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Project: To improve availability of, and access to, financing for renewable energy and energy efficiency initiatives in the energy generation and end-use sectors in Papua New Guinea

Task 1: Brief report on the comparison of the costs of grid extension to the alternative of decentralized RE based mini-grid

Submitted to United Nations Development Programme

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List of acronym, abbreviations, and units

BESS	Battery Energy Storage System
CCDA	Climate Change and Development Authority
DPE	Department of Petroleum and Energy
EE	Energy Efficiency
ESCO	Energy Service Company
EU	European Union
FREAGER	Facilitating Renewable Energy and Energy Efficiency Applications for Greenhouse Emission Reduction Project
GDP	Gross Domestic Product
GEF	Global Environment Facility
HV	High Voltage
ICCC	Independent Consumer and Competition Commission
KCHL	Kumul Consolidated Holdings Limited
km	Kilo meter
kW	Kilo Watt

kW_p	Kilo Watt Peak
kV	Kilo Volt
kWh	Kilo Watt Hour
LCOE	Levelised Cost of Electricity or tariff
LV	Low Voltage
MV	Medium Voltage
MW	Mega Watt
MWh	Mega Watt Hour
NEROP	National Electrification Rollout Plan
NPV	Net Present Value
PGK	Papua New Guinea Kina
PNG	Papua New Guinea
PPL	PNG Power Limited
PNGDSP	Papua New Guinea Development Strategic Plan
RE	Renewable Energy
ROE	Return on Equity
SPV	Solar Photo Voltaic
UNDP	United Nations Development Programme
USD	United States Dollar

Executive Summary

Executive summary

Background

Electricity consumption (per capita) of PNG is one of the world's lowest, and only about 15% of the household population has access to electricity and most of them are in urban centers. Access to electricity is very limited in off-grid rural areas. For consumers, with access to electricity through grid or decentralized options, the supply is often unreliable. Lack of access to affordable, reliable power is limiting economic growth in urban areas, constraining growth in smaller urban centers, and contributing to poverty in rural areas.

The three major grid systems in the country operated by PNG Power (PPL) are the Port Moresby System, the Ramu System, and the Gazelle Peninsula System. Because of the unreliability of the power supply, there is considerable self-generation and back-up generation capacity in the urban areas, which is expensive and inefficient. Large industrial users, particularly mining industry, industry, which is one of the main drivers of PNG's economy, largely depends on captive power stations (off-grid self-generation[1]) for their operations.

In this context, improving electricity supply has been identified as one of the key goals of the country's Development Strategic Plan (known as The Papua New Guinea Development Strategic Plan, 2010–2030 (PNGDSP)). Launched in 2010, the policy called for 70% of the country's people to be connected to electricity within 20 years. It projected that achieving the 2030 goal would lift gross national income by 12% and GDP by 10%.

Challenge

According to the PNG's National Electrification Rollout Plan, around 19% of the Papuan population live within 1 km from a low voltage (LV) transformer. This 19% either has access to electricity already (6%) or requires only improved connections, meters or PPL accounts (6%), or LV extension plus connections (7%). Furthermore, a geospatial analysis performed by the Consultant suggests that around 50% of the Papuan population might be living within 10 km from PPL's assets (considering distribution, transmission lines, and C-centre.

Delivering affordable, reliable electricity to rural areas is one of PNG's primary electricity goals. 65% of PNG's population resides in communities that are more than 10km from the existing major grids[2]. There is an opportunity for investors to prioritise electricity solutions that ensure increased social access and allow for innovative off-grid solutions. Although significant central grid improvements and capacity additions are also needed, the opportunity presented by rural electrification in PNG must not be ignored.

Off-grid renewable energy-based 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

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 and to produce their own electricity.

About project

To overcome mentioned barrier, UNDP in partnership with the Global Environment Facility is implementing the Facilitating Renewable Energy and Energy Efficiency Applications for Greenhouse

[1] Source: https://www.adb.org/sites/default/files/linked-documents/cps-png-2016-2020-ssa-02.pdf

[2] Source: Government of PNG, Proceedings of the National Stakeholders Consultation Workshop, NEROP, p. 85, 2015

Emission Reduction Project or FREAGER (the 'Project'). The project aims to demonstrate the potential of renewable and energy efficient technologies in PNG. It will be delivered under four components. Together they will aim to demonstrate a range of renewable energy and energy efficient technologies to encourage their broader replication and up-take.

This report is prepared as part of component 3 of FREAGER project, which aims development of models to better finance renewable energy and energy efficiency solutions among communities. This report provides outcome of the task related to "Cost comparison of grid extension with off grid RE in context of PNG 2030 Vision 2050 electricity access goals".

Objective of this task and approach

Objective of this task is to compare cost of grid extension with Solar Photovoltaic based mini grid system. This task will also help in estimating the threshold length of grid extension beyond which decentralised system (or mini grid) becomes more affordable/economical than grid extension.

The Levelized Cost of Electricity (LCOE) is a metric that allows the effective cost of energy produced to be compared across power generation technologies that have different cost or generation profiles. The LCOE is calculated by dividing discounted costs by discounted energy generated:

$$LCOE = \frac{\text{Discounted total costs}}{\text{Discounted total energy}}$$

To compare grid extension with off grid option, team has calculated the LCOE for following two cases.

Case 1: Grid Extension: For this case, extension of existing grid to a community of 200 households (with 5 family members each i.e. total population of 1000) was considered. For estimation of LCOE:

- Cost of conductor, transformer, other apparatus of transmission (22 KV) and distribution (415 V) system along with civil and labour cost was considered for estimation of total cost
- Total energy transmitted through proposed gid extension is considered same as the quantum of energy generated through proposed SPV based mini grid system in case 2.

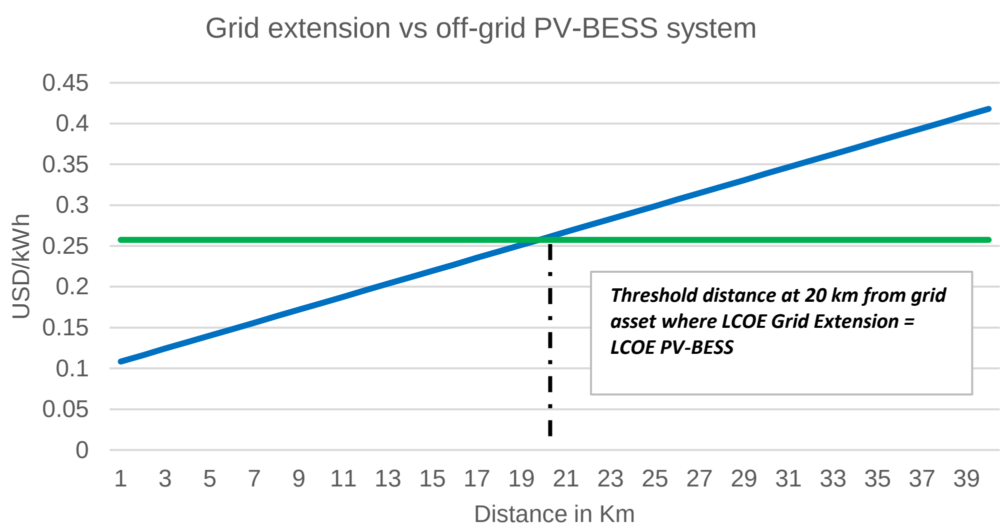
Case 2: SPV based mini grid: For this case, a decentralised system based on Solar Photo Voltaic with Battery Energy Storage System (PV-BESS) of capacity 400 kW_p was considered. For estimation of LCOE

- Cost of panel, battery, inverter, other components of SPV, apparatus of distribution system, civil and labour cost was considered for estimation of total cost
- Total electricity generated by proposed 400 kW SPV system (in its 25-year lifetime with 1% efficiency reduction every year) was considered for estimation of total energy.

Results

The LCOE for case 1 (grid extension) found to be varying from USD 0.11 to 0.42 per kWh for 1 km and 40 km grid extension respectively. Whereas the LCOE for SPV based mini grid (Case 2) was estimated to be USD 0.2575 per kWh.

To estimate the threshold length beyond which the decentralised system (or mini grid) becomes more affordable/economical than grid extension, the LCOE of case 1 for grid extension 1 to 40 km was plotted with LCOE for case 2. The figure below presents the graph of the LCOE calculated for the grid extension scenario (from 1 km to 40 km range) as well as the LCOE that was calculated for the PV-BESS system, which remains constant throughout.



Inference:

- ***Based on above graph, it can be inferred that, the threshold distance at which the LCOE for grid extension becomes equal to the LCOE for an Off-Grid PV-BESS system is at 20 Kms from the grid asset or grid connection point.*** This means that for distances less than 20 Kms, extending the grid supply for the non-connected consumers would be a more cost-effective solution, rather than going for an Off-Grid project that relies on a SPV-BESS system
- Once the distance from existing grid is 20 km or more, it is advisable to go for an Off-Grid solution rather than extending the grid connectivity in such remote areas.
- In other countries like the EU and in India[3], the limit for extending the grid is close to 25 Kms. This is understandable as the cost per Km of Grid extension in PNG is higher as compared mentioned countries and thus, we see the grid extension limit at lower length i.e. 20 Kms for PNG.

Limitation:

- Above threshold length is estimated for grid extension, with an assumption that the project is undertaken on flat or less hilly landscape. For location which hilly or unapproachable landscape, may have much lower value for threshold distance limit than above value.
- In above analysis both in case 1 and case 2, cost of land has not been considered.
- The cost of Solar panel, batteries and some of other apparatus is quite dynamic in nature and may change in short term. Therefore, it is advisable to re-evaluate the threshold limit with updated costs.

[3] Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply, 2008

1. Introduction

1. Introduction

1.1 Power Sector in PNG

Electricity consumption (per capita) of PNG is one of the world's lowest, and only about 15% of the household population has access to electricity and most of them are in urban centers. Access to electricity is very limited in off-grid rural areas. For consumers, with access to electricity through grid or decentralized options, the supply is often unreliable. Lack of access to affordable, reliable power is limiting economic growth in urban areas, constraining growth in smaller urban centers, and contributing to poverty in rural areas.

In this context, improving electricity supply has been identified as one of the key goals of the country's Development Strategic Plan (known as The Papua New Guinea Development Strategic Plan, 2010–2030 (PNGDSP)). Launched in 2010, the policy called for 70% of the country's people to be connected to electricity within 20 years. It projected that achieving the 2030 goal would lift gross national income by 12% and GDP by 10%.

The three major grid systems in the country operated by PNG Power (PPL) are the Port Moresby System, the Ramu System, and the Gazelle Peninsula System. Because of the unreliability of the power supply, there is considerable self-generation and back-up generation capacity in the urban areas, which is expensive and inefficient. Large industrial users, particularly mining industry, industry, which is one of the main drivers of PNG's economy, largely depends on captive power stations (off-grid self-generation[4]) for their operations.

In 2015, PNG had about 580 megawatts (MW) of installed generation capacity, including hydropower (230 MW or 39.7%), diesel (217 MW or 37.4%), gas-fired (82 MW or 14.1%), and geothermal (53 MW or 9.1%).[5] Break up of installed capacity by source is provided in figure below

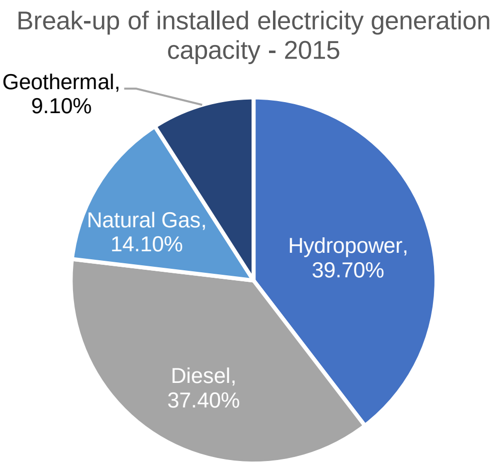
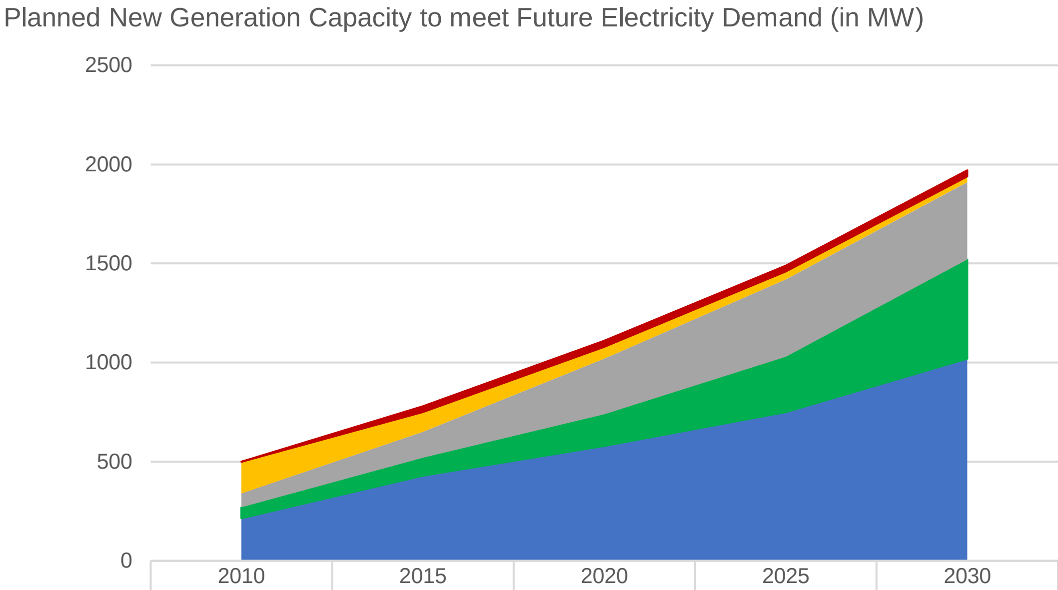


Figure 1 Installed capacity in Papua New Guinea (2015)

[4] Source: https://www.adb.org/sites/default/files/linked-documents/cps-png-2016-2020-ssa-02.pdf

[5] Source: https://www.adb.org/sites/default/files/linked-documents/cps-png-2016-2020-ssa-02.pdf

The Papua New Guinea Development Strategic Plan, 2010–2030 (PNGDSP) estimates that the peak demand for electricity in 2021 will be about 700 MW and increase to over 1,400 MW by 2030. This means more sources of power generation should be identified to meet this expected demand. Plan sets the target of increasing generation capacity to 1970 MW. The plan is to generate 25% of electricity needs with renewable resources and reduce dependence on diesel power generation. Breakup of PNG installed capacity and expected growth till 2030 is provided in figure below:



	2010	2015	2020	2025	2030
Coal	0	30	30	30	30
Diesel	160	100	60	40	30
Natural Gas	70	130	280	390	390
Renewable (non - hydro)	55	90	160	280	500
Hydropwer	215	430	580	750	1020

Hydropwer Renewable (non - hydro) Natural Gas Diesel Coal

Figure 2 Installed capacity as per 2030 plan

Institutional Setup

The Department of Petroleum & Energy is the nodal department for energy sector. PNG electricity sector structure is regulated according to the Electricity Industry Act 2002 and the Independent Consumer and Competition Commission Act 2002.

In 2018, the overarching National Energy Policy (NEP2018) was established and promotes the World Bank-funded National Electrification Rollout Plan (NEROP). The NEROP proposes that the least cost electrification strategy to cover the whole country is, to connect 75% of population through the grid and the rest using diesel-minigrids systems. Key Institutions or stakeholders in energy sector of PNG are listed below:

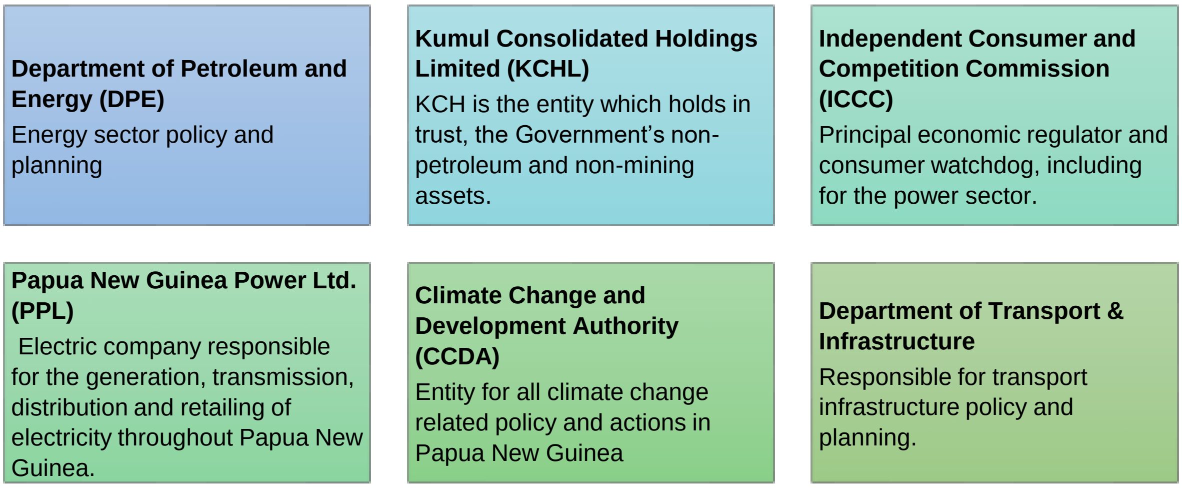


Figure 3 Key institutions in energy sector of PNG

Department of Petroleum and Energy (DPE): DPE is the overarching agency responsible for energy sector policy and planning in the country. It also heads the Electricity Management Committee (EMC), and is expected to oversee the technical regulation of the electricity sector (a function presently performed by PPL). It has three divisions:

- Petroleum Division: It plays focal role in development of country's hydrocarbon resource. The division's role in policy is focused on oil and gas development.
- Energy Division: The division takes charge of policies and oversees the non-fossil energy sources and renewable energy sector. This also covers the retailing and distribution of petroleum products for electricity generation and transmission.
- Consumer Services Division: This division plays a supportive and facilitative role to the other two operational divisions (Petroleum & Energy). It focuses on the development of policies, procedures, organizational structure and human resources. It further focuses on financial and administrative systems and resources to support the Department's core units' strategies and activities.

Kumul Consolidated Holdings Limited (KCHL): Managed by the Ministry of Public Enterprises and State Investment, KCH is the entity which holds in trust, the Government's non-petroleum and non-mining assets. KCH (formerly known as IPBC) was established in July 2002 under the Independent Public Business Corporation of Papua New Guinea Act 2002 (the "IPBC Act"). KCH, is mandated to hold all Government-owned commercial assets in trust and to manage those assets to improve commercial performance and underpin economic development. KCH is not responsible for the Government's mineral, oil and gas assets. As a trustee, KCH is the holding company for nine (9) State Owned Enterprises (SOEs) including PNG Power Ltd.

Independent Consumer and Competition Commission (ICCC): Independent Consumer & Competition Commission (ICCC) is a principal economic regulator and consumer watchdog, including for the power sector. Its primary role is to administer and implement the ICCC Act and other related legislations. The ICCC performs several functions including administration of price regulation, licensing, industry regulation and other matters outlined under the ICCC Act or any other act.

ICCC is also the regulator for electricity tariffs but has little capacity to carry out its mandate and cannot independently take decisions. ICCC employs a revenue cap regulation principle and sets license conditions for market participants.

Papua New Guinea Power Ltd. (PPL): PNG Power Limited (PPL) is an electric company responsible for the generation, transmission, distribution and retailing of electricity throughout Papua New Guinea. PPL services customers in almost all urban centers throughout the country encompassing industrial, commercial, government and domestic sectors. Where possible, the services extend to rural communities adjacent to these urban centers.

PPL is also presently undertaking a regulatory role on behalf of the Independence Consumer and Competition Commission (ICCC). These responsibilities include approving licenses for electrical contractors, providing certification for models of electrical equipment and appliances to be sold in PNG and providing safety advisory services and checks for major installations.

Climate Change and Development Authority (CCDA): It is the coordinating entity for all climate change related policy and actions in Papua New Guinea and the designated National Authority under the United Nations Framework Convention on Climate Change (UNFCCC). The CCDA was established in September 2015 and replaced the former Office of Climate Change and Development. CCDA has a mandate in the climate change mitigation area and can develop and issue legislation limiting GHG emissions from the energy sector.

Department of Transportation: Since, the transportation sector is the second largest end user of energy in nation, PNG's Department of Transportation is a relevant player for energy matters. The Papua New Guinea Department of Transport & Infrastructure is responsible for transport infrastructure policy and planning. It is the lead agency in formulation of policies and planning of transport infrastructure projects, administers transport legislation's (Act, associated Regulations and numerous international conventions etc.).

1.2 Background - Electrification challenge in Papua New Guinea

Most people in PNG – rural and remote urban users comprising over 85% of the population are not connected to the national grid nor benefit from 'owner-operator' capacity. For those with access, average consumption is much lower than benchmarks representing only modest use of electrical appliances[6]. PNG's current electricity supply approach appears particularly ill-adapted to rural needs. PNG's rural electrification outcomes are far poorer than urban outcomes (as shown in the figure below) and PNG's rural populations have some of the weakest electricity outcomes in the region.

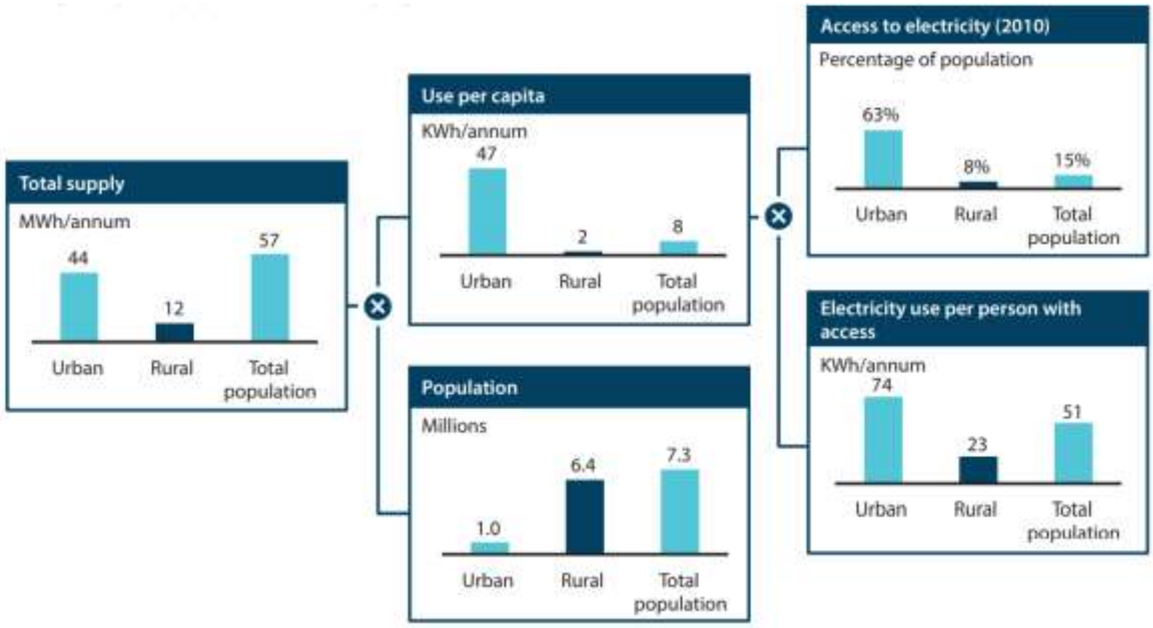


Figure 4: Comparison of Urban and Rural electricity use in PNG (2013)

For those connected to the grid, electricity supply is expensive and unreliable. Although prices are set close to regional benchmarks, in fact electricity costs vastly exceed this level. As such PPL's revenues are currently insufficient to secure an economic return on its assets and low prices may effectively result

[6] Source: Asian Development Bank, 'Country Partnership Strategy 2016–2020', 2015; ICCC, 'Electricity Contract Review', 2013.

in low quality or insufficient service. Large portion of population, connected to grid, pay the price of unreliability by being forced to provide backup generation – even in urban areas.

1.3 Increasing demand to put enormous strain on existing assets

PNG's national development plans aim to have national access to electricity at 70% in 2030[7]. In order to achieve this target, it is estimated that rural access rates will need to rise from below 10% to close to 65% over the next decade[8], while an estimated 90,000 households will need to be connected to the grid each year[9]. The National Electricity Roll-Out Plan (NEROP) study estimates that the total cost of achieving 70% electrification by 2030 is about USD 1.8 billion[10].

To keep pace with the growing needs of the population as well as the ambitious targets of the PNG government, the country has outlined an approach where it plans to invest in:

- Metering of consumers (who already have a PPL account)
- Improved grid connection and metering for consumers without a PPL account but within grid access (within <1km range of LV connection)
- Grid Intensification, i.e. LV line + connection (for consumers with no grid access but within 1km of LV connection),
- Grid extension, i.e. MV line, LV line + connection (beyond range of LV connection >1km) and
- Setting up Off-Grids/Mini-Grids (beyond range of LV connection >1km)[10].

1.4 PNG's unelectrified population and importance of Off-Grid PV systems

According to the PNG's National Electrification Rollout Plan, around 19% of the Papuan population live within 1 km from a low voltage (LV) transformer. This 19% either has access to electricity already (6%) or requires only improved connections, meters or PPL accounts (6%), or LV extension plus connections (7%). Furthermore, a geospatial analysis performed by the Consultant suggests that around 50% of the Papuan population might be living within 10 km from PPL's assets (considering distribution, transmission lines, and C-centre.

Delivering affordable, reliable electricity to rural areas is one of PNG's primary electricity goals. 65% of PNG's population resides in communities that are more than 10 km from the existing major grids[11]. There is an opportunity for investors to prioritise electricity solutions that ensure increased social access and allow for innovative off-grid solutions. Although significant central grid improvements and capacity additions are also needed, the opportunity presented by rural electrification in PNG must not be ignored.

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

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 and to produce their own electricity.

[7] Source: Government of PNG, Papua New Guinea Development Strategic Plan, 2010–2030, 2010
[8] Source: Kaur and Segal, 2017
[9] Source: Going the Distance: Off-Grid Lighting Market Dynamics in Papua New Guinea," International Finance Corporation, Lighting Papua New Guinea, (2019)
[10] Source: National electricity Roll out Plan (NEROP), 2017
[11] Source: Government of PNG, Proceedings of the National Stakeholders Consultation Workshop, NEROP, p. 85, 2015

1.5 About this project

To overcome mentioned barriers, UNDP in partnership with the Global Environment Facility is implementing the Facilitating Renewable Energy and Energy Efficiency Applications for Greenhouse Emission Reduction Project or FREAGER (the 'Project'). The project aims to demonstrate the potential of renewable and energy efficient technologies in PNG. It will be delivered under four components. Together they will aim to demonstrate a range of renewable energy and energy efficient technologies to encourage their broader replication and up-take. Figure below depicts the four components

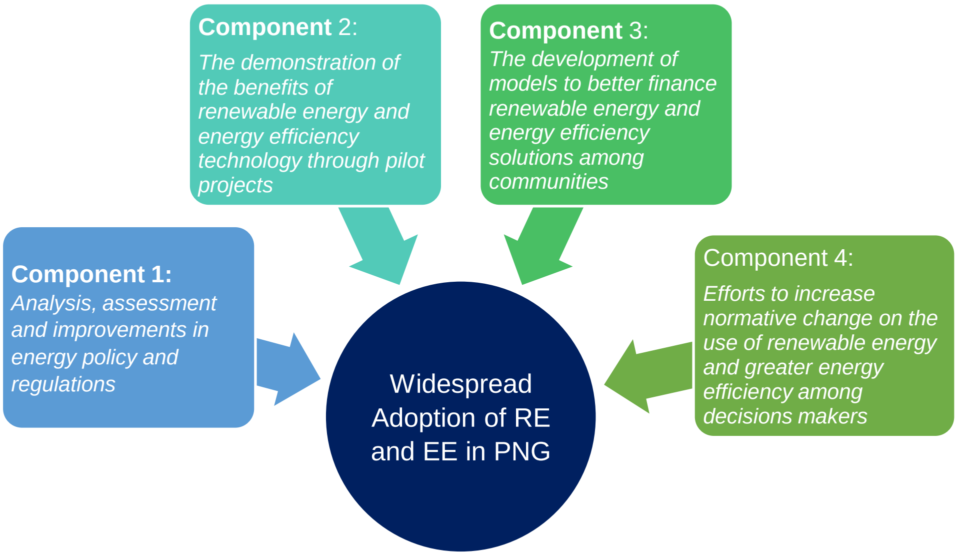


Figure 5 Components of UNDP FREAGER project

Component 1: Analysis, assessment and improvements in energy policy and regulations

This project component envisages development, enforcement and implementation of national and provincial energy policies, plans, and standards to promote the application of renewable energy and energy efficiency technologies.

Component 2: The demonstration of the benefits of renewable energy and energy efficiency technology through pilot projects

This component involves the work directed towards technical-commercial viability and capacity in the application of energy efficiency technologies and development of feasible RE-based energy systems in the country. A number of pilot projects is planed to be implemented to demonstrate viable renewable energy (PV, solar, small hydro) and energy efficiency applications.

Component 3: The development of models to better finance renewable energy and energy efficiency solutions among communities

This component aims to improve an availability of, and access to, financing for renewable energy and energy efficiency initiatives in the energy generation and end-use sectors. The energy efficiency initiatives will primarily target industrial energy users, and social buildings.

The component will carry out a capacity building program for the banking sector, investors in the commercial/private sector (including PPL), and government officials regarding the equity and debt financing of community-based renewable energy mini-grids and of energy efficiency, including building and industrial retrofits and residential appliance and lighting replacement.

It will provide technical support to PPL for the setting up of an "ESCO" fund to finance the upfront costs of energy efficiency retrofits at large electricity consuming customers, who will then pay PPL back based on monthly verified electricity savings. The project will also provide technical support for the setting up of a loan fund at a commercial bank in PNG to finance community-based mini-grid systems.

Component 4: Efforts to increase normative change on the use of renewable energy and greater energy efficiency among decisions makers.

This component will involve the work to improve awareness of, and information about renewable energy and energy efficiency applications in the energy generation and end-use sectors, aiming towards behavioural change. Inter alia, this component will involve development of the database on renewable resources and pipeline renewable energy projects in PNG, as well as development of courses and materials made available for the education sector to promote renewable energy and energy efficiency.

1.6 About this report

This report is prepared as part of component 3, development of models to better finance renewable energy and energy efficiency solutions among communities. This report provides outcome of the task related to "Cost comparison of grid extension with off grid RE in context of PNG 2030 Vision 2050 electricity access goals". The report is divided in three chapters, chapter 1 provides background about power sector, current challenges, potential solutions, and introduction of FREAGER project. Chapter 2 provides detail about the methodology. Chapter 3 provides assumptions used in developing financial model and estimation of levelized transmission tariff to compare grid extension with RE based mini grid options and findings of the study.

2. Methodology

2. Methodology

2.1 Objective of this task and methodology

Objective of this task is to compare cost of grid extension with Solar Photovoltaic based mini grid system. This task will also help in estimating the threshold length of grid extension beyond which decentralised system (or mini grid) becomes more affordable/economical than grid extension.

The Levelized Cost of Electricity (LCOE) is a metric that allows the effective cost of energy produced to be compared across power generation technologies that have different cost or generation profiles. The LCOE is calculated by dividing discounted costs by discounted energy generated:

$$LCOE = \frac{\text{Discounted total costs}}{\text{Discounted total energy}}$$

To compare grid extension with off grid option, team has calculated the LCOE for following two cases.

Case 1: Grid Extension

For this case, extension of existing grid to a community of 200 households (with 5 family members each i.e. total population of 1000) was considered. For estimation of LCOE:

- Cost of conductor, transformer, other apparatus of transmission (22 KV) and distribution (415 V) system along with civil and labour cost was considered for estimation of total cost
- Total energy transmitted through proposed gid extension is considered same as the quantum of energy generated through proposed SPV based mini grid system in case 2.

Case 2: SPV based mini grid

For this case, a decentralised system based on Solar Photo Voltaic with Battery Energy Storage System (PV-BESS) of capacity 400 kW_p was considered. For estimation of LCOE

- Cost of panel, battery, inverter, other components of SPV, apparatus of distribution system, civil and labour cost was considered for estimation of total cost
- Total electricity generated by proposed 400 kW SPV system (in its 25-year lifetime with 1% efficiency reduction every year) was considered for estimation of total energy.

For both the cases, i.e. for grid extension as well as that of installation of a PV-BESS system, a community with 200 households with 5 members in each household has been considered.

The costing of various components of grid extension and mini grid is identified through extensive literature review. After identification of costing of various goods and services for case 1 and 2, financial model for 25 years period was developed to compare LCOE mentioned scenarios, i.e. grid extension Vs RE based mini grid. The parameters used in financial model are provided in subsequent section.

After estimation of LCOE, in case 1, the length of grid was varied from 1 km to 40 km to estimate LCOE for various length options and same is plotted with LCOE of RE based mini grid to estimate the threshold length of grid extension beyond which the decentralised system (or mini grid) becomes more affordable/economical than grid extension. Figure illustrating methodology of this task is provided below:

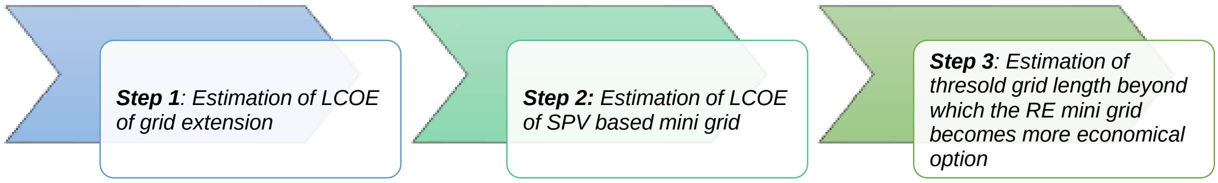


Figure 6 Methodology for comparing cost of grid extension with SPV based mini grid

3. Levelised cost of electricity (LCOE) and comparison

3. Levelised cost of electricity (LCOE) and comparison

3.1 Case 1: Grid Extension

Based on the findings and discussion notes with PPL authorities covered in the NEROP document, line costs as reported by the staff ranged, high in comparison to international standards, i.e. between 150,000 – 250,000 PGK per km of line (US$50,000 - $85,000/km). This was expressed as an "all inclusive" cost, comprising not only MV and LV lines, but also transformers, connections, and "soft costs" such as labour, transportation, taxes, design fees, etc.

The illustration in figure below shows the grid system components considered as part of the system for case 1 i.e. grid extension. (***Note: The generation and HV network cost has been included in the calculations as a recurring cost of power, i.e. "bus-bar cost"***):

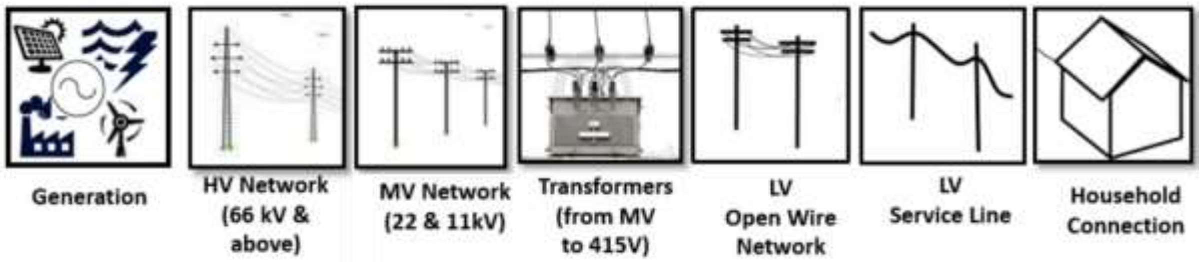


Figure 7: Grid System Components considered for extension

It is critical to note that the "bus-bar cost" is not the retail cost of power paid by the consumer. Instead, it is the "wholesale" cost of power, which includes the cost of generation and transmission (upto HV), and can be viewed as the cost that an electric utility limited to MV and LV distribution would pay for power in an "unbundled" system with separate and independent generation and transmission systems. In our calculations, this cost has been taken as 23 cents per kWh (average cost considering all mainland grids of Port Moresby, Ramu and others as well as smaller, isolated or island grids, which are assumed will remain supplied largely by diesel gensets). The details of other cost components considered for determination of cost per km of grid line extension is mentioned below[12]:

Table 1: Unit cost for Grid Extension components

Description	Rating	Length/Quantity	USD/Km or unit
MV Network	22 kV	1 Km	26773
Transformer	1000 kVA	1 unit	32000
LV Open wire	415V	1 Km	20080
LV service line	415V	1 Km	3346
Metering	-	1 unit	25
Labour	-	Per Km	94
Transportation	-	Per Km	200

Considering the above unit costs, average capital expenditure for grid extension for 200 household community estimated to be **USD 51418 per km** (average cost for estimated for 40 km length). Assumptions regarding financing terms, discounting, and other parameters, used in financial model for estimation of LCOE are mentioned below:

Table 2: Additional parameters for calculating NPV for LCOE of grid extension

Other parameters	Value	Source
Debt-Equity Ratio	70:30	Previous PNG infra projects
Discount rate	10.38%	PNG 10-year treasury bond yield

[12] Source: Preparation of National Electrification Rollout Plan and Financing Prospectus Final Report 11 April 2017 upngcore.org/wp-content/uploads/2019/10/PNG-NEROP-FinalReport-2017-04-11.pdf

Other parameters	Value	Source
Project life	25 Years	Similar to SPV project
Return on Equity	27%	WB 2017 data
Average inflation	5.91%	PNG Historical 20 yr. average
Growth in energy consumption	1.5%	PNG Historical 10 yr. average

Thus, based on the above metrics and assumption, the ***LCOE estimated to be 0.11 USD/kWh for a grid extension exercise of 1 Km*** for a 200HH community with 1000 population. Given below is a plot of the LCOE (in USD/kWh vs Grid extension in Km), keeping all other variables constant.

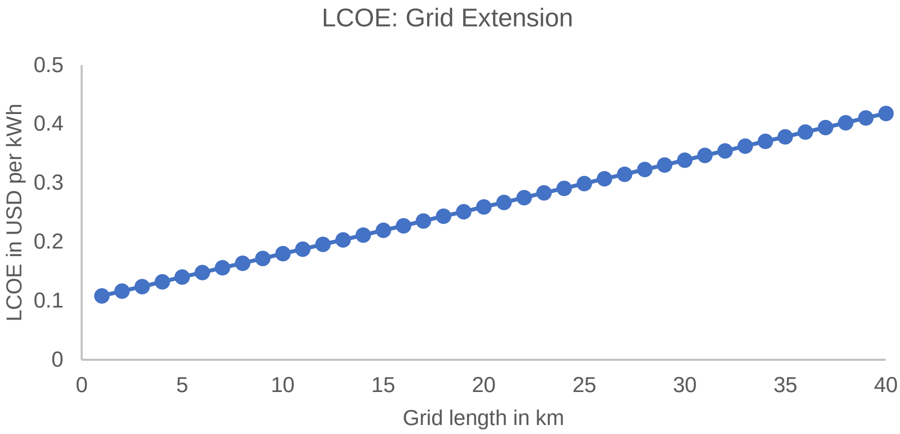


Figure 8: LCOE vs Grid extension distance

As evident from the graph above, the LCOE sees a gradual increase as the grid extension moves farther and farther away from the grid asset or connecting point. This is common across all the geographies across the world and this exercise is fruitful once it is compared with the constant LCOE determination for a PV-BESS system, which will then yield the appropriate distance from the grid, beyond which the decentralised system (or mini grid) becomes more affordable/economical than grid extension.

3.2 Case 2: SPV - BESS system based mini grid

The microgrid to be designed for the community will include solar energy-production and management components. The SPV based mini grid will comprise of solar panel, inverters, battery bank, balance of

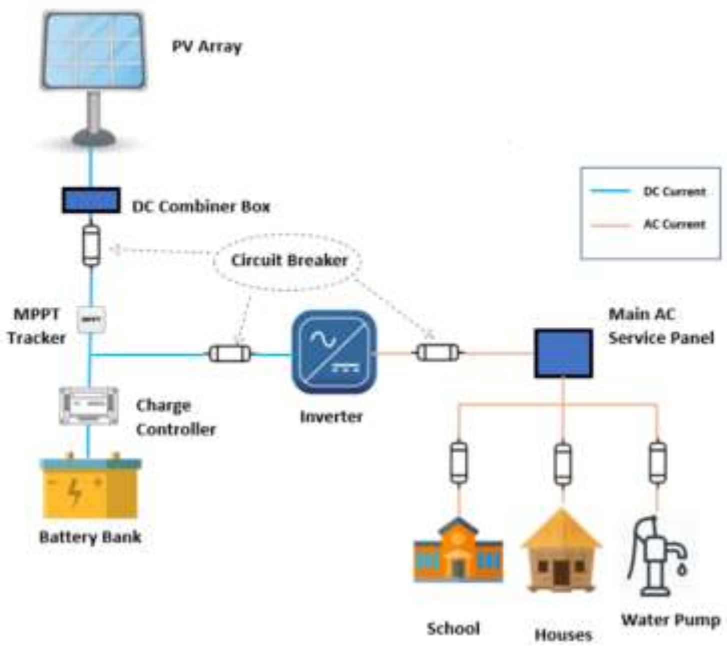


Figure 9: Solar Off-Grid Structure

the plant, distribution network (LV) and household/consumer connections. Schematics providing structure of SPV and distribution network is provided in figure below.

The various capex components considered for the SPV-BESS mini grid system are mentioned in table below[13] (considered for 200 Households):

Table 3: Costing for PV-BESS based mini grid system

Components	Unit Cost (in USD)	Total cost (in USD)
PV Modules (400 kW_p system, with single panel rating of 290 W_p)	540	743040
Battery Bank	140	463680
DC Combiners	110	3604
Charge Controllers	700	22933
Inverter	600	240000
Mounting Racks	600	21600
Wiring	-	11092
Transportation	-	99617
Installation	-	31920
Total Cost		**1,637,486**

Therefore, the overall cost for proposed SPV-BESS mini grid system for comes out to be **USD 1,637,486.** It is to be noted here that in the table above, cost has been considered for replacement of battery 3 times over a 25-year period. The other parameters that have been considered are as follows:

Table 4: Parameters to be considered for SPV-BESS system

Other parameters	Units	Values
PV module model assumed	Watt	290
Type of battery proposed	-	Lead Acid
Battery life	Years	9
Life of PV module	Years	25

The other parameters for the calculation of LCOE for the PV-BESS system project are similar to the one's considered in table-2 of the previous section. Thus, based on the above metrics and assumption, the ***LCOE comes out to be 0.2575 USD/kWh*** for a 200-household community with 1000 population.

3.3 Comparison of LCOE and estimation of threshold length

The LCOE for case 1 (grid extension) found to be varying from USD 0.11 to 0.42 per kWh for 1 km and 40 km grid extension respectively. Whereas the LCOE for SPV based mini grid (Case 2) was estimated to be USD 0.2575 per kWh.

To estimate the threshold length beyond which the decentralised system (or mini grid) becomes more affordable/economical than grid extension, the LCOE of case 1 for grid extension 1 to 40 km was plotted with LCOE for case 2. The figure below presents the graph of the LCOE calculated for the grid extension scenario (from 1Km to 40 Kms range) as well as the LCOE that was calculated for the PV-BESS system, which remains constant throughout.

[13] Source: Design of a Solar Microgrid for the Community of Gabon based on its social and economic context, 2017

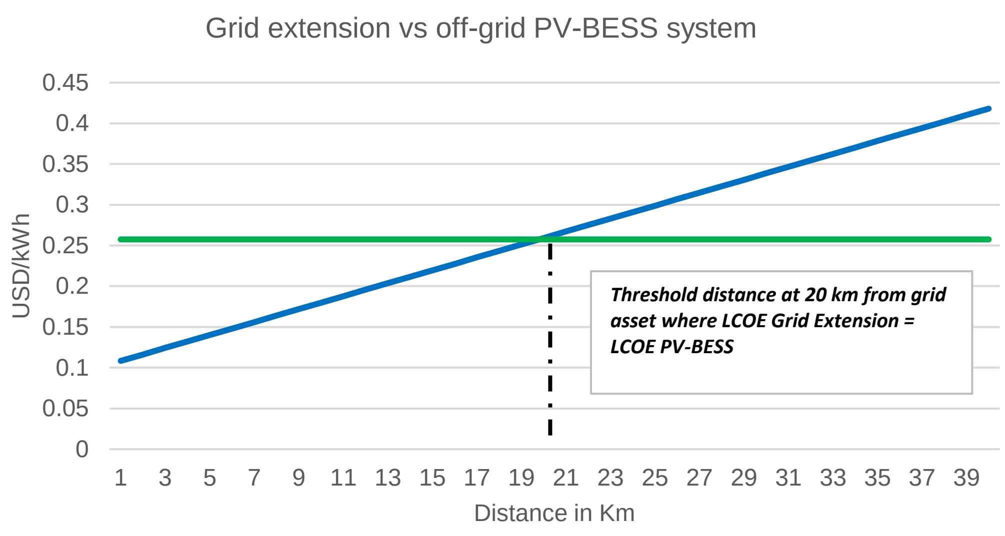


Figure 10: Threshold distance beyond which off-Grid system is more economical than grid extension

Inference:

- ***Based on above graph, it can be inferred that, the threshold distance at which the LCOE for grid extension becomes equal to the LCOE for an Off-Grid PV-BESS system is at 20 Kms from the grid asset or grid connection point.*** This means that for distances less than 20 Kms, extending the grid supply for the non-connected consumers would be a more cost-effective solution, rather than going for an Off-Grid project that relies on a SPV-BESS system
- Once the distance from existing grid is 20 km or more, it is advisable to go for an Off-Grid solution rather than extending the grid connectivity in such remote areas.
- In other countries like the EU and in India[14], the limit for extending the grid is close to 25 Kms. This is understandable as the cost per Km of Grid extension in PNG is higher as compared mentioned countries and thus, we see the grid extension limit at lower length i.e. 20 Kms for PNG.

Limitation:

- Above threshold length is estimated for grid extension, with an assumption that the project is undertaken on flat or less hilly landscape. For location which hilly or unapproachable landscape, may have much lower value for threshold distance limit than above value.
- In above analysis both in case 1 and case 2, cost of land has not been considered.
- The cost of Solar panel, batteries and some of other apparatus is quite dynamic in nature and may change in short term. Therefore, it is advisable to re-evaluate the threshold limit with updated costs.

[14] Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply, 2008