified as an upper middle-income country by the World Bank due to an abundance of forest, mineral, and fish resources. Most of the Pacific Islands Countries including Fiji sources its electricity mostly from large grid connected power plants to power refrigeration, air conditioning, lighting, and household appliances (IRENA 2015). Despite the ambitious national target of Fiji, which is to provide electricity with 100% renewable energy (RE) by 2030, the use of RE technologies for power production has been limited due to the high costs. The condition of dispersed population makes energy system rely on cheap small scale diesel power generators since RE systems have high up-front cost and grid-connection cannot reach remote villages (Dornan 2011).

The main objective of this study is to identify the most cost-effective energy system among various system configurations with solar energy sources. In order to find how feasible implementing a RE system is, a remote island in Fiji called Mavuva Island is selected and HOMER is used to test application of a RE system with relevant economic parameters and reduction of greenhouse gas (GHG) emissions.

Mavuva Island is located in Macuata Province, a traditional community just off the northern coast of Vanua Levu, Fiji's second main island. The island has been promoting its development into a unique off grid island community focused on sustainable living since 2016. Mavuva Island has been designated as one of 43 islands, 8% of all land, in Fiji that is freehold and can be owned outright privately by individuals (all other land only available to lease). The residents will be required to follow the Communities Environmental Management Plan (CEMP) by the Fijian government such as using renewable energy generator power systems and appropriate sewage treatment for environmental responsibility (Mavuva Island 2017).

There are currently various renewable power systems operated in Fiji – hydropower, biomass, wind, PV, etc., to meet the national renewable energy targets. However, these power systems have unique challenges for wider general use based on the specificities of each. The most common problem for remote regions comes from the lack of accessibility to grid connection and local capacity to operate and manage RE technologies including, equipment erosion, malfunction, and poor management.

Various researches have already been done on the application of hybrid RE systems in remote islands, specifically in the Pacific (Palit & Chaurey 2011; Ajal & Krishna 2013; Dornan & Jotzo 2011). Lal (2012) conducted a study on a techno-economic analysis of a Wind-PV-Diesel hybrid mini-grid system for Fiji Islands, Nabouwalu. HOMER was used for optimal configuration, net present cost (NPC), and the levelized cost of energy (LCOE). The study results show that 100% renewable energy system consisting of PV, wind turbines with battery storage is feasible with the flexibility of a 10% capacity shortage. Lal (2012) found that without allowing for 10% annual capacity shortage the optimal configuration is a hybrid system of PV-Diesel. Jung et al. (2017)'s study on the feasibility of a hybrid PV-Diesel-ESS system for Kumundhoo, Maldives. An economic analysis was examined with different discount rates, feed-in tariff (FIT) rates to calculate the benefit-cost ratio, NPC, and internal rate of return (IRR). The study outlined that the hybrid solar PV-Diesel-ESS system is economically efficient for the Maldivian government given that the benefit cost ratio increases along with NPC and IRR over the project lifetime. Their result proves the financial feasibility of the hybrid renewable system given a 9% IRR in 20 years.

In this study, to verify the most cost-effective hybrid energy system for Mavuva island, economic analysis included sensitivity analysis of uncertainty in the financial discount rate and carbon price, which accounts for the social price of CO_2 emissions. In the following sections, HOMER's analysis methods, Mavuva's energy demand assumptions, power system costs will be explained and tested. A conclusion will be made based on the results of the analysis.

II. Methodology

To test the technical and economic feasibility of different configurations of power systems applicable to Mavuva Island, HOMER simulation program was used for analysis. Developed by the National Renewable Energy Laboratory, HOMER aims to identify an optimal energy system by simulating different configurations of renewable and non-renewable energy sources and technologies and finding the optimal system based on cost efficiency. As the final step, sensitivity analysis helps assess the effects of uncertainty or changes in the variables by performing multiple optimizations (Sureshkumar et al. 2012).

1. Economic Analysis with HOMER

HOMER utilizes the total NPC to represent the life cycle cost of energy systems, which includes all costs that could occur during the project lifetime, with future cash flows discounted to the present. Another important cost information of energy system is represented as LCOE, which is the average cost per kilowatt-hour of electrical energy produced by the system (HOMER® Pro 2016). Regarding how HOMER calculates the NPC and LCOE, the following equation should be noted:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (1)$$

where $C_{ann,tot}$ is the total annualized cost, i is the annual real interest rate (the discount rate), R_{proj} is the project lifetime, and $CRF(*)$ is the capital recovery factor, which accounts for the time factor. HOMER uses the following equation to calculate the levelized cost of energy:

$$LCOE = \frac{C_{ann,tot}}{E_{prim} + E_{def}} \quad (2)$$

where $C_{ann,tot}$ is the total annualized cost, E_{prim} and

E_{def} are the total amounts of primary and deferrable load.

2. Input Assumptions for HOMER

According to Mavuva Island's developer, the Pacific Development Group, 86 lots have been designated for residential purposes around the oceanfront as shown in the plan below.

For the purposes of this study, only the residential energy demand of Mavuva Island will be analyzed. Since the island is yet to be developed

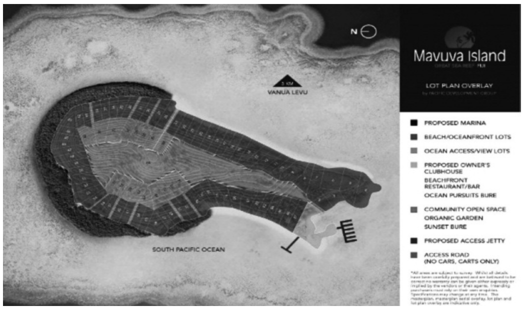

Figure 1. Mavuva Island Lot Plan

Source: Project Development Group (http://www.mavuvaisland.com/index.php)

and inhabited, the energy demand load was constructed based on similar use patterns of previous studies (Lal 2012; Charan 2014; UNDP 2014). Based on seasonal variation, two scenarios of daily load patterns were synthesized as shown below.

The main difference in use pattern between the seasons is the increased use of cooling and decreased use of lighting during the hotter season while decreased cooling during the cooler months. The use of various appliances and number of hours was estimated based on similar use patterns of private resort residences. The table below shows the average energy demands of each household and all 75 households for each season.

Given the total daily demand, variation of demand throughout the day needs to be sketched. Based on literature review of how daily demand scenarios are plotted, an evening peak between 18:00 and 21:00 is used as shown with

Table 1. Household Energy Demand Assumptions by Season

	1 Household			Peak Season (January – March)		Low Season (June – August)	
	Name	#	Energy (W)	Use (hrs)	Total Day Use (Wh)	Use (hrs)	Total Day Use (Wh)
Appliances	TV	1	150	2	300	2	300
	Computer	1	100	2	200	2	200
	Charging	2	25	6	300	6	300
	Washing Machine	1	50	0.5	25	0.5	25
	Vacuum	1	500	0.5	250	0.5	250
Kitchen Appliances	Refrigerator	1	55	24	1320	24	1320
	Microwave	1	1100	0.25	275	0.25	275
	Oven	1	1200	0.25	300	0.25	300
	Stovetop	1	730	2.5	1825	2.5	1825
Cooling	Fan	2	25	9	450	4	200
	AC	1	1500	2.5	3750	1	1500
Lighting	Overhead CFL	12	15	3	540	3	540
	Stand	2	12	0.5	12	1	12
Total				9547 Watts/day		7059 Watts/day	

Source: Based on Author's Calculation

Table 2. Mavuva Island Households Energy

Peak Season			Low Season		
1 H. use/hour (Wh)	75 H. (kW)	75 H./hour (kWh)	1 H. use/hour (Wh)	75 H. (kW)	75 H./hour (kWh)
397	716	29	294	529	22

Source: Based on Author's Calculation

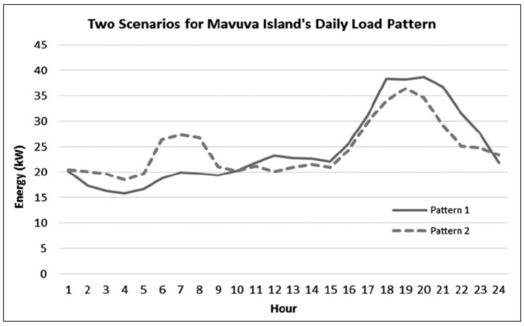

Figure 2. Daily load patterns of Fiji's Remote Island (Pattern1) & load pattern of developing countries (Pattern2)

Source: Based on Author's Calculation

Pattern 1 in the figure below (Lal 2012; Charan 2014).

Another load pattern was found from a United Nations Development Programme report (UNDP 2014) on rural electrification and simulates a load pattern with a double peak ? one in the morning between 6 a.m. and 8 a.m. and second between 6 p.m. to 8 p.m. as shown in Figure 2 as Pattern 2.

3. System Assumptions

1) Economic Inputs (Sensitivity variables)

To determine the feasibility of energy system configurations, the NPC of the system was discounted by 6%, 8% and 10% which accounts for the length of the project (20 years), country and system risk. Discount rates were selected as sensitivity variables based on previous feasibility studies of RE systems in remote islands (Dornan 2011; Charan 2014; Jung et al. 2017).

To account for the social cost of GHG emissions, a price for carbon was inputted. Since the price of carbon has not yet to be stabilized and universally used and accepted via market pricing, three projected prices $5, $10, $15 per ton of carbon were selected for analysis. In previous studies examining the effect of carbon price (Adkins et al. 2011; EIA 2009) an economy-wide price of $15/ton for the first half of the next decade was used. Additionally price projections ($15, $20, $25) by the *Synapse Energy Economics*, a research and consulting firm specializing in energy, economic, and environmental topics, was also noted. (Luckow et al. 2015). For reference, the price of carbon (EU) as of July 7th, 2017 is $5.24/ton (Markets Insider 2017).

Lastly, the cost for diesel used for electric generation was selected as a sensitivity variable considering how the volatility of diesel price greatly affects the greater economy of Fiji. Thus for the purposes of this study the lowest, average and highest price per liter in the past twenty years recorded by German Agency for International Cooperation (GIZ) - $0.37, $0.83, $1.29, were used. For reference, the average price of diesel in 2016-2017 has been $0.75/L (Global Petroleum Price 2017). System technology specifications are explained by each component used for HOMER simulation as shown in Figure 3.

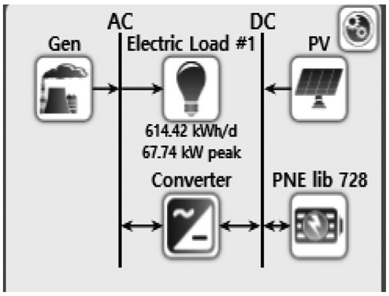

Figure 3. Schematic Diagram of HOMER system inputs

Source: HOMER Pro (version 3.7)

2) Diesel Generator

For this simulation, an auto-size diesel fueled generator designed by HOMER was deployed. The benefit of this model is that the generator automatically sizes itself to the meet the load, particularly useful to model due to ranging renewable energy potential.

3) PV System

HOMER models the PV array as a producer of DC electricity in direct proportion to the global solar radiation, independent of the exposed temperature and the voltage. Power output capacity of PV is calculated based on the following variables: rated capacity (peak capacity), area and efficiency of PV module, and derating factor. For each hour of the year, HOMER calculates solar radiation using the region's solar radiation data downloaded from NASA. In simulation, HOMER's generic flat plate PV was deployed.

4) Batteries – lead acid, lithium

In an effort to seek alternative energy systems reflecting new technologies, a lithium ion battery produced by PNE Solutions was used for simulation. The lithium battery has a higher level of technical capacity than advanced lead acid batteries with extensive flexibility to adapt to load change.

5) Converter

A converter is a device that converts electric power from DC to AC in a process called inversion, and/or from AC to DC in a process called rectification. The converter size refers to the inverter capacity, meaning the maximum amount of AC power that the device can produce by inverting DC power. HOMER assumes that the inverter and rectifier capacities are not surge capacities but rather, continuous capacities that the device can withstand for as long as necessary.

Table 3. Summary of System Costs

Component	Capital Cost	Replacement Cost	O&M cost	Life time
Diesel generator	$500/kW	$500/kW	$0.05 /hr	15,000 hrs
PV panel	$2100/ unit	$2100/kW	$10/yr	20 yr
Lithium Battery (728kW)	$530,000/ unit	$150,000/ unit	$5000/yr	20 yr
Converter	$500/kW	$450/kW	0	20 yr

Source: Jung et al. (2017)

The above table summarizes the systems costs used from Jung et al. (2017)'s study and inputted in HOMER for the present study. Based on these inputs and selected sensitivity variables, including diesel and carbon price and discount rate, the results of the simulations are explained in the following section.

III. Results

Simulation results of the two load patterns did not show much of a difference in LCOE, NPC, and renewable fraction. Thus for the purposes of this study load pattern 2 will solely be used as it most closely reflects the assumed use pattern of Mavuva Island as well as the specific condition of Fiji's location (Lal 2012).

Among 8,298 simulations, 6,732 were feasible cases, 1,566 were infeasible due to the capacity shortage and 3 sensitivity variables in simulating load pattern 2. Electric production is stable for RE sourced power systems just as much as diesel sourced power systems simulation. Further analysis will focus on the economics of the system types.

Table 4. Economic results of each power system type

ST	Cost				IRR (%)	Payback Period (Yr)
	LCOE ($/kWh)	NPC ($)	Initial Capital ($)	Operating Cost ($)		
ST1	0.54	1.66M	36,000	118,449	–	–
ST2	0.54	1.66M	38,587	118,369	–	–
ST3	0.60	1.84M	585,560	91,722		
ST4	0.38	1.16M	970,611	14,981	9	9
ST5	0.61	1.88M	1.73M	10,570	2	16

Among the five technically feasible system types resulting from HOMER's simulation, ST1 consists of a diesel generator only. In this system, the LCOE is $0.54 and the NPC is $1.66 million. Since there is no renewable power source used in this case, the renewable fraction, which is the portion of a system's total electrical production originated from renewable power sources, is 0%. ST2 uses both diesel generator and solar PV to generate electricity. This type has a LCOE of $0.54 and NPC of $1.66 million. Since PV generates only 1.2 (kW), the renewable fraction is 0% and the economics is not much different form ST1. ST3 implements a diesel generator and ESS. It shows a high LCOE of $0.60 and NPC of $1.84 million, compared to other system types due to the high investment cost of the ESS.

ST4 uses all three components evaluated in our study: diesel-generator, solar PV, and ESS. It is considered the most optimal case given that it has the lowest LCOE of $0.38 and NPC of $1.16 million compared to other systems and the highest renewable fraction of 92.4%. The last system type consists of PV and ESS only. Despite the high initial cost of ST4, the reason its NPC is lower than ST1 and ST2 (which have lower initial costs) is because ST4 avoids the reoccurring cost of replacing diesel generators. Additionally, ST4 included environmental benefits evident in the high renewable fraction. Lastly, ST5 has the highest LCOE of $0.61 and NPC of $1.88 million because it is solely sourced by PV and ESS with 100% of RE fraction. However the system's benefits include low yearly operating costs and zero GHG emissions.

1. Economic Analysis

Based on the results calculated by HOMER, between the hybrid RE-diesel system (ST4) and the most traditional option of diesel-only generation (ST1), ST4 is the most economically feasible for off-grid electrification in Mavuva Island given an IRR of 9% and the relatively short payback period of less than 9 years. Table 7 summarizes the economic analysis results.

2. CO_2 emissions

Figure 4, shown below, is a summary of how much each system emits CO_2 per year. ST1 and ST2 emit CO_2 the most, 209 tons per year, among other types since it is fueled mostly by diesel fuel. ST3, composed of a diesel generator and ESS system emits approximately 6 tons of CO_2 per year less than ST1 and ST2. This shows the effect of storing excess energy during off-use times and making use of the energy during peak hours without needing to increase the overall capacity of the generator. ST4, which is a hybrid PV-ESS-

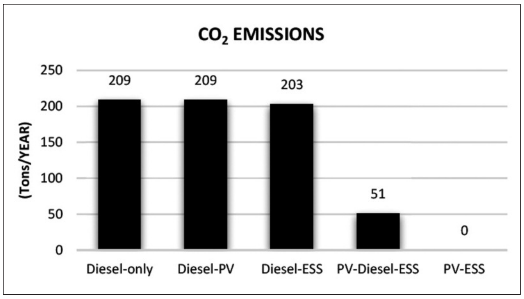

Figure 4. CO_2 Emissions by System Type

Diesel system, emits less CO_2 compared to the previous system types, which were heavily sourced by diesel-fuel. In ST5 no diesel-fuel were used without CO_2 emissions.

3. Sensitivity Analysis

HOMER carried out sensitivity analysis with selected variables including the discount rate (6%, 8% and 10%), carbon price ($5, $10 and $15), and diesel price ($0.37, $0.83, $1.29). Figure 5 and 6 show the results of sensitivity analysis of the LCOE for System Type 1 (Diesel-only) and System type 4 (PV-Diesel-ESS).

As mentioned in the earlier section the cost and benefit of CO_2 emissions could be converted into monetary value to be accounted into the economic analysis of energy systems. For our research, a carbon price ($/ton) was included in calculating the LCOE and NPV as additional

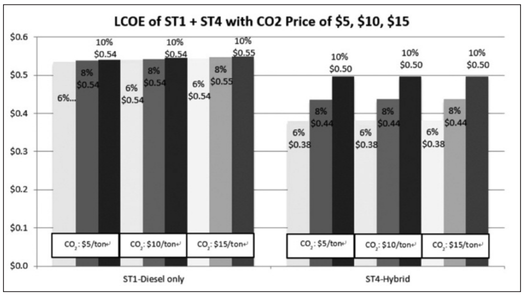

Figure 5. Sensitivity Analysis of LCOE using Carbon Price and Discount Rate Differentials

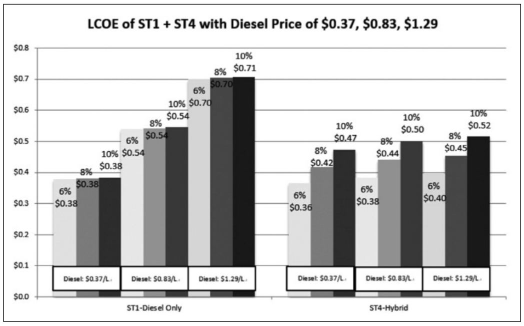

Figure 6. Sensitivity Analysis of LCOE using Diesel-fuel Price and Discount Rate Differentials

O&M (operation and management) costs in HOMER. Figure 5 and 6 show that ST1 is less affected by the carbon penalty and discount rate while heavily affected by fluctuating diesel prices. ST4's LCOE varies only with discount rate changes.

Because the variation in carbon price was not as dramatic as for the diesel fuel prices, it did not affect the overall LCOE of ST1 as much. This result confirmed the issue of economic instability in using energy sourced from diesel fuel. In the case of ST4, due to the high initial investment cost, the financial burden of repayment across the project lifetime is sensitive to the discount rate, which is an indicator of the time factor in monetary value.

Since discount rate has an impact on ST4 as a financial variable for its high initial capital investment, implementing RE system stresses the importance of financial analysis. This study confirms that mitigating such financial risk is required to make more efficient and widespread use of RE systems.

IV. Conclusion

Renewable energy-based, off-grid power systems could play a vital role in bringing sustainable energy system to rural communities in the Pacific Islands. In this study, an economic analysis on decentralized hybrid energy systems in Mavuva Island was conducted with HOMER. The results from simulation and sensitivity analysis showed that a Hybrid PV-ESS-Diesel system is a good alternative for off-grid electrification for the chosen location due to the potential fluctuations in oil price and environmental considerations.

This study specifically compared the current most used energy system, the diesel-based system type 1 and the most optimal energy system, the hybrid system type 4 to stress the different economic and environmental effects. The hybrid PV-Diesel-ESS system is less expensive than the diesel powered system and technically stable with the PV system at a sufficient level and the ESS having enough capacity to handle common variations of insolation and usage. Finally, the sensitivity result of this study concludes that for a successful application of hybrid Diesel-PV-ESS, financial feasibility must be secured due to uncertain future economic conditions, which is the cost of deploying an environmentally friendly energy system than the diesel-only energy type. However with higher and/or stable penalty of carbon price RE systems may have a greater benefit than the analysis done with the economic landscape of this research.

The unstable energy system with RE option only could be supplemented by ESS option. However, the current capital cost of ESS could be burdensome to local people to set up off-grid energy system without proactive and supportive policies from the public sector. For example, financial support and tax incentives for the local people who install the RE energy system with ESS could be carefully developed by comparing the conventional fossil-fuel based system.

To further encourage renewable energy sourced power systems systematically, additional supplementary tariffs are suggested for scaled up, grid-connected RE systems. Such special tariffs, as suggested by Nand (2013) will be based on the benefit added by PVs to the Fiji Electricity Authority (FEA)'s grid during peak demand of electricity or line support during periods of low rainfall or critical dam levels in dry seasons. Further, FEA could also charge Independent Power Producers (IPP's) to interface to their network.

As further measures to induce full penetration of renewable energy systems, the case of Mavuva Island of this study is an example of a bottom up approach to solving the issues of sourcing energy, especially renewable sourced, to remote islands that are most vulnerable to effects of climate change. With more cases of RE deployment as suggested for Mavuva Island, the collective actions of independent initiatives will scale up to become a mobilized global movement towards energy for all and tackling climate change.

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