Techno-economic Analysis of the Implementation and Future Expansion of a Photovoltaic-Diesel Hybrid Power System in the Upper Nile University in South Sudan

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January, 2021

***Abstract* – The aim of this thesis is to analyze solutions and perform the technical design and planification of the Upper Nile University PV-Diesel Hybrid Power System or mini grid, under the scope of the Green Energy Services Team of the United Nations Development Programme (UNDP). The corresponding university is located in Malakal, a city in the northern region of South Sudan, and it is currently under renovation, as it was destroyed during the civil war. The donor of the project is the Japanese government and the responsible to execute it, the UNDP country office in South Sudan. For the data collection, the country office has provided a list of appliances to be installed in the university compound, as well as pictures of the main buildings, among other relevant information. The set of data has been used to obtain three optimal system configurations, including the size of components such as diesel generators, batteries, and PV panels. Three different configurations have been presented and compared, and the country offices' final selection among the three options has been properly described. Finally, a set of suggestions for future expansion opportunities has been included at the end of the thesis, which can be executed once it has been proved that the mini grid is functioning properly in the university compound.**

***Keywords* –** *Electricity access, power system design, sustainable development, South Sudan, United Nations Development Programme, university.*

I. INTRODUCTION

The problem that this thesis will focus on is the lack of a reliable electrical grid in the village of Malakal, South Sudan, which is a clear barrier in the reconstruction of the Upper Nile University, as the use of electricity will be essential for the academic development of its future students. Since the country has been in a long period of conflict, affecting the main infrastructure networks such as electricity and water supply, it is not uncommon that several public buildings rely on their own off-grid energy systems. Hence, the Japanese Government assistance package able to finance the reconstruction of the university [1], will also be used to provide its own solar system, in the scope of UNDP, specifically the UNDP Office of Information Management and Technology (OIMT) Green Energy Services (GES) team based in Copenhagen, which will be responsible for implementing a reliable and green energy system for the compound.

Consequently, the main objective of this thesis is to analyze, assess and discuss a solution to assure a reliable energy solution to power the load of the Upper Nile University in Malakal. As the village lacks a reliable electrical grid and diesel costs in the country are unstable and expensive [2], the designed system will provide a sustainable off-grid electricity supply to the compound by the use of solar energy, avoiding the use of fossil fuels and high CO_2 emissions while increasing affordability and system autonomy.

In the scope of the thesis, the tasks include the planification and performance of the necessary simulations in order to obtain the main parameters used for the system design (number of panels, space availability and usage, estimated annual system power production and consumption, etc.). As the work has been performed in the scope of an internship in the UNDP GES team in Copenhagen, the methodology used, software and main tools have been provided by UNDP, as well as the evaluation of the results for future implementation. Consequently, the results presented in this thesis have been the base of the real system currently being implemented in the university in Malakal.

Other objectives of the project this thesis will be focusing on is the creation of local capacity and local markets for the development of renewable energy projects, to be achieved by relying on local companies for the installation of the system, and by spreading the word about the system benefits throughout the area. However, this objective will not be in the scope of this thesis.

Suggestions for future improvements of the power system designed for the Upper Nile University will be included in the thesis. As a matter of fact, the improvements will also be directed to allow the near local population to benefit from the renewable energy excess produced in the university compound, providing a sustainable growth of the system.

Finally, this thesis describes the methodology and main steps followed to obtain a reliable solar energy system in a very particular environment. Hence, the potential contribution of this thesis is a practical example for other renewable energy project implementers willing to design a solar system in similar conditions such as area to be implemented, electrical load or project boundaries and limitations. Although these types of assessments are performed in a case-by-case basis, the same methodology and software use can serve as a guide to facilitate the process, as well as the type of solution encountered to the lack of sufficient budget for an optimal system at once.

II. METHODOLOGY

To address some of the challenges faced by UNDP Country Offices around the world, the GES team has put in place a very well-defined procedure, called the 7-Step Green Energy Solution Process, which has been recognized best practice by the UNDG for solar project implementation. Figure 1 shows an overview of the 7 steps of the process.

The scope of this thesis includes steps 1 and 2 for the Upper Nile University green energy project. The first step, which includes an energy audit and a load assessment using IoT, aims to collect all the necessary data for the system design, and it is developed closely with the client on-site, in this case through the UNDP Country Office in South Sudan which assists the renovation of the university compound. Power Consumption Monitoring and Measurement devices (PCMMs) are usually used to gather electrical consumption data in step 1. However, as at the moment no electrical devices have been placed yet in the compound, a list of appliances to be installed has been used instead. A Preliminary Site Survey with other relevant information such as space availability for the installation of the PV panels, the presence of a diesel generator on site and its use, fuel price, etc. has also been used, together with the list of appliances, to create a proper daily and yearly load profile of the compound.

Step 2 starts when all the available load data is well received and analyzed by the GES team. It consists of a detailed technical, economic, and environmental analysis, which is presented as the Business Case document. This document is provided to the country office to allow them to make an informed decision regarding the system they want to have installed. To obtain the values shared in the Business Case, PV*SOL and HOMER are the two main software used for the design and optimization of the PV or PV-hybrid systems. PV*SOL is used to perform a 3D analysis of the building, to optimize the position of the PV panels and to obtain the maximum PV capacity available due to shading and space constraints. HOMER (Hybrid Optimization Model for Electric Renewables) complements the previous results with the optimization and feasibility analysis of the system including all the components (solar PV, batteries, electrical grid, and diesel generators), to reduce the overall energy costs.

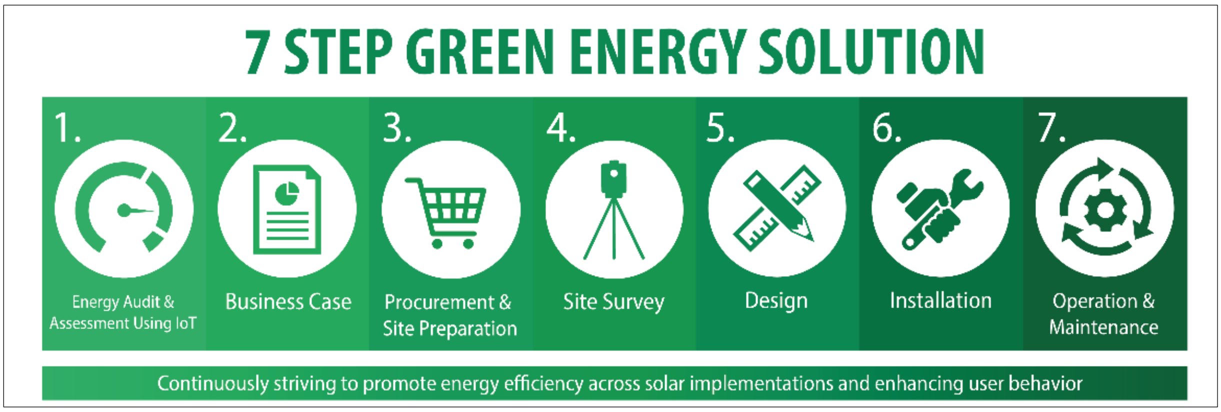

Figure 1. 7-Step Green Energy Solution Process Overview [3].

The results obtained are combined with cost data of previous UNDP projects and UNEP verified emission factors to calculate the total system cost, payback time and CO2 emissions. All the results are included in the Business Case Document and informed to the country office.

Other steps of the process not included in the scope of this thesis involve procurement and selection of the company which will install the system (step 3), on-site audit performed by the company selected in the previous step (step 4), final design of the system (step 5), installation and commissioning (step 6) and operation, maintenance, and online monitoring service for 3 years (step 7).

III. RESULTS

A. Load Analysis

As mentioned before, the first step consists of gathering data of all electrical devices to be installed in the university compound. The devices of all buildings in the university compound have been considered, composed by the Vice-Chancellor, the lecturers and the Dean offices, the lecture halls, the library, and the student rooms.

Using the load data and variability patterns to perform a more realistic analysis, the results have been obtained, shown in Figure 2 as the weekdays' daily load pattern of the compound, with the characteristic values included in Table 1. Although not shown, the daily load patter of weekends has also been estimated.

The peak load of the compound has been calculated as the sum of the nominal power of all appliances by the number of units available for each of them, as if all were operating at the same time. This is a safe assumption, as the worst-case scenario is being considered. Additionally, to estimate the daily and annual average loads, both weekdays and weekends average values have been used in the calculation.

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B. Area Availability

As previously mentioned in the methodology description, one of the main software used in the 7-Step Solution process is PV*SOL [4]. This IT tool is used to analyze a 3D model of the roof of the buildings in which the PV solar panels want to be placed. The objective is to obtain the maximum PV capacity that fit in the considered building, considering parameters such as panels' tilt, available irradiance, and shading of the panels due to near obstacles (trees, other buildings, etc.). This is an important pre-analysis to be performed, as a typical constraint in PV system design is space availability.

Table 1. Resulting values of total load analysis.

Peak Load	189.84	kW
Daily average load	1,055.14	kWh/day
Annual average load	385,125	kWh/year

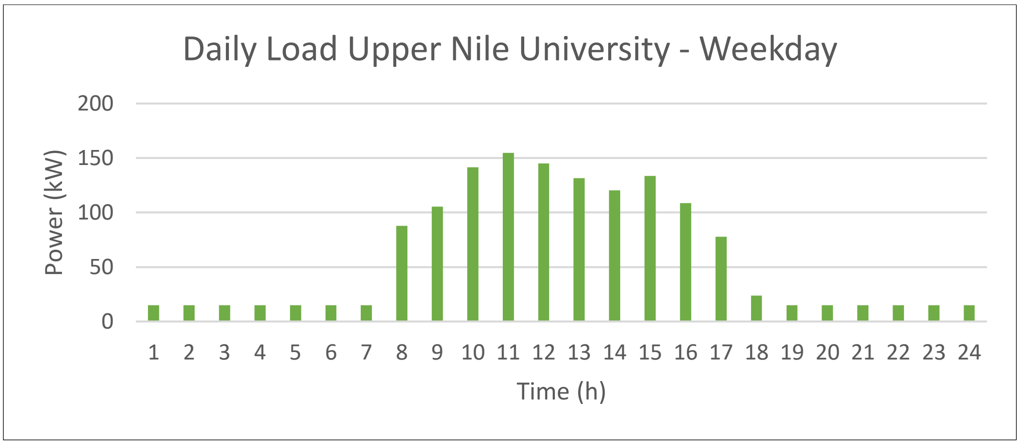

Figure 2. Upper Nile University daily load in working days.

In the specific case of the Upper Nile University project in Malakal, two building roofs have been considered for placing the photovoltaic panels, the VC Office building, and the Lecturers' Office. The available space is not a critical issue in this project, as not enough budget is available to place a high number of PV panels, and thus there is no need to include other buildings in the analysis.

Table 2 shows the main results obtained from both PVSOL simulations. Additionally, Figure 3 shows the shading analysis performed by the software for the facades with minimal shading (less than 0.5% in any case). These results will serve as indicators for space requirements after the design values will be obtained with HOMER.

In this case, as the final system will have 80 kWp of PV, the possibility of placing all the panels in the VC building will be the optimal.

C. Techno-economic Analysis

Techno-economic Analysis Results: HOMER (Hybrid Optimization of Multiple Energy Resources) is one of the leading microgrid modelling software, as it combines different generation technologies, either from fossil or renewable sources, with energy storage technologies and load management control systems, among other functionalities [5].

In order to deal with important budget limitations, three options have been considered for the Upper Nile University project, involving three different simulations in HOMER (Table 3 and Table 4). Important outputs or results in HOMER include solar PV and battery size (kWp and kWh, respectively), renewable fraction of the total energy generation, annual fuel consumption and economic parameters such as needed investment, Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), among others. This makes it a great tool for pre-designing energy systems considering both technical and economical suitability.

After the corresponding necessary inputs are inserted in HOMER (irradiance and temperature data, unit costs of the components such as PV, generators and power electronics, fuel cost in the region, etc.), the results are obtained in the three scenarios considered.

Table 2. PVSOL simulation results for the Upper Nile University project.

	VC Building		Lecturers' Building	
	Southern Façade	Northern Façade	Eastern Façade	Western Façade
Roof Inclination	161° South	340° North	74° East	254° West
Roof Orientation	15º	15º	15º	15º
Mounting Structure	Roof integrated		Roof integrated	
PV Generator Output (kWp)	98.6		76.8	
PV Generator Surface (m^2)	597.6		465.7	
Number of PV Modules	308		240	

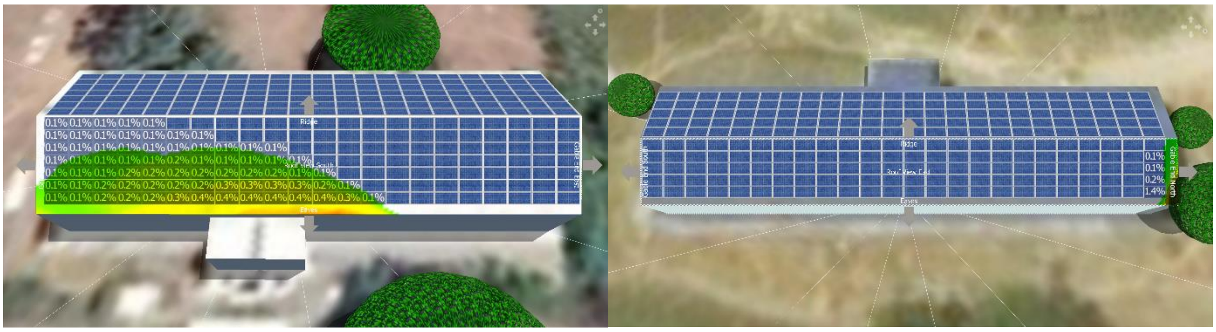

Figure 3. PVSOL shading analysis of VC Building South (left) and Lecturers' Building Eastern Façade (right).

The values of diesel consumption reduction come from a comparison performed by HOMER between the solar system of each scenario and a base case, where 100% of the electricity comes from a single diesel generator. The value of CO2 emissions saved comes from a later environmental analysis using indicators obtained from UNEP reports [6]. The optimal system for each of the options has been chosen as the one that maximizes the renewable fraction while making sense in an engineering point of view and being adjusted to the budget. The results will be presented to the country office to choose among the options.

IV. DISCUSSION

Clearly, the system to recommend to the country office in South Sudan to implement in the university compound is the one described in option 3. It is the optimal solution in terms of highest annual savings and reduction of diesel consumption, and the system that allows the highest control level of the whole university compound, as all the components and loads would be centrally controlled. In addition, the system would be easy to expand, adding batteries or more solar PV panels as to increase the renewable fraction of the bigger load supplied.

As a mini grid, it can even be expanded in the future to benefit other users outside of the university compound.

However, the selected system in option 3 could be extremely improved by the addition of batteries, as it would remove the need to run at least one generator a 100% of the time for grid forming. However, budget restrictions do not allow such improvements, or any addition of PV capacity to the system, in this stage of the project.

Table 3. Upper Nile University options to be simulated in HOMER.

	Option 1: Lecturers' Office	Option 2: VC's Office excluding ACs	Option 3: Mini grid without Batteries
Description	Isolated system covering the load of the Lecturers building	Isolated system covering the load of the VC building, excluding the load of the AC units, which will be part of the remaining loads of the compound	Mini grid covering the load of the whole compound
System Components	PV, batteries, and connected to generator(s) powering the remaining loads of the compound as backup	PV, batteries, and connected to generator(s) powering the remaining loads of the compound as backup	PV and generator(s), batteries out of the scope due to budget constraints
Load	21.9 kWp 41729 kWh/year	24.7 kWp 51726 kWh/year	189.9 kWp 387177 kWh/year
Share of Total Load	10% of total load The remaining load share of the compound will not be in the scope of OIMT	13% of total load The remaining load share of the compound will not be in the scope of OIMT	100% of total load All the load of the compound covered
Budget	US$ 100,000 (Green Energy Solution)	US$ 100,000 (Green Energy Solution)	US$ 201,000 (Green Energy Solution + Generators)

According to further simulations with HOMER, if in later stages the stakeholders decide to optimize the current system, the recommendation would be to expand the PV capacity up to 250 kW and to add 145 kWh of lithium-ion battery storage, as to obtain a system with up to 63.8% of renewable fraction. This system would become much more efficient, as the batteries would be responsible for setting the voltage and the frequency of the grid (grid forming), allowing the generators to stop when not needed. Even though this expansion would cost approximately US$144,000, the payback time would be less than 2 years and the annual savings increased by 33%.

Finally, considering the lack of electricity in the village of Malakal, the addition of a mini grid in the university compound can also be considered as an opportunity to expand it to domestic consumers in the community. The study of Safdar on business models for mini grids [7] suggests innovative approaches directed to implement economically viable mini grids in areas of low electricity demand, including the 'Anchors, Businesses and Consumers (ABS)' approach. This model aims to benefit from 'Anchor' customers that would provide a stable source of revenue from the use of the mini grid and expand the system to other customers such as community buildings or households nearby in a safer way. In this case, the Upper Nile University would be considered the anchor customer, as its management would provide the required investment for the implementation of the mini grid and would become the owner of the system. In the future, the owner may find viable to expand the system to the local community, which would become a source of revenue for the system owner.

Table 4. Upper Nile University Green Energy Solution at a glance.

Description	Option 1 Lecturers Office	Option 2 VC Office	Option 3 Whole university	Unit
Share of the Load	10	13	100	%
Solar PV Energy Production	49,560	66,080	132,160	kWh/year
Renewable Fraction	81.4	78.9	21.6	%
Capital Investment	89,930	101,103	211,729	US$
Estimated Annual Monetary Savings	62,771	70,351	275,189	US$/year
Solar PV Capacity	30	40	80	kWp
Battery Size	64	74	-	kWh
Total Generator Operation Time	439	571	8,760	hours/year
Total Diesel Consumption	2,415	3,619	96,112	litres/year
Reduction in Diesel Consumption	8.2	10.6	44.3	%
Carbon (CO_2) Emissions Saved	72.9	82.2	324.8	tons of CO2/year
Simple Payback Time	1.43	1.44	0.9	years

The expansion and operation costs can be recovered easily with the revenues obtained from the new electricity consumers if the mini grid management is subjected to a well-defined business model, benefitting all the parties involved. According to further simulations with HOMER, the extension of the optimal mini grid in the university compound (250 kW of PV capacity and 145 kWh of battery capacity), could benefit more than 50 small households as reducing their current diesel consumption by 9,924 liters/year (or 19,054 US$/year), with a slight decrease in the renewable fraction of the mini grid of no more than a 3%.

However, the previous data presented in the discussion and not related to the design of the system to be implemented this year includes several assumptions, far to be as accurate as the results presented to the country office in South Sudan.

V. CONCLUSIONS

The benefits of the expansion of the mini grid to be implemented in the Upper Nile University by this year, which characteristics have been shown in Option 3, are highly beneficial. This is due to the high available area for the PV panels, the high solar irradiation in the region and the expensive diesel costs of the country. Furthermore, innovative business models such as the 'ABS' approach can add even more value to the system and thus it can be helpful to attract future investments, either public or private.

Another aspect to highlight is the possibility that a clear and concise methodology such as the 7-Steps could be scalable, used by non-profits and community representatives to highlight the benefits of an energy solution to attract donnors and investors, without the need to pay for a preliminary study. It can also be useful to monitor the work of the companies in charge of performing the Engineering, Procurement and Construction (EPC) of the systems, following steps 3 to 7 of the 7-Steps methodology, not in the scope of this thesis.

Additionally, the benefits of a PV-diesel hybrid system have been featured in this thesis. Such systems can be reliable, affordable and flexible, and still produce a significant emission reduction. The main advantage comes from the decrease in capital costs with respect to PV systems, driven by the support of the diesel generators, and the decrease in the operation costs as well, driven by the PV energy which decreases the diesel consumption. Even if not essential, in the simulations regarding the university system expansion it has been noticed that batteries are key to improve the system profitability, reducing drastically the operating hours of the generators, among others. However, these components are expensive, and in situations of limited budget they can be removed and still obtain a beneficial system.

Finally, future relevant work could be related to energy resources data in the country, as the big lack of data is still a constraint to perform studies regarding the potential of distributed energy resources in rural areas. Other future work could relate to innovative business models for mini-grid expansion or implementation in similar environments, or it could focus on how increasing energy access impacts the socio-economic development of a country, which could be useful to promote public investment.

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