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An analysis of solar P.V. access to alleviate energy poverty in Benin

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Abstract:

The solar resources of Benin have the potential to provide enough access to modern energy for the entire country's energy-poor population, the benefits of decentralized solar systems in the rural communities can create employment and provide the much-needed access to electricity. This paper identifies the available solar resources and how these resources could be accessed in the two types of solar installations: centralized, and decentralized systems. Utilizing the Sustainable Energy Access Planning framework guidelines, and an energy consumption survey in Kandi Benin, a simplified 10kW solar system was designed to assess the cost of the technology and how it affects debt levels among those who can afford to enter into payment agreements. The decentralized system has been addressed as to the functional reliability within an integrated Western African Power Pool scenario, specifically for the diesel hybrid P.V installation type. The impact of Benin's level of governance has been reviewed with regards to their land-use policies and the effectiveness of their funding management in state-owned enterprises.

Keywords:

Energy access, Grid networks, (P.V.)– Photovoltaic, Solar resource assessment, (SEAP framework)- Sustainable energy access protocol framework, Diesel P.V. hybrid

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I. INTRODUCTION

One-third of the world has no access to electricity of a suitable standard [1]&[2]. This lack of essential service delivery in many developing countries covers a wide range of services which include the cooking resources, electrified lighting devices, washing of clothes, proper sanitary disposal, water supply and medical attention.

The United Nations has declared by the year 2030, all developing nations need to be included under the charter "sustainable energy for all". The aim is to provide a certain level of access to essential services to empower these communities and assist with the individual and collective improvement of health and wellbeing on a macro and micro level. The main challenge is that each region uniquely defines stable energy access based on the demographics, culture and location.

The international energy regulatory bodies assist in defining the various definitions of energy access, each providing details on a framework that can be used for assessing how basic needs can be met.

The purpose of this study is to utilize the sustainable energy access planning (SEAP) framework as a guideline in understanding the energy demands and potential use of both centralized and decentralized solar energy installations in Benin, along with the potential risk that can be encountered due to the complexities of energy exchange. The non-energy poor region of Kandi, Benin was used as the survey region for a resource assessment which formed the basis of a solar P.V. design to arrive at a direct technology cost vs the average income. The basic cost estimate was done with South African supplier information and is limited in the understanding of the Beninese tax regulations, which could be further investigated.

I. SOLAR PV IMPLEMENTATION

A. General theory of stand-alone solar PV

A study was conducted into the design and performance of a household solar system[3], the essential components of a stand-alone system are listed by the design equations [3]&[4].

The solar array coverts the sun's radiation to electrical energy, which run in the solar cables. The peak power demand (P.P.D.) is estimated to find a solar array size to meet the energy demand.

$$P.P.D = \frac{Energy\ (daily\ consumption)}{Peaks\ hours\ sun\ load} \qquad (1)$$

The required P.V. size is calculated by dividing the peak power by overall efficiency, more commonly known as the panel generation factor (PGF).

$$PV\ array\ size\ = \frac{E\ avg\ (daily\ energy\ rqd.)}{\sum (Efficiency\ factor\ or\ PGF)} \qquad (2)$$

The battery which is responsible for storing the energy for off-grid demand is estimated by:

$$B.S.C = \frac{E.L}{\eta inv\ x\ Vb\ x\ D.O.D}\ x\ D.O.A \qquad (3)$$

Where: B.S.C = Battery storage capacity (Ah)
E.L= Daily energy consumption (kWh/day)
ηinv = Inverter efficiency (unitless)
Vb = Battery voltage (V)
D.O.D = Depth of discharge (%)
D.O.A = Day of autonomy (days)

The charge controller regulates charging and discharging of the battery, is given by the short circuit current (S.C) multiplied by a factor of safety

$$Charge\ controller\ = S.C\ (A)\ x\ FOS \qquad (4)$$

$$Where:\ Short\ circuit\ (A) = panel\ (W) / panel\ (V) \qquad (5)$$

The inverter which transforms the D.C. voltage to A.C. must be 30% greater than the total appliance load, noting that three times a motor power should be allowed for surge current.

$$Inverter\ size\ < Total\ Appliance\ load * 30\% \qquad (6)$$

The geographical location plays a vital role in defining solar irradiance where solar panels are to be installed. It was shown that solar P.V. systems rely on the best irradiance rates [3], therefore to evaluate the P.V. potential in detail, a simulation of peak demand would have to be done with software tools. Utilizing software tools will allow the design engineer to analyze further, the effects of varying solar irradiance loads and the of cell performance efficiency which directly impacts power output. As this study aims to analyze the cost of a basic P.V. design in the tier energy categories, a detailed performance modelling analysis has been excluded.

B. Electricity demand estimation

The demand assessment looks at the entire sector within a region. For a home, these energy loads would be from items such as cooking, lighting, space heating and other electrical devices. The assessment is aligned to three main frameworks namely; sustainability energy for all (SE4ALL), the global tracking framework and World bank[1]&[2].

The SEAP framework has classified electricity access in multi-tiers (0-5) over potential access scenarios in the years 2017,2022 &2030. Table 1 indicates the purpose of the tier system, which is to gauge the increase in consumption according to the level of access, table 2 is where each category is grouped into their respective energy consumption levels, and table 3 which is the required level of access over the current and future year scenarios.

Table 1 Electricity access multi-tier framework [1]

Item	**T1**	**T2**	**T3**	**T4**	**T5**
Radio	✓	✓	✓	✓	✓
Task light	✓	✓	✓	✓	✓
Phone Charger	✓	✓	✓	✓	✓
General light		✓	✓	✓	✓
Fan		✓	✓	✓	✓
T.V.		✓	✓	✓	✓
Food processor			✓	✓	✓
Rice cooker			✓	✓	✓
Washing mach.				✓	✓
Phone Charger				✓	✓
Iron				✓	✓
A.C.					✓
Total (kWh / yr)	3	66	285	1464	2267

Table 2 Electricity consumption tiers [1]

Tier level	**Electricity consumption range (kWh)**
Tier 0	$E < 3$
Tier 1	$3 \leq E < 66$
Tier 2	$66 \leq E < 285$
Tier 3	$285 \leq E < 1464$
Tier 4	$1464 \leq E < 2267$
Tier 5	$E \geq 2267$

Table 3 Electricity access multi-tier framework [1]

Electricity access	**2017 (kWh)**	**2018 (kWh)**	**2019 (kWh)**
ELA 1	3 (Tier 1)	66(Tier 2)	285 (Tier 3)
ELA 2	66 (Tier 2)	285 (Tier 3)	1,464 (Tier 4)
ELA 3	285 (Tier 3)	1,464 (Tier 4)	2,267 (Tier 5)

The demand projection of a typical home was taken from a study conducted into the application of an off-grid power system in the rural Fouay village of Kandi, Alibori in northern Benin [6]. The onsite survey in this study includes the average energy consumption over a wide range of building classifications, only the 50 randomly selected households was used as the basis to determine the average energy consumption of non-energy poor homes in the Fouay village. The appliance usage time assumptions [7], were based over summer, and winter periods, noting that the loads remained similar except for a slight deviation in winter.

Table 4 Demand category survey per season [6]

Loads categories	Rating (appliance)	Loads (S/W)
Radio	30	62.7
TV	120	45
DVD	24	1.7
Phone	5	35.5
Fan	55	5.1/0
Fridge	100	9.2
Light	3/10	213.8
Total daily	344 (Watts)	372.9/367.9 (kWh)

C. Stand-alone solar P.V. design

Using the formulae (1-5), and the energy usage data, a simple household solar P.V. design was estimated. The rural area of Alibori, receives a lower irradiance average of 5.67 kWh/m^2/day, which means that there is a peak solar irradiance of 1 kWh/m^2/day for a total of 5.67 sun hours in the lowest irradiance period of the year [7].

Using equation (1), to determine the peak power demand based on the daily estimate per household:

Energy (daily consumption) = Maximum of summer vs. winter load in table 4 = 372.9 kWh/day

$$\therefore \text{P.P.D} = (372.9\ \text{kWh/day}/50\ \text{homes}) / (1\ \text{kWh}/\text{m}^2/\text{day}) = 9.75\ \text{kWh/day /home for 5.67 hours of the day}$$

Using equation (2), to estimate a P.V. array size:

Energy (daily consumption) = Maximum of summer vs. winter load in table 4 = 372.9 kWh/day

The panel generation factor (PGF) is a complicated parameter of the site irradiation and various other variables which can be determined experimentally [8]. Generally, 3.2 is acceptable, but since Nigeria is close to Benin, a PGF of 3.596 was adopted [9].

$$\therefore \text{P.V array size} = 9.75 / (3.596)$$
$$= 2.7\text{kW solar system}$$
$$= 27\ \text{crystalline 100W series units}$$

Using equation (3), to estimate a battery size:

Energy (daily consumption) = 9.75kWh

The days of autonomy is limited to budgetary constraints as an oversized battery storage component can become very costly. For a solar household system, three days is ideal [3].

The average two stage power conversion, transformerless inverter efficiency is rated 97% [10], the rapid advances in inverter technology has allowed for better operation of solar plants and overall energy improvements of the system.

The depth of discharge (D.O.D) is the amount of energy remaining in the battery after a sufficient energy release over time, a 50% battery charge use would mean a remaining 50% D.O.D is available. In order to ensure that Lithium-ion solar batteries operate at the best efficiency and lifespan, an ideal D.O.D is 80% [11], this means that the battery should never be fully utilized to its full capacity.

$$\therefore \text{B.S.C} = (9.75 * 3\ \text{days}) / (.80 * 24 * .97)$$
$$= 1570\text{Ah} = 1600\text{Ah (rounded up)}$$

Using equation (4&5), to estimate the capacity of a charge controller:

$$\text{Short circuit current (A)} = 100\ (W) / 24\ (V) = 4.17A\ \text{per panel}$$
$$= 4.17A \times 27\ \text{panels} = 113A$$

The factor of safety of a charge controller design should be taken as 25%, according to the national electricity control 2017 guidelines [12].

$$\therefore \text{Charge controller} = 113\ (A) \times 1.25 = 140A$$

Using equation (6), to estimate the capacity an inverter module.

Total appliance wattage from table 4 = 344W

Inverter size = 1.3 (30%) x 344W = 447W = 500 W (round up), however a standard 5kVA inverter was selected for future capacity allowance.

Table 5 Tier 3 Solar system specification

Loads categories	Rating (appliance)
Tier 3 P.V. system	9.75kWh output rating
Panel type	27 series modules of 100W crystalline
Battery Storage	24V 1600 Ah Li-ion
Charge controller	24 – 140A

II. SOLAR RESOURCE ASSESSMENT

A. Availability of solar resources

Availability of resources in the context of this assessment is a naturally occurring substance which is exploitable economically to the benefit of the country, which includes both centralized and decentralized energy options [1]&[2]. The solar & wind energy potential of Benin as of 2015 only accounts for 1.5% of total electricity production of a total 105kW per capita consumption [13].

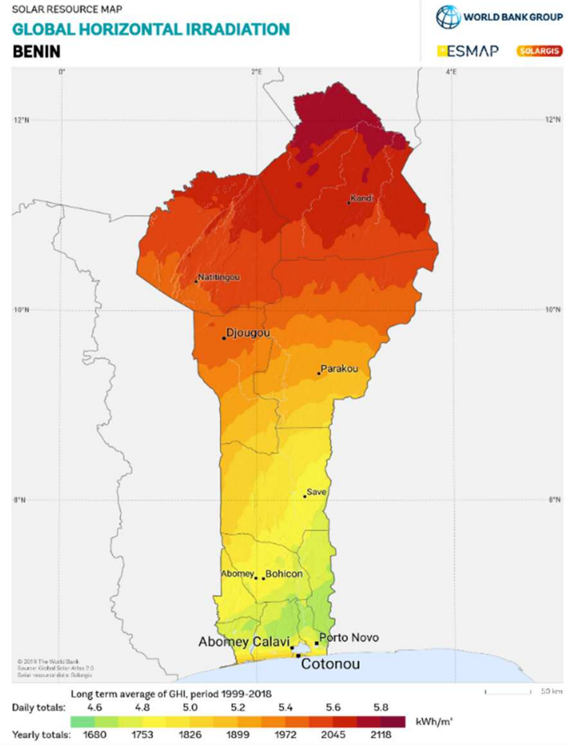

Fig. 1 Global horizontal irradiance [14]

The Global horizontal irradiance is a sum of direct normal and horizontal diffuse irradiance on the surface of the region of the earth, as seen in figure 1. the region of Kandi is indicated in dark red which is approximately 5.6 kWh/m2 which correlates to the value of 5.67kWh/m2 used in the P.V. system design calculations. The G.I.S. map data is an indication that northern Benin has a better surface irradiance for P.V. potential of power production. This is confirmed in figure 2, which is a representation of how much electricity can be produced from a 1 kWp crystalline panel installed at the correct inclination, this is approximately 4.4 kWh/kWp in Kandi, Benin. The southern regions of Benin being closer to the ocean display a lower irradiance and P.V. power potential, meaning more panels would be required for the same power output for the southern region of Benin.

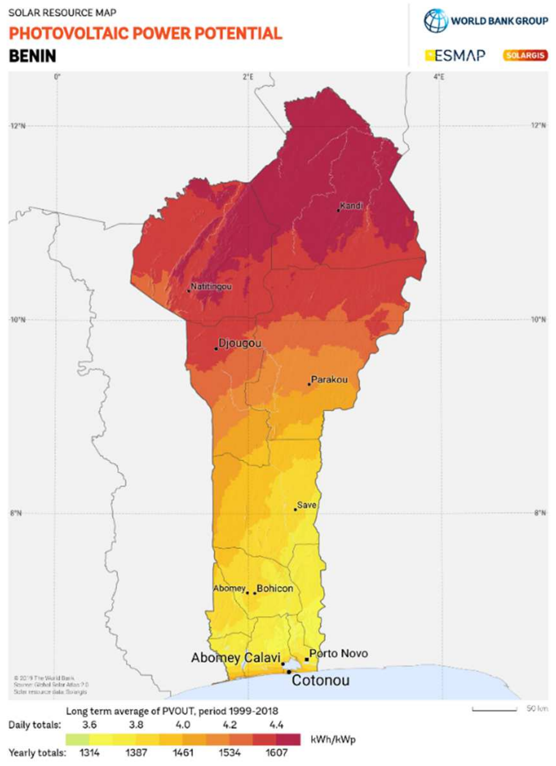

Fig. 2 Photovoltaic power potential [14]

The utilization of solar resources is based on the demand by the end-user. By the year 2030, there would be a significant underutilization of the planned interconnected grid network, and this would automatically increase the demand to integrate both solar and hydro renewable energy from both internal and external parties[6]. The external aspect comes from importing electricity from surrounding areas, namely; Ghana, Nigeria, Niger and Burkina Faso. Benin could benefit from additional generation capacity if the demand exceeds supply in remote areas where grid planning has not been implemented. An important aspect to consider is that even though the solar resources are in abundance, the more impoverished remote communities remain energy-poor.

The degree of energy readiness is a crucial factor in resource availability of North African countries. There are vast renewable energy resources in North Africa, and even though the primary exported and utilized resource is oil, there is severe lack of; regulatory frameworks, human capital, stabilized grid networks, well developed financial markets, infrastructure and market deregulation [15]. These factors lead to a delay in external investments as the risk of loss is more significant.

B. Adequacy of solar resources

Adequacy of resources in the context of this assessment is an estimation of the ability to meet the short, medium and long term energy demands, the SEAP framework focuses on the consistency of long term availability [1].

Solar resources in Africa is challenged by nuclear technology as an alternative to fossil fuels. The level of adequacy between the two was previously analyzed by using a levelized cost of electricity (LCOE) metric analysis, it was shown that a 20MW solar plant vs a 1500MW nuclear could yield faster result in short to medium term and in the longer term, the nuclear option would suffice. This conclusion notes that Ghana is a developing country which has already planned nuclear integration in 1961, allowing for initiatives to be set in place over time to move towards a nuclear option. Solar power, on the other hand, does not require long term planning and mainly depends on initial start-up investment which is much lower than nuclear power plants, the start-up time can also be similar to a plug and play solution as components are off the shelf and installation is faster for immediate power [16].

A critical aspect of the short term benefits of solar power implementation in Benin is shown by the existing and planned interconnected network in Benin, the West African Power Pool (WAPP) is a framework that was designed to integrate the operation of the national power of fourteen continental countries. The analysis focuses on Benin, Togo and Ghana in terms of their respective current and planned network infrastructure [17].

Table 6 Benin forecasted energy 2018 - 2023[17]

Year	Energy (G.W.H.)	Peak Power (M.W.)
2018	1381	276
2019	1472	294
2020	1575	314
2021	1691	337
2022	1799	359
2023	1913	382

The critical importance of solar infrastructure planning is that with the current average growth rate of 6.7% per year, to alleviate pressure on the additional demand, a short term solution has been implemented for renewable projects which include a smaller solar production capacity installed.

Table 7 Benin solar capacity 2018 - 2023 [17]

Technology type	Rating (appliance)	Loads (S/W)
Solar PV	Innovent Djougou	1.5
Solar P.V.	A.F.D.	25
Solar P.V.	M.C.A.	45

Solar energy production serves as a short term solution, implementation in energy-poor homes is still at the initial stages, the demand vs the installed capacity leads one to assume little effort is being made for P.V. in the long term.

Hybrid systems are being considered in their ability to provide energy relief in the short to long term phases of power production as to its effectiveness to supply continuous power in public areas [18]. The demand for such a system varies rapidly throughout a typical day, the power supply is thus proven unstable and not guaranteed for optimal performance. The associated cost of running diesel has high expenditure, even though the short term demand can be delivered, it is too expensive unless a hybrid system has been considered, which can deliver consistent power. As cloudy weather slows down P.V. power production, a diesel backup will kick in after the available battery storage has been depleted, reducing CO2 emissions by 55% [18].

The introduction of diesel-based start-up systems integrated into decentralized power units has also been reviewed, as solar systems can function independently in the short and long term, larger plants might be considered. In these remote where stand-alone systems are not cost-effective, there might be higher demands, which require an initial diesel power injection (diesel generators) with the primary goal being adherence to the voltage sensitivity index of the overall power plant. The focus on removing voltage fluctuation via a decentralized diesel system improves network stability in the short to long term periods [19].

The primary fuel in West Africa is fuelwood for heating and cookstoves, and there is a growing need in these rural areas due to dependency on these natural resources. The issue arises that the forests are degrading at a much faster rate than before, leaving arable land in a worse state than it was ten years ago. If solar power technology is to act as a long term replacement of fuelwood, the current dependency needs to be understood. The analysis reviewed [20], looks at how much mangrove fuelwood is depended on in Benin and why it is so essential to preserving the mangrove forests in the long term. It is noted that 75% of domestic heating energy is delivered by charcoal and 448 kW of solar energy supports rural electrification in telecommunication and healthcare in the region of Cotonou Benin. This amounts to a minute quantity of what is expected for the global solar electrification of Benin's potential future renewable footprint. Wood energy is also substituted by liquid petroleum gas (L.P.G) which not only serves as a short term solution but also is costly. This reliance on wood energy for burning fuel requires an immediate intervention to replace this outdated form of heating.

A stand-alone solar plant might not seem viable for isolated communities in the immediate timeframe, although the future demand for fuelwood is increasing. Ultimately this leads up to a damaged mangrove ecosystem, which provides the fuelwood for the essential cookstoves and winter heating. A simple two-element cookstove can provide heating with solar power, it is an option that is intended for the long term strategy. Sustainability of a resources is addressed here by the reduction of environmental effects in addition to P.V. systems having virtually no carbon footprint in the field.

Fig. 3 Parabolic cookstove [21]

A more straightforward option is to supply the rural areas with an inexpensive parabolic cooking device, as indicated in figure 3, this could lead to a short term solution of a reduction in the demand for wood fuel in summer periods.

C. Sustainability of solar resources

Sustainability of resources in the context of this assessment is a measure of the potential rate to supply the community's energy needs. The SEAP framework focuses on environmental, health, economic standpoint, and energy security [1] &[2]. This component addresses not only solar potential but also looks at the interconnected networks of various renewable energy to quantify the level of energy security as a whole.

i. Energy security

Benin and Nigeria currently have a 330V interconnected power line [17], grid failure is an issue that seems to affect energy security.

The reliability of a transmission company in Nigeria was analyzed, it is noted that due to the low reliability of electrical energy supply in Nigeria, diesel generators are open to a lucrative market to capitalize on. This should not be confused with a hybrid system, rather over-reliance on diesel systems changed the priority where the power generation unit almost seems to back up a primary energy supply of diesel injection [22]. As a result, pollution levels are increased to a dangerous level, and the overall power system reliability has received more attention as opposed to the optimal performance of the power networks. The main issue in Nigerian power stations according to this reliability analysis is that there are low-quality feeders at the power station which are responsible for electricity supply to the communities.

As an interconnected network with Benin is both part of current installations and future projects if solar energy were to be grid-connected, this would pose a severe problem to continuous power supply along the grid, the consequences could result in voltage fluctuations, or the solar plant could be rendered useless if a feeder failure causes power outages. One recommendation for solar plants in remote areas is that it could be best if solar plants were designed in such a manner as to consider the possibility of voltage fluctuation or in rural areas, stand-alone hybrid diesel P.V. systems would serve a typical household to meet its energy needs.

The importance of importing energy from continental neighbours is an important issue which is considered in-network stability, in order to ensure the demand is met for both Benin Togo, the import of electricity is done from the Volta river authority in Ghana [23]. The electricity imports are considered as constructive progress under the WAPP initiative, note the rural areas receive electrification at the very end, securing the market of stand-alone P.V. systems in the short term.

In order to identify energy delivery in Benin, a similarity is drawn from the neighbouring country Nigeria, with whom Benin has an interconnected energy line. The network in Nigeria faces many challenges, the most significant obstacle is that the extension of the grid seems to be outpaced by the increase in demand. Although like Benin, Nigeria also has an abundant amount of renewable resources, the energy mix seems to be in favour of immediate access through a faulty grid system which is only able to operate at 50% of the installed capacity is available due to several technical issues. Only 2% of the rural population have access to the grid [24], solar power is thus recognized as one of the best alternative sources of energy as Nigeria, along with Benin. These countries are known to have some of the best solar irradiance averages due to the location, making it the best alternative energy to serving not only isolated communities but also industrial sectors, delivering a high level of energy security as connecting to an unstable grid network is not required for stand-alone systems.

ii. Energy security

Energy economics of the interconnected grid is a highly complex activity, the disparity of electrification among the various makes it challenging to implement considering the lack of economic motivation [25]. A centralized grid vs decentralized grid has been the topic of discussion over many research papers. In the West African region, the centralized grid has seen much delay due to the highly remote rural communities and the challenges between navigating to these areas, this initial start-up cost has been proven highly unfeasible and private companies are now gaining traction in the independent power producers market as decentralized power resellers. Kenya has had success by innovating a payment model scheme with the various I.C.T. companies to offset the initial cost of miniature decentralized grid systems. This shows the high success rate of solar plants due to their low maintenance and operational benefit.

The need to review the potential energy trade issues of solar P.V., in an interconnected power hub across sub-Saharan Africa is required. Solar P.V. is potentially able to supply up to 866TWh of energy demand [26], however regional gas installations would see higher reliance rather than larger solar installations, P.V. systems are still favoured in integrated energy systems.

With these increased generated capacities and complex relationships of power systems, there is an urgent response required by the respective government to assist in a bilateral trade agreement which facilitates mutually beneficial contracts between power producers of interconnected countries. This requirement is lacking at this time due to the intense amount of inter-country cooperation required to align the complexities of trading energy. In the case of Benin, a developing country would experience similar trade issues, slowing down the injection rate of investment capital to fund these projects over the long term. The lack of a regulatory framework is supported by other research [15], as energy readiness of North African countries weaknesses lies in the economic framework to safeguard energy trade.

The small to medium enterprises (S.M.E.'s) are the drivers of business in developing countries, and this relates to the implementation of solar P.V. as the S.M.E.'s would compete for the tender process to undertake installations, supply and design logistics, and the list goes on. The shared challenges that these businesses face in Benin are as follows [27]:

- Access to information
- Access to finance
- Access to the market
- Access to training and skilled labour
- Gaining a competitive edge

A solar installation needs to be done correctly, a skilled labourer would need to be employed and trained by a business, this would require the cooperation of the regulatory bodies/government.

The primary policy listed was the decision of the Beninese president to ensure that the private sector would be the primary source of wealth and job creation. A ministry was assigned that focuses solely on S.M.E. development and promoting employment opportunities, however even with this in place, the challenges above are still present and provide a risk to solar installations through the lack of quality assurance by skilled technicians.

State-owned enterprises (S.O.E.'s) carry the critical role of managing and delegating state operations that affect the position of ownership and privatization against the government. An S.O.E. is faulted in the following characteristics [28]:

- Government employees (managers) maximize their benefits over a firm / S.M.E. providing service
- Private firms are held responsible with an open-ended interpretation of contract negotiations
- There are little legal repercussions for an S.O.E. under poor management
- No control mechanism and incentive structures
- Corruption is very hard to avoid
- Budget control lacks precision

With these negative aspects of S.O.E.'s, it is essential to note that solar installations which come from externally funded parties have a high risk of non-completion of works due to mismanagement of the project budget allocations by S.O.E.'s.

Trade laws determine whether or not a commodity can be traded with a neighbouring country, in the case of Benin and Nigeria, Benin is known to have increased dependence on Nigeria and thus, a lower rate of competitive pricing and benefits is observed [29]. Though there is a disadvantage of dependency on Nigeria, Benin has immense potential to develop along with neighbouring countries. There is a more reactionary step taken by Nigeria by borders being closed down, and this volatility results in slower economic growth which is highly risky for an investment analyst. These trade restrictions that take place from time to time has negative consequences for grid interconnected solar P.V. as investors keep clear of market volatility.

Land law is essential to the feasibility studies of solar P.V. investments strategies. Benin has a government policy that prevents 100% ownership by external investors [30]. The government of Benin owns the rights to all land, and dual ownership is required, this will inevitably slow down the investment of capital for investors wishing to own land where a central solar plant would be installed for example. The policy should not impact stand-alone P.V. systems.

D. Ease of access of solar resources

Ease of access to resources in the context of this assessment focuses on the direct effort required, such as travelling hours and fuels cost averages. The SEAP framework weighs in on the user's level of effort required to access a resource [1]&[2].

The stand-alone P.V. systems and solar cookstoves require no effort from the end-user to travel anywhere. The aspect of access risk to P.V. installation is thus considered from an interconnected grid P.V. plant. The extension of grid systems is a critical fact that in the majority of rural areas, in rural Benin, grid electrification is non-existent [31], thus regions where electrification is available, only represent the smallest percentage of the energy-poor population. In terms of effort required, this is a major stumbling block as energy creates economic opportunities.

The "pay as you go" (PAYG) instalment contracts are available in Benin [32], this is a significant aspect of access to solar resources as consumers are using PAYG to buy small solar kits.

Table 8 ARESS popular solar sales [32]

Technology type	Cost (Euros)
Sun king pro	42
Sun king boom	56
Sun King home 60	96

There are approximately 10120 energy consumers connected to this system network in Benin. There are several units which are sold by ARESS., and the preferred option for more expensive solutions are monthly instalments [32].

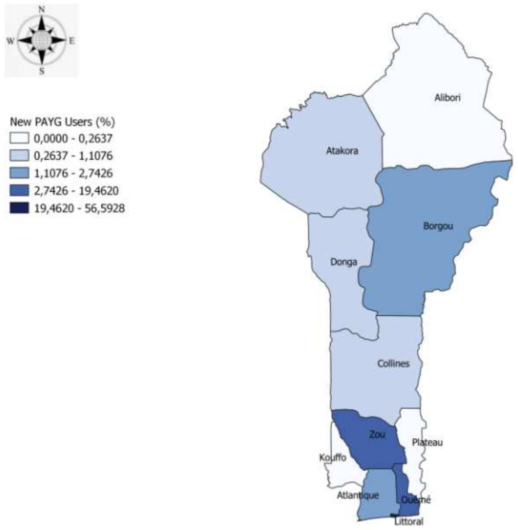

Fig. 4 New PAYG users [32]

Figure 4 represents the new PAYG users in Benin per location; the most interesting observation is that electrified areas have the most consumers and are on the increase.

Fig. 5 Rural applications of small solar P.V., ARESS 350kW solar contract [33]

Figure 5 is a representation of the investment that was made available for the electrification of 5000 rural households; the contract awarded to ARRESS for supplying a cumulative 350kW over two years.

E. Technology generation costs

The cost assessment is carried out to identify the lowest cost available for providing access universally. The analysis attempts to determine the generated power capacity of a chosen access technology within the budgetary confinements to meet the demand in specific years and electrification levels [1]&[2].

The interconnection of the grid network, however, is an essential aspect of grid cost. A review of the network integration of the WAPP observed that if there is an increase in grid-connected solar and hydropower plants, the feasibility of interconnection between grid networks across countries becomes much more affordable by reducing the cost by up to 53% and decreasing the cost of electricity access over time, this substantiates the value of grid-connected solar [34]. This statement is also supported by other research [35], observing a total of 40% savings per WAPP region due to the avoidance of generation cost as a result of direct solar injection into the interconnected grid network.

The following is a selection of what a stand-alone system would cost for a typical Tier 3 household.

Fig. 6 Alpha-ESS Smile5 11.4kWh Energy Storage & 3.66kWp Solar Array [36]

Table 9 **Design selection of a P.V. system [36]**

Components	Warrant & life (years)
3.66 kWp Canadian Solar Array of 12 panels crystalline	10 years & 25 years of performance
Battery storage: Intelligent 11.4kWh Lithium-ion with built-in 5kVA Inverter & charge controller	10 year warranty & 10000 life cycle
Inverter: 5kVA	15
Solar Cables (5m) and installation	15 (cables) 1 year (O&M)
Total	R 153,470 tax included R 133,452 tax excluded
Benin currency conversion	CAF 4544358,58 (Tax and other charges not included)

Table 9 Design selection of a P.V. system [36]

Benin's current cost, according to table 7, carries a direct cost of CAF 4544358,58. This essential cost exercise does not take into consideration several factors such as taxes and special import rates within Benin; it is assumed that based on the South African equivalent of "total direct technology cost" and the average salary of Beninese residents. The conclusion could be assessed as to the rate of affordability for a solar system in a typical household in Benin (Tier 3). The average salary in Benin, according to Barry et al. (2020), was reported at 40000 CFA or 61 Euros. The "cost per wattage" rating is taken from the total cost of the system over the installed solar P.V. capacity of 3.66 kW, this works out to approximately R41, 93per kWp or CAF 1241.62 per wattage (installed).

III. RESULTS AND DISCUSSION

i. Solar P.V. system design

The solar system designed for Tier 3 household was estimated for a peak power demand of 9.75kWh/day with an array size to generate that amount of storage was estimated as a 2.7kW solar system. The solar installation selected to meet was an off the shelf supply and fit unit which would allow for delivery into rural areas.

The design calculations yield a similar estimation of a plant size to that produced by another study in a developing country who reported a 2.56kW solar array size with a 9.75kW peaks power demand[4].

The P.V. array size is greatly affected by the panel generation factor, this factor changes per location, thus for detailed engineering designs of solar plants in Benin, each remote region requires an experimental analysis [8] for large scale design.

The battery storage capacity is greatly influenced by days of autonomy and depth of discharge. The D.O.A. is determined by the client whose decision can be influenced by various factors, including the distance from remote areas to the nearest national, local grid network. The depth of discharge in remote areas will more than likely run to 100% if care is not taken, as the dependency on stand-alone systems would be that of a primary energy source, significant lifespan reduction of the battery storage component is expected, adding maintenance costs.

The improvements of solar P.V. operation is further investigated by the use solar tracking, which changes the orientation of the panel through the use of programable logic control motors to ensure a constant peak voltage and increased current throughout the day, directly increasing irradiance rate and subsequently, the maximum power output [5]. Solar tracking is highly recommended for anyone who can afford the additional overheads.

ii. Electricity demand estimation

The demand profile was identified as a non-energy poor region because the majority of rural areas utilize traditional cookstoves, and the grid network is unavailable in remote locations. An average daily consumption per household of 9.75kWh over one year yields an estimated 985.5kWh/year level of consumption, this corresponds to a Tier 3 category as indicated table 2 where Tier 3 is given by; $285 \leq E < 1464$. Table 1 identifies that the appliances which are used to arrive at a base load of 285kWh, whilst the survey region is estimated at 372.9 kWh, this is a 23.5% increased utilization over the planned energy Tier 3 category, raising concern that demand will more than likely be above the base cases as time moves. A more detailed analysis of the population growth and energy-poor statistics could yield a better overview of what the actual expected energy consumption is expected to be.

iii. Availability of solar resources

The renewable resources in Benin are in abundance, mainly solar energy is one of the highest averages due to the equatorial distance, the lowest irradiance load is rated at 5.67 kW/m2, however, the average seasonal load certain regions of Benin is around 8.5 kW/m2. The unfortunate fact is that solar and wind energy only accounts for 1.5% of total electricity production and according to figure 7, the surveyed area of Alibori has a 7.5% electrification rate, which is the lowest of all the regions in Benin, leaving the majority of the population with insufficient energy access even though the weather data suggest some of the best available renewable resources. The focus on fossilized fuels unfortunately still receive too much attention as network planning was geared up in that way in the early stages of Benin's energy planning.

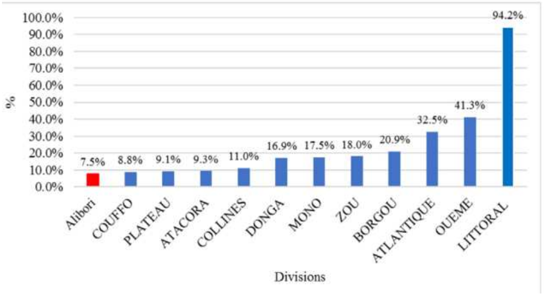

Fig.7 Benin electrification rate by area [6]

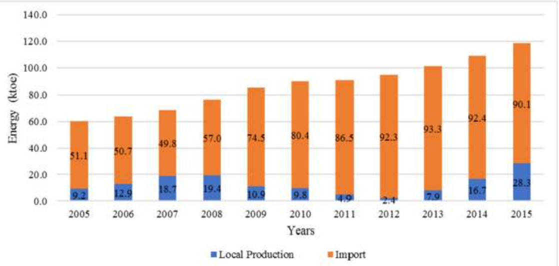

Fig.8 Benin electricity supply (2000-2015) [6]

The production of electricity is however on the increase as shown in figure 8, there is evidence of decreased electricity imports, leaving the assumption that even though solar resources are not yet fully utilized to their full capacity, it is more than likely the solution to energy shortages in the urban and specifically remote locations of Benin.

iv. Adequacy of solar resources

Solar resources are ideal in the short term and long term, nuclear however is only efficient in the long term and requires immense coordination of a countries energy readiness. In the short term 2018-2023, there is an expected increase of 6.7% in the energy demand, and this could see solar gaining traction in the energy mix. The addition of hybrid systems integrating solar P.V. and diesel injection was proven to be a useful technique to alleviate short term to long term energy demands by increasing the operational efficiency by 50%. Solar cooking is a suggestion that needs to take priority in the more impoverished communities, in addition to long term benefits on mangroves, parabolic solar devices will alleviate the pressure on wood fuel reserves by removing the summer cooking loads.

v. Sustainability of solar resources

Decentralized solar systems do not have many risks attached due to the robustness of the solar systems, the energy security of the grid-connected solar systems, however, has a clear direction from the WAPP framework that promotes renewable injection into the grid. The technical faults of

Nigeria's power transmission line, poses a risk to energy security. The network stability of grid-connected solar is thus challenged by a 50% running capacity with decentralized diesel units operating as a primary source during blackouts that occur the majority of the time. The economics between Benin and Nigeria is known to have political tensions, thus an improvement in the trade negotiations is required as West African countries lack the regulatory frameworks for fair energy trade. Another severe economic barrier in Benin is the lack of attention given to S.M.E.'s by the S.O.E.'s. The last aspect which is by far a vital aspect of an investment is that Benin does not allow external investors to have 100% ownership, expropriation is at the government's discretion, introducing a risky element to investors.

vi. Ease of access of solar resources

Access to decentralized solar installations is not a risk factor, the initial cost for transportation and installation does require careful coordination. Grid-connected solar is not currently a possibility for rural areas, as there is virtually no infrastructure in place to tap into, rural residents will remain energy-poor unless grid expansion is planned for in rural communities. There is a "pay as you go" (PAYG) solution which brings solar kits to the nearest location and payment is handled through monthly instalments, this system also allows for purchasing electricity for grid-connected customers. Access in rural areas is not possible except through external funding, the average monthly salary in Benin is half of what a small-sized solar system will cost, leading to hefty instalments and debt rates soaring.

Utilizing Worldbank income statistics over the period of 2006 – 2018 [13], it is observed that current service debt has linearly increased over time. From 2014 – 2018 there is an exponential increase and as the population grows, so would the dependency on solar power, eventually leading towards more PAYG debt contracts being signed.

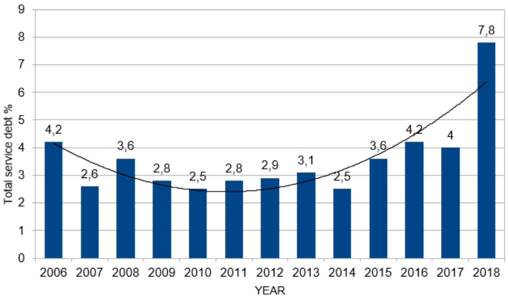

Fig.9 Benin total service debt over time [13]

vii. Technology generation costs

Grid-connected solar systems have the advantage that they reduce capital expenditure of the interconnected network in each region by an estimated 53%; the cost-benefit is ideal motivation towards countries investing in major solar plants.

Utilizing the The "cost per kW rating" associated for stand-alone systems , a comparison is drawn in figure 9, proving that stand-alone installations become unaffordable in the Tier 4&5 categories as the more expensive solutions are more inclined towards bond agreements using the PAYG due to level of unaffordability in the low income areas.

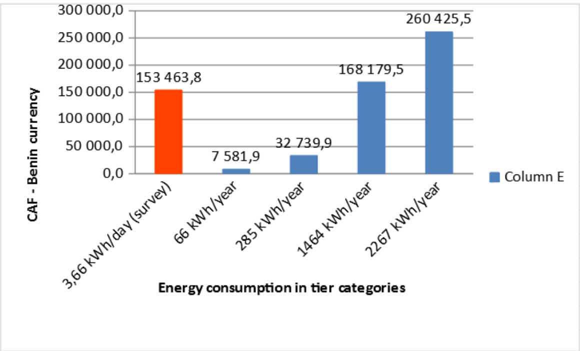

Fig.10 Tier energy demands vs. cost per watt

Utilizing the Worldbank income statistics throughout 2006 – 2018 [13], and the values derived from figure 10, it is observed that debt levels would likely increase current as the rate of future income growth is being worked against the increased demands for suitable energy access. In the short term, national debt levels become unmanageable towards the Tier 4 & 5 categories.

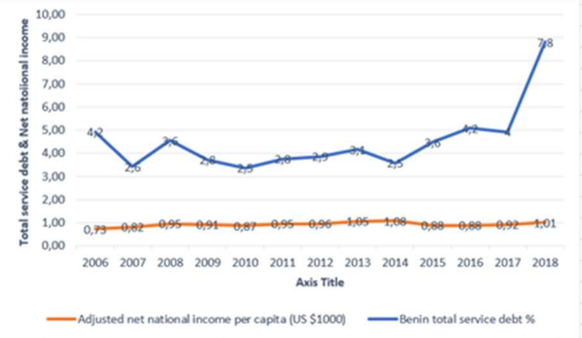

Fig.11 Service debt vs. net national income [13]

IV. CONCLUSIONS

A study into the available solar resources of Kandi, Benin has been undertaken, the potential to empower energy-poor communities is high, as these communities grow, so do their energy needs.

The results show that the average installation for a tier 3 household is estimated at an installed capacity 2.7 kWh with a battery storage component of 9.75kWh to allow for 3 days of autonomy is required. The supply and fit system selected was an “Alpha-ESS Smile5 11.4kWh Energy Storage & 3.66kWp Solar Array “, which is designed to operate as a stand-alone system. The grid connected solar systems on the other hand face many technical and political challenges, suggesting that interconnection of Beninese solar farms on a larger scale will not move at the intended pace to meet the WAPP and SEAP framework requirements for energy access, specifically in rural communities. Diesel P.V. hybrid system, however, would be the optimal choice of installation if and when grid-connected solar becomes a reality.

Investments are vital in ensuring communities are empowered, as the only option at this current time being bond agreements through the PAYG system.

The mangrove resources of Benin depletion rate is rapidly decreasing; the use of parabolic cookstoves is recommended to ensure the existing wood fuel reserves stand a chance of recovery.

The government of Benin needs to give more attention towards innovation policies and consider a review of land uses ownership for investments, along with ensuring proper accountability to the governing representatives that manage S.O.E.’s.

In a future study, the tax policies, rules of governance and the technical aspects of solar design could be addressed per region in Benin to gauge the greater effects on the WAPP initiative. A further investigation should be done into a complete energy access assessment aligned to the SEAP framework to have a true picture of the reality on the ground, this would provide immense coordination and funding, however it is worth the effort as the study presented the associated risk.

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