SUSTAINABILITY OF PV SYSTEM FOR ISOLATED AND FRAGMENTED COMMUNITIES IN PAPUA NEW GUINEA

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Abstract: The electricity accessibility in Papua New Guinea is one of the lowest with less than 15 percent of the population having access to electricity. Given over 80 percent of the population are subsistence farmers living in the rural areas compounded by the challenging topography of the country, extending electricity grid to these rural areas where some are very remote and isolated is not financially feasible. Nonetheless, the PNG Government is optimistic of electrifying over 70 percent of the populace by 2030 as envisaged in one of its Millennium Development Goals. The recently established Papua New Guinea Electrification Partnership under the APEC agreement will drive growth and development for many isolated and fragmented communities in the country through off-grid and grid connected electricity network. Off-grid electrification is more feasible by empowering rural communities to produce their own electricity through photovoltaic systems. The solar insolation in the country is 4-6 hours of sunlight all year around hence utilization of solar energy will not only benefit the rural communities but also contribute towards the global aspiration of promoting clean energy in the world thus alleviating impacts of climate change. Therefore, to accelerate electricity penetration in PNG requires collective input from all relevant stakeholders to support and empower the rural communities by providing necessary mechanisms and incentives so they become proactive partners in the development of off-grid electricity in the country.
Keywords: electricity accessibility, off-grid solar solution, solar insolation.

1. INTRODUCTION

Access to clean, affordable and reliable energy has been the foundation for prosperity and economic growth since the beginning of the industrial revolution. Nonetheless, access to electricity has always been a challenge especially in the developing economies. An estimated 1.64 billion people worldwide lack access to electricity most of whom live in rural areas.[1] In Papua New Guinea (PNG), electricity penetration rates is one of the lowest with less than 15 percent of the population having access to electricity. It is estimated that electricity access in rural areas is estimated to be under 3.7 percent[2] despite the abundance of renewable energy sources and the vast reserves of hydrocarbon sources in the country.

Inaccessibility to electricity and rural poverty are closely correlated because electricity is not only a pre-requisite for improving living standards, it is also an indispensable input for productive and economic activities. For vulnerable rural populations, the positive impacts of electricity inputs for basic activities such as lighting for extended hours and learning hours, powering household chores and powering small-scale primary industry are considerably greater due to building of socio-economic benefits.[1]

There is an emerging opportunity to provide clean, sustainable and affordable lighting solutions to under-served and off-grid energy consumers in PNG through quality 'pico-powered lighting systems' (PLS). Off-grid solar is the most cost-effective solution for a significant proportion of people lacking electricity access. Furthermore, to achieve universal access requires the collective input of public and private sectors in scaling off-grid solar solutions. Where government lacks the resources to deliver universal energy access through subsidised grid extension and off-grid incentives, the private sector can play a vital role in filling the gap. This is especially true for achieving household electricity access through off-grid solar solutions. Off-grid solar can deliver basic electricity more quickly than on-grid solutions[3] for a country like Papua New Guinea.

2. CHALLENGES OF ELECTRICITY ACCESSIBILITY IN PNG

The Government of PNG, under its Electricity Industry Policy (EIP) of 2011, Development Strategic Plans (DSP 2010-2030) and Vision 2050, has expressed the goal of attaining 70% access by 2030. Reaching that goal, however, needs careful and strategic planning. Geographical spread of the market for electricity in rural PNG, coupled with rugged terrain and very thin population density, makes it techno-economically unviable to develop grid connected rural electrification infrastructure in many parts of the country.[4]

During the recent 2nd Petroleum and Energy Summit in Port Moresby – 2018, the Minister responsible for Energy mentioned three key challenges in the energy sector which need to be addressed. These challenges as highlighted are;[5]

(a) Household energy (electricity) access which has been outstanding for over 50 years;

(b) Sufficiency of energy for industrialization which is needed to modernise PNG; and
(c) Importance of renewable energy to address the global crosscutting issue of climate change.

The Ministry developed a National Energy Policy 2018 – 2028 attempting to address these three challenges. Prior to this policy, the government with the support of World Bank developed a National Electrification Roll-Out Plan (NEROP) to expand on-grid electricity extension which has progressed at snail's pace though. This is largely attributed to costing hence full implementation of NEROP to achieve good results will require large financial envelopes and concerted efforts of various key partners. The total cost of achieving government's access target of 70% electrification by 2030 is US$1.4 - 1.7 billion.[4]

In spite of the various energy reforms and policies drafted to improve electricity accessibility, the challenge faced in terms of widening access to electricity in PNG is still significant. The vast majority of un-electrified household in PNG live in rural areas, justifying a focus on rural electrification (households in informal urban settlements comprise only a small proportion of households without access to electricity). Households in rural areas are commonly distant from electricity grids. Connecting these households to an electricity grid is not financially feasible, given low levels of demand, low population density, and geographical constraints (such as archipelagos of islands). Off-grid electrification is more feasible, but involves significant upfront costs for households. These upfront costs are often beyond the capacity of rural households to fund, given lack of cash income and available credit.[6] This is where the government must come in to provide necessary leeway through right mix of policy and regulatory reforms, incentives and facilitate marketing flexibility for rural folks to become proactive partners in the development of electricity within their respective localities.

3. PNG ELECTRIFICATION PARTNERSHIP

The recent energy funding support established under the PNG Electrification Partnership through the APEC 2018 agreement will see Australia, Japan, New Zealand, and US governments committing about US$1.7 billion into electricity rollout program within the country.[7] Further, the Papua New Guinea Electrification Partnership is intended to focus on the importance of principles-based, sustainable infrastructure development that is transparent, non-discriminatory, environmentally responsible, promotes fair and open competition, upholds robust standards, meets the genuine needs of the people of Papua New Guinea and avoids unsustainable debt burdens. The partnership is envisaged to provide employment and training opportunities and improved coordination and governance within the energy sector.[8]

Further, PNG Electrification Partnership can be an emerging opportunity to provide clean, sustainable and affordable lighting solutions to isolated and fragmented communities in PNG through quality 'pico-powered lighting systems' (PLS). The demand for PLS in PNG is also likely to be driven by the rapid growth in mobile phone ownership. Currently, 62 percent of individuals and 88 percent of households own a mobile phone but many have no capacity to charge their phones in their own homes.[9] PNG has a favourable regulatory environment with zero kerosene or diesel subsidies and zero tariffs on solar panel or component part imports which makes off-grid solar solution indulging.

PNG market is ready to enter a new phase where commercial models can be developed and new market entrants can achieve scale to accelerate off-grid solar solution. There are, however, some significant challenges to entering the PNG market such as lack of consumer awareness on solar devices, current underdeveloped state of the market, ongoing security issues, and challenging landscape and highly dispersed and diverse off-grid populations. This is where the government needs to come in by providing incentives and facilitate market awareness for off-grid solar solution as a driver to increase electricity accessibility.

The PNG Government must facilitate flexible market where innovative distribution and retailing models effected to serve PNG to the last mile. Off grid solar product manufacturers and distributors will need to keep open to innovative business models as well.

4. BASIC SOLAR PV DESIGN AND IMPLEMENTATION

Off-grid solar PV system is not only urgently needed in PNG to connect the vast number of people especially in rural areas with a source of electricity, but is also most appropriate due to geographical constraints and costs for grid extension. At the same time, off-grid systems could become an important vehicle to support the development of solar-based grids. Furthermore, declining costs for solar PV and reduced costs for battery storage makes this option attractive for households and small communities to create their own mini-grids by producing and consuming their own electricity.

4.1 Background Information

The sun is a nuclear fusion reactor and is likely to continue to shine for a few million years yet. While it does, energy from the sun arrives at the top of the earth's atmosphere at a peak value of 1,367 kW/m^2 and this is called the solar constant. This energy is attenuated as it traverses the atmosphere and reaches the sea level at a peak of about 1 kW/m^2. The amount of solar power available per unit area is known as irradiance.[10]

Latitude, time of day and season all affect the amount of energy impinging on a surface laid flat on the earth's surface. For a solar module to obtain maximum power from the irradiance it must always be facing the sun. This could be achieved by the use of a "tracking" device, which follows the sun. Though trackers might be used in larger stand-alone PV power systems, the cost of a tracker for small systems may be too much to make it economical.

Ideally, the solar module should therefore be tilted at an angle to the horizontal (β deg) as shown in Figure 1, facing either true north, such that there is 90° between the sun (at solar noon) and the solar module.

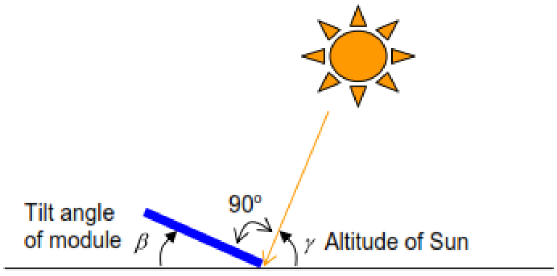

Figure 1: Placement of solar module in relation to Sun's altitude - at Solar Noon.[10]

Solar Noon is the time of day when the sun is at its highest altitude and in PNG this is typically around 12:15PM. In the southern hemisphere, where PNG is located, the modules will be positioned facing due north. The optimum tilt angle is generally latitude plus 10° to 15° but this is dependent on the exact location and the application.[6]

The radiation reaching the surface of the earth is made up of direct and diffuse radiation. Diffuse radiation is not usually as intense as direct radiation, but can still produce heat for solar collectors and energy for solar cells. It is important that the solar radiation data is used for the area where solar PV system will be installed. This data is often available from the meteorological bureau or it might be supplied by the solar module supplier.

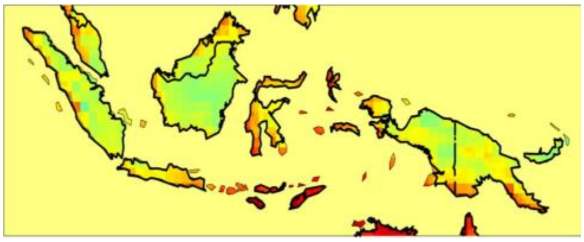

Figure 2: Good to very good PV Resource condition in PNG evenly distributed throughout the country.[11]

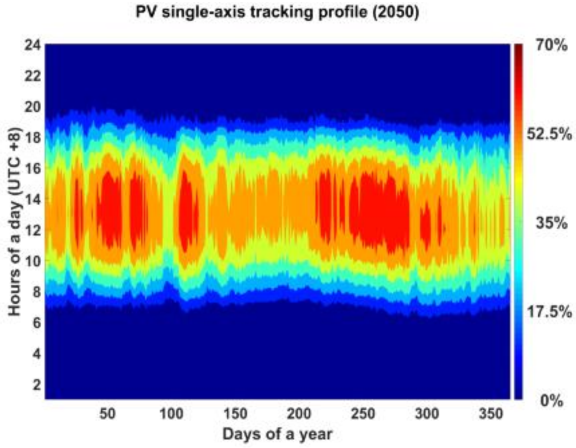

Figure 3: PV evenly distributed throughout the year with diurnal variation.[11]

Solar radiation tables are often developed based on measurement of the direct and diffuse radiation each hour and recorded as hourly irradiance (W/m) which then provides the total daily irradiation (MJ/m^2). The sum of direct and diffuse irradiation provides global irradiation which is then used to calculate peak sun hours. Table 1 shows the peak sun hours (PSH) for Port Moresby and Goroka.

Table 1: Solar irradiation Data for Port Moresby and Goroka[10]

Month	PSH (kWh/m^2) Port Moresby	PSH (kWh/m^2) Goroka
January	5.82	4.84
February	5.46	4.76
March	5.39	4.76
April	5.39	4.75
May	5.01	4.67
June	4.71	4.61
July	4.80	4.73
August	5.33	5.00
September	6.01	5.36
October	6.51	5.24
November	6.67	5.13
December	6.16	4.83
Average	**5.60**	**4.89**

4.2 PV Design Consideration

There are generally two types of electrical designs for PV power systems for homes; systems that interact with the utility power grid and have no battery backup capability; and systems that interact and include battery backup as well. For PNG however, the PV system design considered is practically stand-alone with battery backups. Figure 4 shows basic components of a solar PV system.

Figure 4: Basic components of a solar PV system.

Essentially a basic solar PV system is comprised of solar modules, storage batteries, solar charge controller (regulator), and inverter. There are also additional components used such as fuse and circuit breakers for efficient, reliable and safe operation of the system.

It is imperative to do a proper system sizing because it establishes the sizes and ratings of major components needed to meet a certain performance objective. The size of solar PV systems may be based on any number of factors, depending on the type of system and its functional requirements.

4.3 Sample Calculation

(a) System Sizing

During system sizing, the first part of the process is to calculate the daily energy requirement of the proposed system in Watt-hours per day. Energy requirement of the system is calculated using the following formula;

$$E = n \cdot P \cdot T \qquad (1)$$

where;

E is the energy requirement in Watt-hour/day (Wh/day)
n is the number of appliances
P is the power rating in Watts (W)
T is the average usage in hours (hr)

For any mains voltage or AC appliances it is necessary to account for inverter efficiency. This is because some power is lost when an inverter converts low voltage DC into high voltage AC. Divide the result above by 0.9 (90%) unless the efficiency of the actual inverter that will be used is known.

Now the total results or all the loads is:

$$E_T = E_1 + E_2 + \ldots. \qquad (2)$$

where;

E_T is the total energy requirement

E_1, E_2...are the energy requirements of the individual loads

This will give a total figure for the energy requirement of the system. A numerical example of a typical rural household in PNG (with a latitude of 5.48°S) is used to determine the system requirement for a solar PV system. The design process encompasses an analysis of energy services, an assessment of electrical loads, the selection and sizing of major components and the calculation of major performance parameters.

Table 2: Typical wattage requirements (the ratings are only estimates)

Appliance	Quantity	Rating (W)	Usage (h)	Wh/day each	Total Wh/day
Light	3	40	4	160	480
Cell-phone Charging	5	13	3	39	195
TV	1	60	4	240	240
Others	1	100	2	200	200
Total	**10**	213			**1115**

(i) 3x 18W Lights used for 4 hours daily;

$n_1 := 3 \quad P_1 := 40W \quad T_1 := 4hr$

$E_1 := n_1 \cdot P_1 \cdot T_1$

$E_1 = 1.728M \cdot J \quad \text{or} \quad 480 \frac{Wh}{day}$

The total energy requirement for a typical rural household is therefore;

$E_T := E_1 + E_2 + E_3 + E_4 \quad E_T = 3.996M \cdot J \quad \text{or}$

$E_T = 480W \cdot hr + 195W \cdot hr + 240W \cdot hr + 200W \cdot hr$

$E_T = 1115W \cdot \frac{hr}{day}$

As shown in the system sizing the electric load requirement for a typical rural household in PNG is around 1.115kWh/day. The maximum power demand basing on above calculation is 213W but inference can be made to be between 200W to 250W for a typical rural household in PNG.

The system DC voltage for this design is selected at 12V considering a balance in cost and power requirement. Using a 250W solar panel module, only one module is required to provide sufficient power for a rural household in PNG.

(b) Battery Sizing and Selection

Batteries used for stand-alone power systems should be of a type suitable for the duty and operating environment they will experience. Clause 3.4.7, sub-clause 3.4.7.1 of AS/NZS 4509.2:2010 outlines the factors needed to be considered in battery sizing and selection.

Equation 3 is used to size batteries for energy storage.

$$C_x = \left(\frac{E_{tot}}{V_{dc}}\right) \cdot \left(\frac{T_{aut}}{DOD_{max}}\right) \qquad (3)$$

where

C_x = battery capacity, specified for an appropriate discharge rate *x*, in ampere-hours (Ah)

E_{tot} = total design daily energy demand from the DC bus, in watt hours (Wh)

T_{aut} = number of days of autonomy

V_{dc} = nominal voltage of the d.c. bus (i.e. battery voltage), in volts (V)

DOD_{max} = design maximum depth of discharge of the battery, expressed as a percentage

Therefore, the battery capacity required for this design is;

$E_{tot} := 1115W \cdot hr \qquad DOD_{max} := 30\%$

$T_{aut} := 1$

$V_{dc} := 12V$

$$C_x := \left(\frac{E_{tot}}{V_{dc}}\right) \cdot \left(\frac{T_{aut}}{DOD_{max}}\right)$$

$C_x = 309.722A \cdot hr$

Based on this calculation, a 309.722Ah is required. Three of 100Ah maintenance free batteries connected in parallel should suffice for a rural household in PNG.

(c) Regulator Sizing and Selection

AS 45011.2 recommends that the regulator should be able to carry 125% of the short-circuit current of the array. This is to allow for those days where greater than 100% sun is achieved. Regulators shall withstand the open circuit voltage of the array at the lowest expected operating temperature.

(d) Invertor Sizing and Selection

Clause 3.4.9 of AS/NZS 4509.2:2010 outlines the minimum criteria to be used in inverter selection and sizing for stand-alone power systems.

Paragraph [c], sub-clause 3.4.9.1 recommends inverter sizing should be based on apparent power (volt-amperes), rather than real power. However, instances where apparent power is not known for each load, it may be estimated from real power consumption divided by an assumed power factor of 0.8.

$P := 213W$

$pf := 0.8$

$$Inverter_{Size} := \frac{P}{pf} \qquad (4)$$

$Inverter_{Size} = 266.25W$

An inverter rating of 300W is sufficient for use in this design.

Inverter ratings are limited by heat dissipation within the equipment, which is a function of the output current. Sizing should therefore be based on apparent power (volt-amperes), rather than real power. Where apparent power is not known for each load, it may be estimated from the real power consumption divided by an assumed power factor of 0.8.

(e) Battery Charger Sizing and Selection

AS/NZS 4509.2 recommends battery chargers should be typically sized at the 10h rate. Charging rates and voltages should be to manufacturer's recommendations.

The following Equation can be used to estimate the required size:

$$I_{bc} = 0.1 \cdot C_{10} \qquad (5)$$

where

I_{bc} = maximum charge current of the battery charger, in amperes (A)

C_{10} = 10 h rate capacity of the battery, in ampere hours (Ah)

4.4 Cost Estimate

Table 3: Cost estimate for a solar PV system for a typical rural area in PNG

Component	Quantity	Unit Cost (K)	Total (K)
250W Module	1	900	900
45MPPT-Regulator	1	2000	2000
300W Inverter	1	700	700
12V-100Ah Batteries	3	200	600
Ancillary Equipment, CBs, Fuses, Wirings, Connectors, tools, lugs, etc.	1	2500	2500
Sub-Total			**K6,700.00**
GST	10%		K670.00
Grand Total			**K7,370.00**

Apparently, the initial upfront (capital) cost is substantial as expected however, considering return on investment and other benefits this system brings, it is worth the spent. Obviously, the rural population mostly subsistence farmers will not have such money to finance this important system. Therefore, it is in the interest of the PNG Government to provide incentives and mechanisms to facilitate a conducive market for the people to embark in such undertakings with the purpose to improve their living standards. With large distances separating villages from urban areas becoming a disincentive to investment in energy transportation and grid extension to these areas, it is absolutely vital that the government seriously indulge all relevant stakeholders including private sectors if PNG is truly to achieve 70 percent electrification by 2030.

4. SOCIO-ECONOMIC IMPACTS

According to the World Bank's 2017 State of Electricity Access Report 'a review of all SDG targets indicates that energy is interconnected with 125 (74 %) out of the 169 targets, making it crucial for all societies to recognize the key interlinkages of energy and the wider development agenda'.[4] The benefits of supporting the off-grid solar sector go way beyond the sector's contribution to the achievement of energy access goals:

(a) Household Savings

In PNG, fuel costs have increased by over 30 percent in recent years hence off-grid households are now spending more and more of their income on fuel-based lighting. Retail prices in rural areas increased even further. Expenditures on kerosene can take up a significant proportion of household income, on average accounting for nearly 50 percent of a household's lighting expenditure - and almost 60 percent for off-grid households.[3] Cost savings from the adoption of solar lighting products is a significant benefit.

In some parts where kerosene lamps, battery powered torches or candles, are replaced by basic solar lights has saved cost up to 4% of total household income.[4]

(b) National Savings

As off-grid solar markets continue to grow, there will be a positive impact on the balance of payment and on foreign exchange reserves, as the import of batteries, torches, and candles are replaced by off-grid solar.

(c) Education, Health, Safety and Well-Being

According to a 2010 household survey, 38% of the population aged 8 and older are not able to read and write, and illiteracy rates are even higher in the Highlands (47%) and Momase (40%). In addition, only 23% of the rural population enrols in some form of secondary education.[3] Furthermore, the quality of learning in rural areas who do not have access to lighting for further studies during the night is quite low compared to age group of the same who have access to light. Teachers also need good lighting to prepare proper lessons plan.

Meanwhile, a research by the UK non-government organization Solar Aid found that access to clean, safe light helps students to study for an extra hour a night. If pupils have access to solar lights, head teachers report improvements in performance, attendance and motivation.

On the other hand, the health implications of fuel-based lighting are two-fold: chronic illness due to indoor air pollution, and risk of injury due to the flammable nature of the fuels used. Kerosene lamps emit fine particles that are a major source of air pollution. These particles quickly become lodged in the bronchial system and can result in chronic disease and death. Solar lights reduce these detrimental health implications and provide clean and safe lighting environment. Solar lights also reduce the risk of fire and accidents and improve safety and security. With safer and brighter homes, children studying better at school and with more income available, families have a better quality of life.

(d) Job Creation

The off-grid solar value chain creates far more jobs than value chains for inefficient lighting technologies. In addition, jobs created by the off-grid value chain are more likely to be in the formal economy, thus contributing to tax revenues. According to UNEP en.lighten, off-grid solar employs around 30 people per 10,000 people living in rural areas, compared to just one person per 10,000 people in the case of kerosene. In Bangladesh, the off-grid solar industry already employs an estimated 127,000 people, whilst in India it employs 72,000 people.[4]

Globally, the decentralized renewable energy industry, including both mini-grids and standalone solutions, is expected to directly employ 4.5 million people by 2030. There is also likely to be additional economic activity as a result of businesses being able to stay open at night without incurring additional costs.

5.0 CONCLUSION

The PNG Government's ambitious plan of electrifying 70 percent of the population by 2030 is huge feat given the current trend electricity penetration is moving. The challenging geography, remoteness and isolated rural areas has been and will be an impediment for on-grid extension and financially not feasible. Therefore, it is imperative government seriously push for reforms in off-grid solar solution and empowering the rural people to produce their own electricity. This can be done by providing incentives and facilitating a conducive market for them and the private sectors. The key private sectors such as ADB that are investing in energy sector must be provided the necessary support so their assistance and commitment to improving electricity accessibility is undiminished.

While acknowledging the challenges, the way forward is through off-grid solar PV system. This system is easy to setup and maintain. The design is straight forward and with little training or workshop, an uneducated villager can be able to operate and/or produce his own electricity. In retrospect, the initial capital cost is undeniable massive but is worth the investment as the solar PV modules has a life expectancy of 25 years. Therefore, the return on investment plus the other benefits outweighs the cost involved.

If the Government's goal of 70 percent electrification by 2030 is anything to go by, it must be at the forefront of promoting off-grid PV solutions for isolated and fragmented communities in PNG. The local people are showing great interest in off-grid solutions hence they must be empowered to invest in this area by providing incentives and necessary policy and regulatory reforms to encourage involvement of key development partners and stakeholders in the energy sector. This is because there are overwhelming benefits in terms of socio-economic impacts and lifestyle improvement especially for the rural communities.

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