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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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

To...

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Abstract

The aim of this thesis is to analyse 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. The corresponding university is located in Malakal, a city in the northern region of South Sudan, and it is currently under renovation. For the data collection, the client or 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 client or 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

Sustainable development, electricity access, power system design, university, South Sudan, United Nations Development Programme

Resumo

O objetivo desta tese é analisar as soluções e definir o desenho tecnico e planear as fases de aquisição para uma Universidade de um sistema de Energia Híbrido PV-Diesel da Upper Nile University, ou mini rede, suportado pela equipa de Serviços de Energia Verde do Programa das Nações Unidas para o Desenvolvimento. A universidade está localizada em Malakal, uma cidade na região norte do Sudão do Sul, e atualmente está em reabilitação. A lista de equipamentos a serem instalados no complexo da universidade, além de fotos dos principais edifícios, entre outras informações relevantes foram fornecidos pelo promotor. O conjunto de dados foi usado para obter três configurações ideais do sistema, incluindo o tamanho de componentes como geradores a diesel, baterias e painéis fotovoltaicos. Três configurações diferentes foram analisadas e comparadas, e a seleção final para o promotor entre as três opções foi detalhada. Por fim, um conjunto de sugestões para futuras oportunidades de expansão é incluído no final da tese, que poderá ser executado uma vez que tenha sido comprovado que a mini rede está funcionando adequadamente no complexo da universidade.

Palavras-chave

Desenvolvimento sustentável, acesso à eletricidade, projeto de sistema de potência, universidade, Sudão do Sul, Programa das Nações Unidas para o Desenvolvimento

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List of Acronyms

AC	Air Conditioning
CAPEX	Capital Expenditure
CO	Country Office
DES	Distributed Energy Sources
EEP	Energizing Education Program
EER	Energy Efficiency Ratio
EIA	Energy Information Administration
GES	Green Energy Services
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
LDCs	Least Developed Countries
NPC	Net Present Cost
OIMT	Office of Information Management and Technology
OPEX	Operational Expenditure
PCMM	Power Consumption Monitoring and Measurement device
PSU	Procurement Service Unit
PV	Photovoltaic
SDG	Sustainable Development Goals
SOC	State of Charge
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNDG	United Nations Development Group
UNDP	United Nations Development Programme
US	United States
US$	United States Dollars

List of Software

PVSOL	PV*SOL premium is a dynamic simulation program with 3D visualization and detailed shading analysis for the calculation of photovoltaic systems in combination with appliances, battery systems and electric vehicles.
HOMER	The HOMER Pro® microgrid software by HOMER Energy is the global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected campuses and military bases. Originally developed at the National Renewable Energy Laboratory, and enhanced and distributed by HOMER Energy, HOMER (Hybrid Optimization Model for Multiple Energy Resources) nests three powerful tools in one software product, so that engineering and economics work side by side:

Chapter 1

Introduction

This chapter gives a brief overview of the importance of the area and this type of project. Before establishing work objectives, the scope and motivations are brought up. The current background and boundaries concerning the scope of the work are also presented.

1.1. Overview

The United Nations Sustainable Development Goals (SDG) were embraced by all country members in 2015 as a call to end poverty, war and guarantee basic human rights to the world's population by 2030. ***Figure 1.1*** shows the definition of the 17 SDG that aim to drive the economic, social, and environmental strategy of all UN organizations.

Figure 1.1*. United Nations 17 Development Goals* [1].

The scope of this project lays within the United Nations Development Programme's (UNDP) efforts to fight poverty in about 170 countries, while preserving the environment. In order to help these territories to progress, UNDP counts on country offices to help the local population to develop beneficial policies, skills, partnerships, and institutions. As an example, in the specific project described in this thesis, UNDP aims to tackle objectives 4, 7, 9, 11, 13 and 17, by providing affordable and clean energy to a public educational compound, by promoting local markets, community empowerment and enriching partnerships between the government, international organizations and international donors.

As to guarantee the optimal operation of UNDP, the Office of Information Management and Technology (OIMT), located in Copenhagen, helps country offices to become Smart Facilities, as to build local capacity and inspire a movement. ***Figure 1.2*** shows the main action points followed by OIMT with the objective of spreading the Smart Facilities' concept around the globe. The concept of Smart Facilities intends to bring to UNDP Country Offices around the globe the opportunity to improve its services to the surrounding community, as they are usually placed in developing countries, by experiencing innovating concepts described in the quadrant in ***Figure 1.2***. For example, the installation of solar streetlamps in the UNDP Country Office in Comoros allowed a more secure environment in the surrounding community in a sustainable manner. Communication services also allow the improvement of UNDP services in these countries.

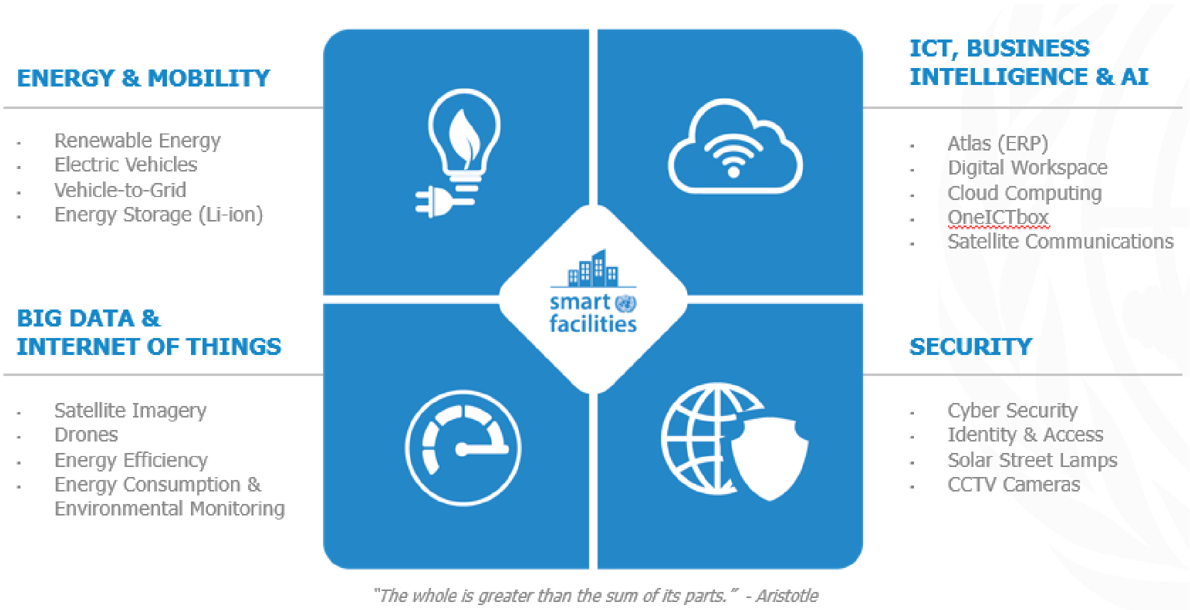

***Figure 1.2**. UN Smart Facilities Concept Components* [1].

As seen in ***Figure 1.2***, one of the action lines of UNDP's OIMT is the implementation of Green Energy solutions to power Smart Facilities. The Green Energy Services (GES) Team will be the unit in charge of developing renewable energy projects for both country offices and UN driven stakeholders, in any of the countries under the scope of UNDP. Furthermore, the GES team's goal goes beyond green energy systems implementation, as it aims to inspire a movement among other agencies and companies in the region as well. In this extent, green energy solutions become a tool to stimulate local capacity and promote sustainable progress in less developed areas. For this purpose, the team provides other services such as training on energy equipment management and energy efficiency, as to create local capacity, as well as Electric Vehicle solutions.

The current master thesis aims to provide an analysis of one of the real cases in which the UNDP GES team will provide a country with very low energy access ratios, in this case South Sudan, with a renewable energy system. The design of the mini grid has been performed in the scope of a 6-months internship in-situ with the team based in Copenhagen, by using their tools and methodology, which will be described as well. The corresponding system is expected to be implemented before the end of 2021 in the Upper Nile University of Malakal.

1.2. Case Study Background

South Sudan has been an important focus of attention for renewable energy projects in Sub-Saharan Africa for the last few years, besides its long period of war and socio-economic recession. This is mainly due to the huge solar and hydropower potential of the region, as well as the high fuel costs that the local population experience, and the lack of a national electric grid that provides security in the power supply

[2]. As a matter of fact, last year the South Sudanese government announced its plans of building the country's first large scale PV power project, a 20 MW solar PV park with a 35 MWh storage system [2].

However, a big part of the interest in the country's development comes from international stakeholders. The special case of the interest from the government of Japan in South Sudan's peacekeeping and development leads to the launching of this project. As to extend the support they have been providing to the country for many years, an assistance package of $25 million was approved last year in order to assist the local government in projects that would lead to the reconstruction of the country after many years of conflict and socio-economic recession [3]. However, the Japanese government would only assist the country with the corresponding budget through partnership with international organizations, and in the case of this project through the UNDP Country Office in South Sudan.

Consequently, this thesis will focus on a project requested by the South Sudan UNDP CO to be developed within the budget provided by the Japanese Government assistance package. The overall project consists of the rehabilitation of the Upper Nile University of Malakal, one of the main high educational compounds in the area, as it was forced to close its doors during periods of political instability [4].

More specifically, this thesis case study includes the design of the power supply system or mini grid to be provided to the university, a challenging and crucial part of the whole project as for the lack of a reliable electrical grid in Malakal. The development of the corresponding power system will be under the scope of the UNDP OIMT in Copenhagen, which supports UNDP Country Offices around the world with ICT and Green Energy Solutions. More specifically, the OIMT GES team will be the unit responsible for the development of the Upper Nile University Power System, in direct collaboration with the South Sudan UNDP CO. As a matter of fact, the OIMT GES team has previous experience in green energy project development under the assistance programme of the Japanese government in South Sudan. Some examples include the recently commissioned green energy system powering the Rajaf police office [5], near the capital, and the ongoing installation of similar systems located in three different State Revenue Agencies, concretely in Jubek, Aweil and Yambio.

1.3. Objectives

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, will also be used to provide its own solar system, in the scope of the UNDP, specifically the UNDP OIMT 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 analyse, assess and discuss a solution to assure a reliable energy solution to power the load of the Upper Nile University in Malakal, South Sudan. As the village lacks a reliable electrical grid and diesel costs in the country are unstable and expensive [31], 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, with the possibility to include other stakeholders more than the UNDP Country Office, the international donor and the OIMT GES Team in Copenhagen. As a matter of fact, the improvements will be also 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.

1.4. Methodology

This section defines the methodology followed in this thesis, as well as the main tools used, being either software and/or communication techniques among stakeholders.

Both the 7-steps solution methodology and software tools defined in the following lines have been provided by the UNDP OIMT GES Team in Copenhagen, during a six-months internship in the department. Below, the description of each of the steps can be found, followed by the specific process that has guided the development of the thesis.

1.4.1. The 7-Steps Solution for Project Management

In order 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 1.3*** shows an overview of the 7 steps of the process.

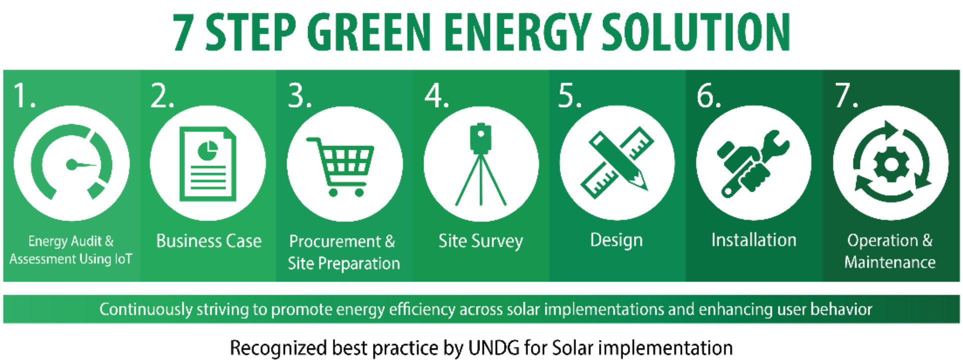

Figure 1.3*. 7-Step Green Energy Solution Process Overview* [1].

A more detailed description of each of the steps can be found below:

Step 1: Energy Audit and Assessment Using IoT.

I. The country office installs the Power Consumption Measuring and Monitoring Device (PCMM) if applicable.
II. The country office is required to complete the Preliminary Site Survey form which will provide information on the physical structure and more details on electrical installations.

Step 2: Business Case.

I. This step serves to provide essential information and data for decision-making. With the information gathered during Self-Assessment through the PCMM and CO schematics, OIMT compiles a load profile of the energy consumption for the respective country office. This enables an analysis resulting in drafting of a business case which presents a potential green energy solution for the country office.

Step 3: Procurement and Site Preparation.

I. The aim of this step is to find a suitable company/institution to carry out the project, which is required to have a local partner in the corresponding country in which the installation will be developed.

II. For this purpose, a Request for Quotation (RfQ) will be shared for all companies or vendors holding a Long-Term Agreement (LTA) with OIMT, in accordance with UNDP rules as applied by the Procurement Service Unit (PSU).
III. Evaluation of bids/proposals will be carried out jointly between OIMT, CO, and PSU.
IV. The vendor whose proposal complies with all the minimum requirements established by OIMT with the minimum price among all the bids will be the one selected to carry out the corresponding project.

Step 4: Site Survey.

I. The selected vendor carries out an on-site survey to exhaustively take into consideration all aspects that can adversely affect the implementation of the project, and information for the final costing of the project including required materials/equipment and time frames.
II. The vendor will act as the implementer, working closely with a focal point at the CO, and OIMT will exercise a technical oversight and project management. Submission of the final Site Survey Report marks the end of this step.

Step 5: Design.

I. The selected vendor drafts the final system design, taking into consideration findings from the site survey in the previous step.
II. As part of the technical oversight, OIMT will endorse the final design before actual installation starts. Submission of the final design and implementation schedule marks the end of this step.

Step 6: Installation.

I. The vendor carries out all the necessary installations, giving regular progress updates to all stakeholders during the process.
II. A six-month system stabilization period is defined, to allow the end user to get acquainted with the system and basic troubleshooting.
III. Among other critical requirements, this step entails end-to-end testing, physical inspection of the installation, user training, and complete documentation of the system.
IV. This step involves carrying out User Acceptance Testing (UAT) in which all parties play a role. A signed checklist confirming full compliance with all requirements marks the end of the step.

Step 7: Operation and Maintenance.

I. Regular bi-annual maintenance (the first 3 years of maintenance is included in the contract), and regular monitoring from UNDP.

The scope of this thesis includes steps 1 and 2 for the Upper Nile University green energy project, starting with the energy consumption data gathering of the compound and ending at the beginning of the procurement phase. Consequently, for the elaboration of this thesis, the specific steps followed can be summarized as the following:

1. Step 1 in the 7-steps solution. Includes data acquisition, by communications with UNDP South

Sudan Country Office (meetings and emails). Data is specifically obtained by collaborating with their staff to fill the Preliminary Site Survey with relevant site information and to obtain the electrical load data of the university.

2. Use of PVSol and HOMER software with the previous data as input, to obtain the optimal solar solution to be implemented in the university within the budget provided.
3. Step 2 in the 7-steps solution. Includes elaborating a Business Case document to show the results to the country office. In the document, several options are analysed with the corresponding economic and environmental results, so that the country office can make an informed decision. A meeting is also held with them as to present the results.
4. Once the final system characteristics have been agreed with the country office, and before moving to step 3 in the 7-steps solution which includes system procurement, a further analysis of the expansion opportunities for the energy system to be implemented in the university have been performed and included in the thesis.
5. Steps 3 to 7 in the 7-steps solution process have not been included in the thesis, as they mainly involve logistics and technical documentation.

Communication and Publicity.

Following the 7-Step Green Energy Solution process, the promotion of the successful project is carried put within the country and globally through the UN network. This process involves highlighting the benefits of the installed system and spread the word about its environmental and social impact. As a matter of fact, this aims to motivate similar installations in other parts of the country.

1.4.2. Data Analysis and System Design Tools

In step 1, electrical consumption data of the corresponding building(s) is gathered. For this purpose, Power Consumption Monitoring and Measurement devices (PCMMs) are usually used. These are IoT sensors which are installed in the electrical systems of the country offices' building(s) to display real-time electricity consumption data. The PCMMs can also be installed in several lines, enabling the possibility to see how the load is distributed among the different devices/rooms. In this way, the high energy consuming devices can be isolated, and energy efficiency measures can be easily suggested, besides the usual data usage for PV system modelling. The dataset obtained with these devices is accessible through an online portal, to which both the GES team and the end user have access, so that the energy consumption of the corresponding building(s) can be monitored by both parties (see ***Figure 1.4***).

Additionally, when it is not possible to install PCMM devices in the CO or building that will host the future system, a load estimation based on the list of appliances can be performed. This usually happens when dealing with buildings that are new or under renovation, or when there is no staff with sufficient technical background to install the PCMMs on site. However, if correctly analysed, the list of electric equipment installed or to be installed in the building(s) can be sufficient to obtain a realistic daily load profile. Furthermore, a Preliminary Site Survey is also sent to be filled up by the country office, as an interactive application. It is composed by a set of questions that will provide the GES team information about space availability for the installation of the PV panels, reliability and rates of the local grid, the presence of a diesel generator on site and its use, fuel price, etc.

***Figure 1.4**. PCMMs for gathering consumption data and data visualization portal* [1].

When all the available load data is well received and analysed by the GES team, a detailed technical, economic, and environmental analysis is performed, and presented as the Business Case document. This document is provided to the CO focal points to allow them to make an informed decision regarding the system they want to have installed. Additionally, until this document is shared, the process is free of cost and non-committal for the country office in consideration.

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, in order 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. HOMER considers parameters such as cost, size, efficiency, and lifetime of the system components, as well as electricity and fuel prices on site. 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 CO_2 emissions. A detailed Risk & Safety Assessment is also performed at the end. All the results are included in the Business Case Document and informed to the country office. The Business Case document of the Upper Nile University project has been presented and accepted by the UNDP South Sudan Country Office.

1.5. Scope and Contents

This thesis is divided into six chapters:

- Chapter 1 – Introduction
- Chapter 2 – Literature Review
- Chapter 3 – Power System Design for the Upper Nile University in South Sudan
- Chapter 4 – Mini Grid Expansion Opportunities in Upper Nile University
- Chapter 5 – Discussion of the results
- Chapter 6 – Conclusions

Chapter 2 includes a literature review about the importance of energy access in the socio-economic development of a country, and consequently, how Distributed Energy Sources (DES) can be crucial in rural countries. A special focus is given to South Sudan, where the project here reported will take place. The literature review also includes an overview of the technology involved in off-grid PV-diesel hybrid mini-grids, and some existing examples in rural areas.

Chapter 3 includes the description of the PV-diesel hybrid power system design for the Upper Nile University in Malakal, South Sudan. The design has been divided into load analysis, area availability for the solar panels with PVSOL and techno-economic analysis with HOMER. The results of the design phase include three options for the country office to choose, with different system characteristics such as levels of PV penetration, fuel usage and CAPEX and OPEX values. The country offices' choice and thus the final system that will be implemented in the university compound is described at the end of the chapter, after a deep analysis and comparison of the results for the three options presented.

Chapter 4 covers a definition of the opportunities for a future system expansion, in case one of the project stakeholders or a third party is willing to invest further in the system. The suggestions here included will aim to increase the renewable energy penetration and furtherly reduce fuel usage of the base system after commissioning and stabilization. It will also contain innovative business model suggestions as to maximize revenues while minimizing costs and involve new key stakeholders, with the possibility to expand the mini grid out of the university compound to the village of Malakal.

Chapter 5 discusses the limits of the approach, the results, boundaries and limitations of the project and potential opportunities to be considered in future thesis and projects.

Additionally, chapter 6 provides a concise conclusion and learning experience of the project and the 6-month internship in UNDP GES Team developed by the student.

While annex A includes the detailed analysis of the electrical load of the university, annex B shows the historical economic data of different projects performed under the scope of the UNDP GES Team used as input in HOMER for the unit costs of the different components of the hybrid-solar mini grid. Finally, annex C shows the project cash flow of the three options presented as possible energy systems for the university.

Chapter 2

Literature Review

This chapter includes a review of the existing literature concerning the role of energy access in the socio-economic development of a country, and the benefits of Distributed Energy Sources in this context, with a special focus in South Sudan. The literature review also includes an overview of the technology involved in off-grid PV-diesel hybrid mini-grids, and some existing examples in rural areas and university compounds.

2.1. Energy Access and Development

Most of us agree in what economic growth refers to, but the term 'development' is not that straightforward in terms of scope and boundaries. As a matter of fact, development is not restricted to economic growth, but based on a deeper structural economic transformation, including the increase in productivity and the implementation of a mature industrial sector, as well as more valuable services. However, this leads to requirements in different capacity levels, as the need of relevant resources (natural, human, or financial), the availability of basic and technical competencies, as well as integration among parties (e.g., information fluxes, links between companies) [7]. In this context, the lack of energy access as a primary resource becomes a huge barrier preventing development, among others such as water scarcity, or limitations due to the low demand as a consequence of the low purchase power of the population. In fact, according to the IEA, over 770 million people in the world did not have any access to electricity in 2019 [48]. The low level of education also becomes an important obstacle to development, linked to the unavailability of local competencies, especially in remote areas where energy access is also a bigger problem. As a matter of fact, the evidence of a direct positive impact of rural electrification in the education level of a country [9] multiplies the impact of this valuable resource to a country's progress. A similar response would be encountered as of health improvements related to electrification of rural hospitals. Additionally, the energy sector can also provide economic growth to a country in a simpler way by generating revenues in the exportation of electricity or fuel.

Related to the previous assumptions, the definition of energy access cannot be limited to domestic consumers as, even if still essential, it does not reflect the real needs of a developing country. The concept of the organization SE4ALL (Sustainable Energy for All) [10] clearly reflects this issue, providing an improvement of the definition of energy access, which complements the previous concept by adding companies, community, and public buildings as required energy consumers. It also considers modern fuels for cooking and heating, access to low-energy consuming technologies, different levels of energy access and the importance of energy quality, quantity, reliability and affordability.

For a better understanding, the impacts of electrification in developing countries could be categorized as experienced in a short or long term. In a shorter term, both direct and indirect impacts can be defined. Direct impacts would include the production of new goods or the upgrade in the productivity of the activities, as clear examples. On the other hand, an example of indirect impacts would be the advantage on the use of new electric equipment in the productivity of a certain activity. Finally, impacts in the long run would include improvements in health or education, or synergies such as a higher time availability to be used in other activities that also promote development [6].

2.2. Barriers to Electrification

There are a few barriers to overcome when considering the improve of electrification rates in countries with less available resources that lead to economic, social, and technical development. One of the first challenges to be considered, despite its apparent lack of significance, is the lack of high-quality data about energy poverty. According to the United Nations Conference on Trade and Development (UNCTAD) [10], in the World Energy Balances of the International Energy Agency (IEA), data about energy access is available for only 19 out of the 47 Least Developed Countries (LDCs) listed by the United Nations (UN), compared to the 46 countries with such data registered in the World Bank. Additionally, mismatches between the different data sources have been noticed [11]. The lack of reliable data about energy access represents a barrier for the identification of problematic areas in which action needs to be prioritized, as well as for the study of the impact in such locations when energy access increases.

Another big challenge preventing the increase of electrification is the big difference between rural and urban areas in LDCs [12]. Indeed, for such countries, contrary to others positioned at later stages of development, an improvement in the electrical grid is translated into an increase in the economic gap between rural and urban areas. This is mainly due to the migration waves from remote areas to the cities lead by a fast and irregular development, especially concerning professionals in sectors such as health and education. However, rural areas are often less appealing for investments in electrification, as for the low density of population, which increases the distribution costs of the electricity while the demand per unit area becomes lower. Consequently, policy improvement and public investment becomes crucial for the proper electrification of LDCs, and as governments of such countries are usually represented by big financial limitations, electrification processes become highly dependent on international cooperation programmes.

2.3. Potential of Distributed Energy Sources in Rural Areas

Distributed Energy Sources (DES) can be defined as decentralized and flexible technologies for energy generation, which are generally located close to the load they serve [12]. They avoid the requirement of electric energy to be transmitted over long distances, which would be the case of more conventional power plants such as coal-fired, gas or large hydro-power plants. Additionally, DES systems usually use renewable energy sources such as solar power, small hydro, wind power, biomass or geothermal. Hybrid systems including renewable sources combined with diesel generators are also very common in remote areas, where the population usually relies on individual off-grid solutions using fuel-based generators for power supply. DES usually rely on mini or micro-grids for energy distribution, which can either be connected to the main grid, in case of a micro-grid, or completely autonomous, as a mini grid. According to the IEA, “for the large rural population that is distant from power grids, mini grids or off-grid systems provide the most viable means of access to electricity" [13]. This is especially true in regions where most of the population live in rural areas and public investments cannot cover a centralized power system. Additionally, in conflictive areas, DES are specially advantageous as the investments would be distributed thorugh small infrastructures among the region and not in big power plants and substations, which would make them less risky [48].

Although off-grid or standalone systems are currently the most popular solution for electrification in rural areas, such installations are usually designed for low power rates, with a focus on domestic applications, mostly to provide lighting and cooking. Their success come mainly from the strong customer focus and scalability of the business models, which make the investments more appealing for both public and private entities. An example of a successful public initiative following this type of business models is the Rural Electrification and Renewable Energy Project in Bangladesh, which can be considered the biggest by now, as by 2015 it had already driven the installation of three million Solar Home Systems (SHS) [14]. From the private sector, successful stories can be heard as well. For solar home systems in Africa, customer-financing business models such as pay-as-you-go (PAYG) have allowed companies as M-Kopa to provide, by 2016, more than 300,000 homes with solar energy, by allowing customers to own their solar system after a few years of paying a monthly fee using their phones.

On the other hand, a mini grid is defined as an "isolated, small-scale distribution network typically operating below 11 kV that provides power to a localized group of customers and produce electricity from small generators, potentially coupled with energy storage systems" (World Bank) [15]. Until a few years ago, mini grids have been usually powered by diesel generators. However, in the last few years, a strong development of diesel mini grids hybridized with renewable generation (or even 100% renewable mini grids) has been taking place, in order to overcome the dependency on fuels as for their price volatility and high running costs. Contrary to standalone systems, mini grids generally serve a community of users, including domestic, public (such as schools or hospitals) and local businesses. However, as they are usually less cost effective and scalable than standalone systems, they strongly rely on local governance plans or some other existing infrastructure that can provide a framework for their development, regulation, and maintenance [15].

2.4. Photovoltaic-Diesel Hybrid Power System Review

PV-diesel hybrid systems are already known as a reliable energy source throughout the world. As a matter of fact, several studies prove their potential for remote areas, where a grid extension or diesel-only mini grids would be too costly. For example, the study in [16] analyses the technical and economic feasibility of a PV-diesel hybrid system powering the remote village of Rawdhat Bin Habbas, in Saudi Arabia, with the use of the HOMER software. The results show that, even without storage, an optimal PV fraction of 27% with respect to the Cost of Energy (CoE) would result in fuel savings of up to 17%. However, the addition of storage highly increases this value, although it increases considerably the CoE.

Another study in [17] performs a techno-economic analyses of the same kind of off-grid systems but with a different approach. In this case, the RETscreen software tool is used to compare systems with different PV solar tracking techniques, as fixed, one-axis and two-axis systems. The results show that even if the energy production is higher for one and two-axis systems, the CoE is the lowest for fixed-axis systems in the case of residential loads in China. Another example in [18] analyses the profitability of a hybrid system to supply the load of a group of ten houses in Argelia, using their own optimization code run in Matlab, in terms of economic performance. The results show that the most profitable system is a combination of diesel, wind, solar PV, and batteries, in front of a system with the same components but diesel or a diesel-only system. However, the results also show that by reducing the wind capacity (down to 1 wind turbine) and by increasing the PV capacity (up to 53 modules) the system becomes gradually more profitable, as for the big solar resource in the area.

As this study focuses as well on an energy system that will power a university compound, some research has been done about already implemented mini grids in similar settings.

According to a study performed by Hafer [19], in which the electricity consumption of the plug loads positioned at Stanford University's campus (California, USA) is analysed, plug loads represent a 32% of the total electricity consumption of the campus, which leaves the remaining 68% as the energy consumption of Heating, Ventilation, Air Conditioning (HVAC) and lighting systems. Additionally, the United States Energy Information Administration (US EIA) [20] states that the share of lighting electricity consumption with respect to the total in the US is similar for commercial buildings of all the sizes, which would be an average of 15%. If this value is applied to the case of Stanford's University, it would mean that more than half of the total electricity consumption of the compound is used for HVAC systems. A different case study focused on the Democritus University of Thrace (Greece) [21] also concludes that the highest share of energy consumption relates to HVAC systems, concretely to heating purposes during winter. Additionally, this study states that it is highly difficult to forecast the load data of the university using historical values, as its operation is deeply flexible, changing from one year to the other. According to the study, the alternative use of other values to estimate energy consumption in the compound, such as environmental parameters and load appliances data, can lead to more accurate results.

Additionally, in the literature, some examples of PV-diesel hybrid mini grids powering high-education compounds in rural areas can be found. To begin with, the technical college in Cambodia, Kampong Cheuteal, is powered by a PV-diesel hybrid mini grid consisting of 120 kWp of PV, a diesel generator of 100 kW and a lead acid battery bank of 1500 Ah [22]. It is important to mention that the power produced by this system represents a rough 1% of the total load of Stanford's university compound, proving the big differences found among university compounds depending on their location and characteristics. It is also worth to study the case of four Nigerian universities which are currently in the process of becoming energetically self-sufficient with off-grid PV-diesel hybrid mini grids. The success of these projects will be crucial for the future of other Nigerian educational settings, as the government has established a rural electrification initiative to power 37 universities and seven teaching hospitals, by the Energizing

Education Program (EEP), with the financial help of the World Bank [23].

As the cases above, the upcoming electrification of the Upper Nile University will set an example for similar programmes planning to bring green energy solutions to power community settlements in poorly electrified areas.

2.5. Technical Overview of Off-Grid Photovoltaic-Diesel Hybrid Power Systems

Diesel generators are currently the most popular solution for off-grid systems, which makes them popular in low-electrified and/or remote areas. This is due to the low investment they require, their switch on-off flexibility, and their relatively high shaft efficiency, when operating at full-load mode if properly sized. However, their performance decreases drastically in case of load variations up to 30%. As to overcome this issue, a smaller generator can be used instead in periods of lower loads as in a dual generator system. Nevertheless, this practice, as usually manually executed, can be time consuming and even problematic. Other disadvantages of electric systems run by diesel generators include high operating costs, due to the high fuel consumption, and high maintenance costs as well, as these depend on the generator operating hours and not the load delivered, which makes the level of required maintenance strongly dependent on the load response and proper design of the system. Indeed, most of the genset systems located in remote villages are highly oversized, and thus maintenance costs become a big issue to overcome. If, additionally, the operating costs deeply depend on fuel costs, which are usually high and volatile in remote areas, due to added transportation costs, these systems become hard to maintain in such areas. Finally, another disadvantage on the use of diesel generators would come from the high CO_2 emissions generated by the consumption of the fuel, which would affect all of us in a more global perspective [24][25].

Contrary to the previous, photovoltaic (PV) solar energy systems are highly advantageous in terms of low operating and maintenance costs, as they do not depend in fuel prices and availability, especially in areas with high solar radiation. However, if a high reliability and autonomy is desired, purely PV systems would require a high CAPEX, as even if battery prices are deeply decreasing in the last few years, they are still expensive for such strong requirements. Consequently, PV-diesel hybrid technologies are worth of consideration in off-grid applications for remote areas. Even with higher investment requirements, such systems become less dependent on fuel costs and availability, being cheaper to operate and maintain while preserving their reliability during cloudy days. Consequently, they represent a more sustainable energy solution, with a big potential of increasing energy availability and security in less electrified areas while reducing CO_2 emissions globally, closing the gap between resource availability and socio-economic development in such regions [26].

2.5.1. Components in Off-Grid PV-Diesel Hybrid Power Systems

Despite the clear advantages of PV-diesel hybrid mini grids, their complexity is obviously higher than simple diesel-powered grids. Thus, several components other than PV solar panels and diesel generators may be needed, especially when adding a battery bank in the system. The use of batteries in hybrid mini grids is highly advantageous although not mandatory, and it requires the addition of battery charging control systems.

Battery charge controllers regulate the voltage and current levels from the PV system to the battery, as to protect the battery bank from under or overcharging. When a Maximum Power Point Tracking (MPPT) device is included, an additional DC/DC converter between the PV array and the battery bank guarantees the optimal voltage and current levels in the PV side to maximize the solar energy input, while keeping the adequate operational levels of the battery.

In most of the cases, PV-diesel hybrid mini grids power AC loads. Consequently, DC/AC converters, or inverters, are needed between the PV array and the loads. These can be standalone or grid-connected, although only the first ones will be considered for off-grid applications. Standalone inverters can be categorized as simple or bidirectional, which suitability will depend on the system configuration, that can be either DC or AC-coupled in the case of off-grid installations. AC or DC coupling refers to the way solar panels are coupled or linked to an energy storage or battery system. While DC-coupled systems are usually used to power smaller loads up to 5 kW, AC-coupled systems are cheaper and more efficient when used to power larger loads [27]. When a DC-coupled configuration is considered (see ***Figure 2.1*** left), simple inverters can be used, as for the unidirectional power flow conversion from DC to AC. However, in AC-coupled systems, bidirectional inverters will be required, as the power flow will go both ways, from the AC bus to the battery bank and vice versa. In this case, an additional inverter will connect the PV array to the AC bus (see ***Figure 2.1*** right). Inverters can also have additional functionalities, acting as control systems of other components, for example as a battery charge controller.

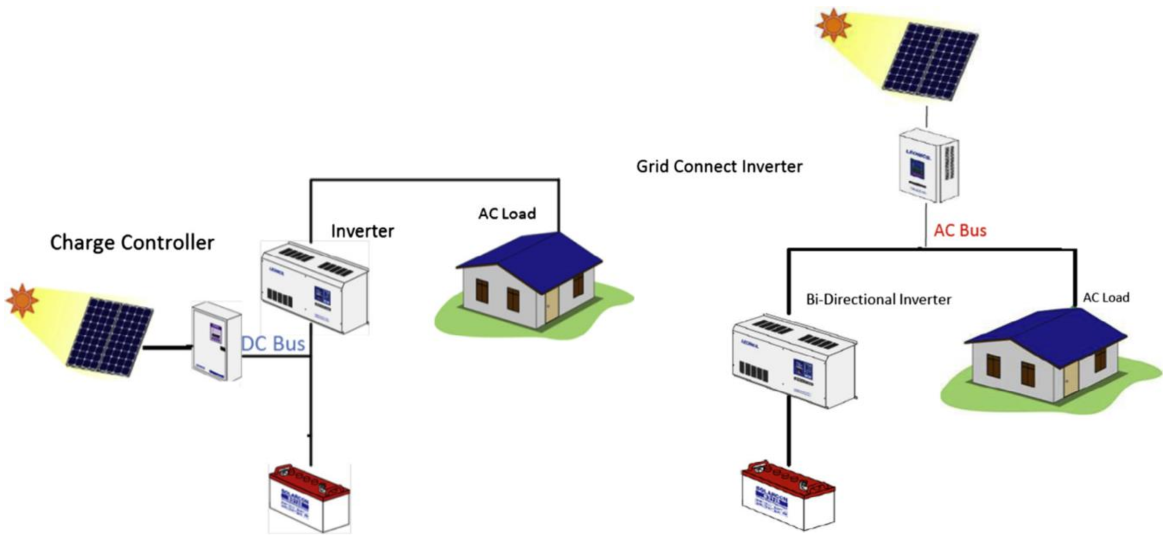

***Figure 2.1**. DC-coupled (left) and AC-coupled (right) PV and battery systems* [27].

2.5.2. Power Management and Control in Off-Grid PV-Diesel Hybrid Power Systems

The level of control and power management of a PV-diesel hybrid mini grid will depend, among others, on the renewable penetration, or fraction of PV installed capacity with respect to the load. In systems with a low renewable penetration (less than 20%), the genset or set of gensets will operate full time as the main power supply, and the PV power input will reduce the fuel usage. Accordingly, the genset system will be in charge of setting the voltage and frequency levels of the grid, while the other sources will synchronize with it, and thus no specialized control system will be required.

For systems with low-to-medium renewable penetration (20-40%), a similar operation could lead to unacceptable operating points of the generator, especially in occasions when the load decreases while the irradiation level is high. Indeed, if the generator power input is reduced too much due to high solar power inputs, the voltage and frequency levels of the grid are in risk, as well as the efficiency of the generator set. As to avoid this to occur, active control would be required as to keep those parameters into specific limits, even if it means reducing the solar power feed-in during certain time periods, affecting the economic model of the system.

When the renewable penetration is even higher, in a medium-to-high level (40-65%), energy storage systems are required as to guarantee the grid stability. Additionally, it becomes highly recommended to provide the system with several gensets of different sizes, operated in a continuous or intermittent basis, as to guarantee a minimum efficiency on their performance when load fluctuations and PV power inputs are higher. This can also help with the preservation of the system stability and with the protection of a minimum diesel load while the performance of the each of the gensets is guaranteed. As the previous case, a control system is required, but this time with the additional function to determine which of the genset(s) will be operating at a given time and at which rate, as well as the maximum power the inverters can supply from the PV arrays for the system to keep stable.

Finally, mini grids with high renewable penetration (65-100%), have even harder requirements of minimum energy storage capacity and active control level. ***Table 2.1*** below summarizes the control minimum requirements with respect to the renewable penetration of PV-diesel hybrid mini grids without storage.

Table 2.1. *Mini grid control system requirements with respect to PV penetration* [28].

Renewable Penetration Level	Minimum Control Requirements	Characteristics
Low Penetration (< 20%)	No specific control	Genset(s) run at full time to guarantee frequency and voltage levels of the mini grid while PV energy reduces fuel consumption
Medium Penetration (20 – 40%)	Simple active control as to keep frequency and voltage of the mini grid into specific limits when PV input is high compared to the load	Secondary genset units are recommended
High Penetration (40 – 100%)	Energy storage is required, as well as sophisticated active control systems, to maintain the frequency and voltage of the mini grid into acceptable levels	Primary and backup generators to cover different levels of PV feed-in

The Grid Forming Architecture can be defined as the methodology for setting the voltage and frequency of the grid. This function will be attributed to the generators on genset dominated systems, as required in low renewable penetration systems (see ***Table 2.1***). In single switched master architectures, the grid forming control is switched between gensets and bidirectional inverters, typical in AC coupled system configurations. However, in this case a minimum energy storage capacity is required. Finally, in a multi-master inverter-dominated architecture, any element with an inverter can cooperate to have control of the grid forming, including the PV source, the battery bank and even the genset in some cases.

Finally, the Supervisory Control in a PV-diesel hybrid mini-grid is in charge of allocating the load demand among the different energy sources, with the objective of maximizing the economic benefits of the system while guaranteeing a safe operation of all the components. There are different supervisory control logic possibilities, depending on the priorities and characteristics of the system. In a scheduled genset system operational mode, the PV is the chosen source when available, and the choice on which of the gensets will operate at a certain time depends on a predefined time schedule. For systems with storage, a common supervisory control logic would be a State of Charge (SOC)-based diesel operation, where the genset operates when the SOC of the battery crosses a predefined lower boundary. Other supervisory strategies include the load-based diesel operation, in which the genset operates only as a backup source, turning on when the load exceeds both the PV and the battery capacities. Finally, in the cycle charging operation strategy, the generator always operates at its maximum load, while the excess of energy produced is stored in the battery bank [29].

Chapter 3

Power System Design for the Upper Nile University in South Sudan

This chapter starts with the identification of opportunities of electrification in South Sudan. Next, once the electrical load of the compound is analysed, the area availability for solar panels is studied with PVSOL. Finally, a techno-economic analysis of the optimal system with HOMER can be found, which leads to a final discussion on the best options to electrify the compound.

3.1. Opportunities of Electrification in South Sudan

The Republic of South Sudan, with Juba as its capital, is currently the world's newest internationally recognized country, which independence was declared on July 9, 2011. South Sudan is also one of Africa's most diverse country, with over 60 different major ethnic groups [30]. However, constant conflict in the country has been the main reason for it being listed as one of the world's Least Developed Countries and ranked the most fragile country for many years. Despite its area is bigger than the Iberian Peninsula and its population goes up to 10 million, in 2017 the country only had approximately 35 MW of installed capacity of electricity distributed across the country [31], without an interconnected transmission grid, and only 25.4% of the population had access to electricity [33]. Instead of a national electricity grid, the country accounts for six distributed networks, three being commercial center networks (Juba, Malakal and Wau) and three being rural mini grids (Yei, Kapoeta, Maridi), all powered by oil-fired thermal plants. The largest is the one in Juba, with only 8000 customers. However, the country does count with big plans for future hydropower plants in the Nile river, as the Gran Fula which is planned to have 890 to 1080 MW. Other plans include electricity grid interconnections with Uganda, Sudan and Ethiopia. All this information was facilitated by the government in 2017 and no further official data regarding the development of such plans have been obtained [31]. Although the country is recognized as a big oil producer, being its oil reserves estimated as 1,083.71 billion barrels by 2015 [33], several sporadic oil crises have hit the region since 2011. The high oil dependency of the South Sudanese population for energy consumption has led to painful socio-economic consequences during the periods of crisis.

To begin with, one of the main factors causing such events has been the lack of infrastructure. Despite South Sudan inherited 75% of the oil producing blocks when it seceded from Sudan, most of the downstream facilities as refineries, pipelines and depots are in the northern country, which makes the South Sudan a big exporter of crude oil but also a big importer of usable fuel. As the storage capacity of the new country became approximately enough to cover not even one month of the total demand, any delays in imported fuel end up as a brutal fuel scarcity throughout the area. The infrastructure distribution of Sudan before the independence of the South can be seen in ***Figure 3.1***, which clearly reflects the drawbacks of the division as for the oil sector in South Sudan, which experiments a big loss in downstream infrastructures such as refineries and pipelines.

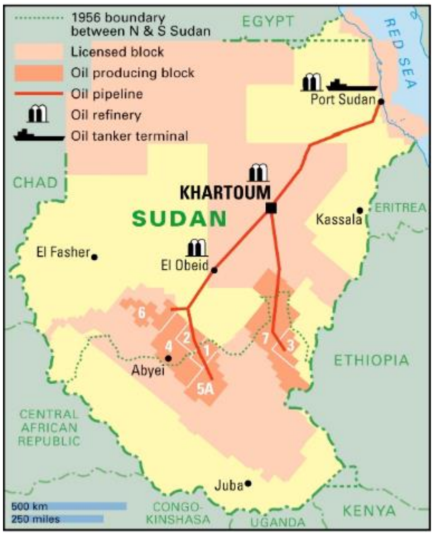

***Figure 3.1**. Oil facilities' location in Sudan before the independence of the South* [33].

Without proper storage facilities, South Sudan mainly depends on imports from Kenya, as the main fuel supplier to the whole region, which does not always deliver as predicted.

Therefore, it is not a surprise how massive the impacts of the fuel crises are, both in an economic and social point of view. All sectors impacted by the high fuel prices become affected, especially the most crucial ones such as transportation, water, electricity, and health. All goods that require energy to be produced or transported increase in price, and thus the purchase power of citizens becomes dramatically reduced, leading to hunger and sickness throughout the population, due to the low availability of affordable food or the lack of sanitized water, among others [34] [35].

As seen above, the South Sudanese population currently face high and volatile energy prices, due to a fuel dependency for socio-economic development as for the absence of a national electricity grid. In the positive side, this can be translated as a big opportunity for electrification led by DES, with the development of off-grid systems or mini grids, based or partially based on renewable energy sources. Other impacts such as the reduction of CO_2 emissions in South Sudan would become beneficial side-effects out of this movement. As a matter of fact, according to Farhani [36], whose study analyses data of 12 Middle East and Northern Africa countries between 1975 and 2008, panel cointegration techniques show that, in the long run, the variables CO_2 emissions, economic growth and renewable energy consumption have a clear correlation. However, the case of South Sudan does not only represent opportunities for investment in DES systems involving renewable energies. Several barriers, as low public financial capacity and low purchase power in the demand-side can affect the rentability of such investments. Additionally, the big conflict uncertainty still very present in the country would impact in a negative way the current energy infrastructure-building strategies as well. Nevertheless, according to a Patankar et al. study [37], a high probability of conflict in a country affects big, centralized power plants the most, as in the contrary of distributed systems, the probability and level of damage would be higher for more valuable assets located in a single place, other than less valuable assets distributed throughout the country.

3.2. Upper Nile University Electrical Load Analysis

The Upper Nile University was founded in 1991 and is one of the five public universities in South Sudan. The total area of the compound is around 6.4 ha. Due to the civil war in the country before the independence in 2011, some of the faculties were relocated to Khartoum, Sudan, for safety. As stated above, the Upper Nile University has been under renovation since the government decided to reopen it.

As for the undergoing works, no electrical equipment has been installed yet in the university. Consequently, the PCMM devices could not be installed to monitor the load, so the available data has been collected from a table of electrical appliances to be placed in the compound. The information available from the appliances list includes the number of equipment units per building in the compound, the nominal power of each of the appliances, the hours of use per day and the load pattern, among others. The appliances list with all the information available can be found summarized in ***Table 3.1*** and in ***Table 3.2***, where more specifications can be found.

Table 3.1*. Appliances list to be installed in the Upper Nile University per building.*

Category	Electrical Equipment	VC[1] Office	Lecturers Office	Dean Office	Lecture Halls	Library	Student Rooms	Total Units
Lighting System	Internal	46	29	60	150	70	70	425
	External	20	15	12	65	20	30	162
HVAC System	Fans	40	40	30	200	25	30	365
	ACs	13	0	0	0	0	0	13
Plug Loads	Laptops	9	9	0	0	0	0	18
	Desktop Computers	45	40	20	0	10	0	115
	MFP Printers	2	1	2	0	1	0	6
	Phone Chargers	35	35	50	50	50	50	270
	Projectors (LCD)	9	9	1	9	2	0	30
	VSAT/ Switches	1	1	0	0	0	0	2

[1] VC stands for Vice-Chancellor.

Table 3.2. *Upper Nile University electrical load information.*

Category	Electrical Equipment	Nominal Power (W)	Operating Time (Hours/day)	Load pattern
Lighting System	Internal	36	8	Working Time
	External	36	16	Night Time
HVAC System	Fans	80	8	Working Time
	ACs	1085	8	Working Time
Plug Loads	Laptops	80	8	Working Time
	Desktop Computers	200	8	Working Time
	MFP Printers	500	2	Working Time
	Phone Chargers	10	2	Working Time
	Projectors (LCD)	350	2	Working Time
	VSAT/ Switches	750	24	Base Load

The main objective of the load data analysis is to obtain a daily energy consumption profile. However, with the data available, only absolute daily values can be obtained. Consequently, variability patterns depending on the load category have been established, as to create a realistic daily load profile. The load curves obtained as a result of the analysis can be found in ***Figure 3.2*** and ***Figure 3.3*** for both weekdays and weekends, respectively. The calculations performed to obtain both figures will be further detailed in this section, categorized by lighting system, HVAC system and plug loads. Additionally, ***Table 3.3*** shows the main values obtained from the calculations. The corresponding load curves and values found in ***Table 3.3*** will be directly used later to simulate the optimal size of the Upper Nile University power system.

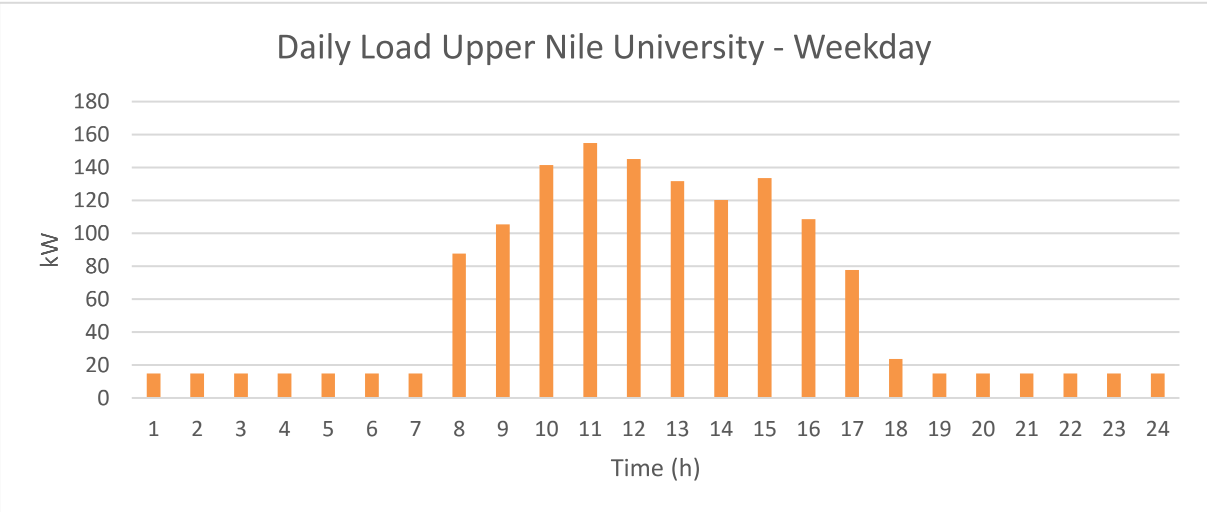

Figure 3.2*. Upper Nile University daily load in working days.*

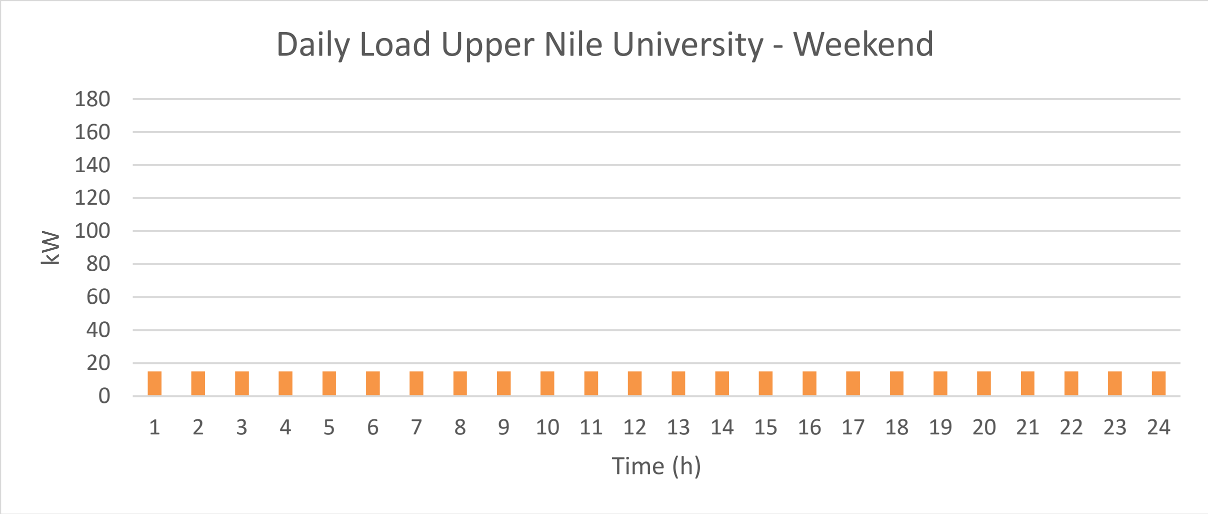

***Figure 3.3**. Upper Nile University daily load in non-working days.*

***Table 3.3**. 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

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.

Finally, the full set of calculations performed during the load analysis can be found in Annex A of the thesis.

3.2.1. Lighting System

For the data validation of the lighting system, the final share of total electricity consumption from the lights has been compared to relevant literature. According to the EIA [32], the share of total site electricity in commercial sites consumed for lighting is similar across buildings of different sizes, which would be approximately a 15% of the total consumption. The value obtained for the Upper Nile University lighting system corresponds to an average consumption of 164.09 kWh/day, a 15.47% of the total, very similar to the one expected from the literature. Nevertheless, although the compound is not considered a commercial site, most of the energy use comes from office buildings, and thus its consumption behaviour would be similar.

Additionally, a variability pattern has been used to create the daily load profile, following the guidelines seen in ***Table 3.4***. The load multiplier considers the sunlight and user behaviour and multiplies the load by a number between 0 and 1 accordingly. For example, from 11h to 17h during a workday, a considered building in the compound would be occupied, but the sunlight would be maximum, so the internal lighting load would be multiplied by 0.5 as an approximation (equivalent to only half of the units switched on). On the other hand, the external lights are switched on when the compound is unoccupied during the night, for security purposes.

Table 3.4. *Variability guidelines for lighting system in the Upper Nile University.*

		Load Multiplier						
Location	**Operating Time**	**19h to 7h**	**8h**	**9h**	**10h**	**11h to 17h**	**18h**	**Final Energy Consumption (kWh/day)**
Internal lighting	Working hours	0	0.8	0.7	0.6	0.5	0.8	69.9
External lighting	Night	1	0	0	0	0	0	94.2
						TOTAL		**164.09**

3.2.2. HVAC System

The HVAC system proposed for the Upper Nile University can be considered as simple and minimal. It is composed by a total of 13 Air Conditioning (AC) split units (12 000 BTU/h of cooling capacity each) and 365 ceiling fans. However, the AC units will only be placed in the Vice-Chancellor's office building and technical rooms, being the last in charge of maintaining the electronic equipment such as servers at a safe temperature.

For the load estimation of the AC units, the values of an LG Air Conditioning model similar to the one used in the UNDP Country Office in South Sudan is considered, as the model to be placed in the university will probably be similar. From the specifications of the model [38], the Energy Efficiency Ratio (EER) value is extracted. To obtain the power consumption of one AC unit, the cooling capacity of 12 000 BTU/h is divided by the obtained EER value of 11.06 BTU/h·W, which results in 1.085 kW of power consumption per AC. The power consumption per fan unit is directly obtained from the appliances list.

Finally, as to obtain the daily load profile of both the AC units and the fans, an intense variability pattern is used, which results in a random load multiplier with a value between 0.8 and 1 in each hour, for a total of 8 hours per day. The results of the total HVAC energy consumption can be seen in ***Table 3.5***. As it can be observed in the table, during the weekends only the ACs in the technical rooms will be working.

Table 3.5. *HVAC systems energy consumption in the Upper Nile University.*

	Energy Consumption in Weekdays	Energy Consumption in Weekends	Unit
Fans	240.0	0	kWh/day
ACs	114.2	26.0	kWh/day

3.2.3. Plug Loads

Finally, the plug loads of the Upper Nile University compound consist mainly on the set of electronic equipment (desktops, laptops, printers, etc.) located in the lecture rooms or offices to be used either by the students or staff. In this case, a random multiplier between 0.6 and 1 has been used to consider variability in equipment usage, estimated to be from 8h to 18h in weekdays. For the appliances with less working hours, such as printers, phone chargers and projectors, the variability multiplier has been set as a value in between 0.2 and 0.5 for the same period.

Additionally, an extra load has been added in order to consider the server loads of the compound. As no information has been received for this type of load, an extra 20% has been added to the total plug load (not including the accommodation building, due to its lack of electronic equipment) to consider the servers. This value comes from the consulted literature about weight of different loads in university compounds, taken as the main driver the example of the Stanford University, where a 22% of the total plug load comes from the servers' energy use [21].

No additional information has been received from the UNDP Country Office regarding the criticality of each of the loads. However, it would be highly recommended to separate those loads considered more critical, which could include the lights, fans and the VSAT for communication purposes.

3.3. Area Availability Analysis with PVSOL

As previously mentioned in the methodology description, one of the main software used in the 7-Step Solution process is PV*SOL [39]. This IT tool is used to analyse 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, taking into account 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, and thus this analysis allows the OIMT GES team to identify how restrictive this can be for each case analysed. In those cases where the roof space is limited, due to events such as shading from near objects or an inconvenient roof tilt and availability, several solutions can be considered. For example, the use of a built-in structure that allows to place the panels above parking areas provides other advantages such as additional shading for vehicles. In other cases, the trimming of nearby trees preventing a proper use of the panels can be suggested as well.

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. The choice of the buildings comes from the country office, the UNDP Country Office of South Sudan. As a matter of fact, when evaluating the options for green energy solution implementation in the compound, the possibility of powering each of the corresponding offices individually will also be considered. However, if either the VC Office or the Lecturers' Office is powered separately from the rest of the compound, the remaining buildings will be 100% powered by diesel generators, and thus other options will be considered too, where the PV panels are still placed in either one of these two buildings, but the load is shared with the rest of the compound.

***Figure 3.4**. Aerial view of Upper Nile University compound.*

In order to run the PVSOL simulations, the main parameters to be inputted are aerial pictures of the corresponding structures, the dimensions of the two buildings and other information as the tilt of the roof, all extracted from the preliminary site survey filled by the country office. Regarding the geometry of the buildings, both are rectangular-shaped and have simple 15º-tilt gable roofs, oriented approximately towards East/West for the case of the Lecturers' office, and towards North/South for the VC's office. While ***Figure 3.4*** shows an aerial visualization of the compound (GPS coordinates: 9°32'57.6"N 31°39'04.0"E), a more comprehensive idea of the structure of both buildings can be extracted from ***Figure 3.5***.

Figure 3.5*.VC Building (left) and the Lecturers' Building (right).*

Table 3.6 shows the main results obtained from both PVSOL simulations. Additionally, ***Figure 3.6*** shows the shading analysis performed by the software.

Table 3.6*. PVSOL simulation results for the Upper Nile University project.*

	VC Building		**Lecturers' Building**	
	Southern Facade	**Northern Facade**	**Eastern Facade**	**Western Facade**
Roof Orientation	161° South	340° North	74° East	254° West
Roof Inclination	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	

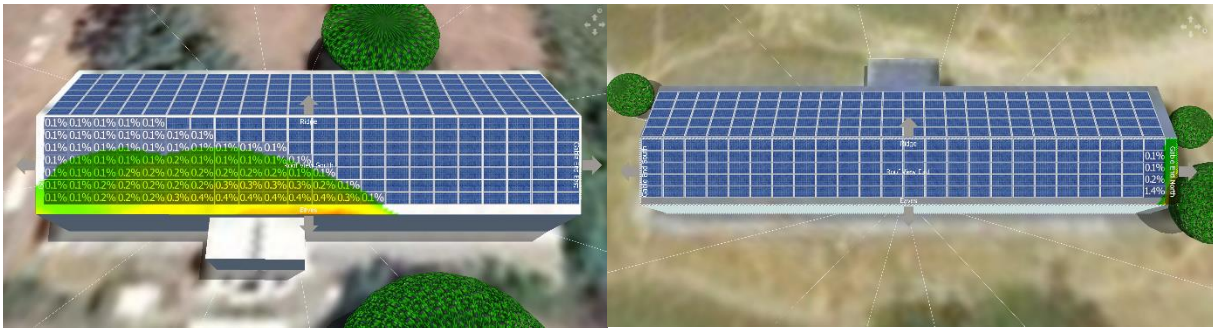

Figure 3.6*. PVSOL shading analysis of VC Building Southern Façade (left) and Lecturers' Building Eastern Façade (right).*

In conclusion, a total value of 98.56 kWp of PV power can be placed in the VC building's roof, with a total available area of 597.6 m2 to place the PV panels. Parallelly, 76.8 kWp of PV power can be placed on the 465.7 m2 area available in the roof of the Lecturers' office building. As it can be observed in ***Figure 3.7***, a roof-integrated PV panel structure has been chosen for both buildings to cut costs in mounting structures, as the optimal tilt for PV panels of the country is almost horizontal [40], being the 15º of the roof towards different orientations good enough to obtain a high solar power production.

Figure 3.7.*3D PV system representation of the VC Building (left) and the Lecturers' Building (right).*

3.4. Techno-economic Analysis with HOMER

As previously mentioned in the methodology description, one of the main software used in the 7-Step Solution process is HOMER Pro [41]. HOMER is a simulation model that simulates a viable system for all possible combination of the equipment chosen to be considered. In this case, these components include solar PV, batteries, and diesel generator capacity. HOMER simulates the operation of a hybrid mini grid for an entire year, in time steps from one minute to one hour. This allows to identify the optimal energy system given a certain load, climate conditions and components selected, and simulations can be later modified to be adjusted to a certain budget.

HOMER components can be categorized in the following way:

I. Energy Generation Components: including Fuel Generators, PV, Wind Turbines, Hydropower and Electrical Grid, among others.
II. Energy Storage Components: including Electrochemical Batteries (Li-Ion, Lead Acid, etc.), Pumped Hydro and Flywheel, among others.
III. System Converter: AC to DC and/or vice versa.
IV. Microgrid Controller: different set ups available such as Cycle Charging, Load Following, Generator Orders or Own-Programmed with Matlab, among others.

Figure 3.8 shows how the selected components for a determined HOMER simulation are visualized in the dashboard of the software.

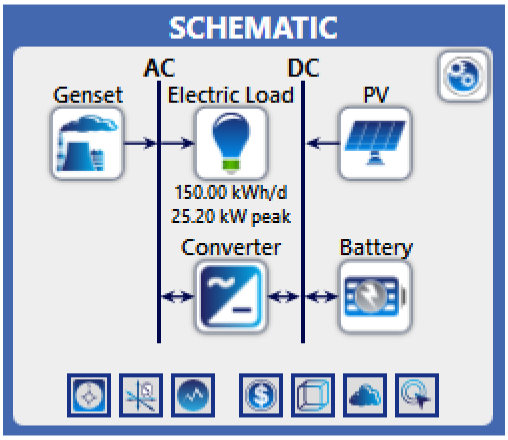

Figure 3.8.*HOMER schematic of components of a simulation.*

Some examples of input data required for running a HOMER simulation are costs per unit for the different components ($/kW or $/kWh), grid characteristics and costs (for grid-connected systems), daily and seasonal load curves and data variability (kWh/h), load peak value (kW), system control logic, and environmental data, such as solar radiation and temperature in the corresponding system location, among others.

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 Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), among others. All the results are shown in terms of system configuration and sorted by economic performance along the projects' lifetime (lowest NPC) of each of the configurations. As a matter of fact, HOMER will calculate the optimal system for each of the possible configurations, and then show the comparison among configurations. However, the user can also see the performance of each possible system inside one configuration if desired, but the usual analysis involves the user directly comparing among different configurations. ***Figure 3.9*** shows an example of how the results comparison is visualized in HOMER, although some secondary items have been disregarded in the figure.

Architecture						Cost			
PV (kW)	Small Genset (kW)	Primary Genset (kW)	1kWh LI	Inverter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
328	25.0	230	275	167	LF	$1.73M	$0.409	$83,381	$762,934
153	25.0	230		88.7	LF	$2.61M	$0.616	$196,603	$328,858
	25.0	230			LF	$3.00M	$0.709	$252,369	$75,000
	25.0	230	7	1.58	LF	$3.00M	$0.710	$252,317	$79,379
123		230	84	88.3	LF	$5.39M	$1.28	$437,689	$324,050
139		230		82.8	LF	$5.41M	$1.28	$441,680	$298,931
		230	583	71.3	LF	$5.61M	$1.33	$448,940	$412,026
		230			LF	$5.72M	$1.35	$487,889	$67,500

Figure 3.9.*HOMER table of optimal results for a specific simulation.*

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. The results of each of the options will be presented in this section and included in the Business Case to be presented to the country office, including advantages and drawbacks involved in each of the alternatives. Finally, the country office, South Sudan UNDP Country Office, will choose one of the options according to its needs and expectations, and the selected system will be the base for the future system design that the selected vendor will conclude. Consequently, the output of the HOMER simulations is a guideline for the CO so that they can understand better the available options in terms of system characteristics according to the corresponding budget, but the final design will not be performed by the OIMT GES team, but by the future specialized company in charge of the installation and commissioning of the power system.

The characteristics of the three options that will be presented to the country office have been summarized in ***Table 3.7***.

Table 3.7. *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	13% of total load	100% of total load
	The remaining load share of the compound will not be in the scope of OIMT	The remaining load share of the compound will not be in the scope of OIMT	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)

The available budget of this project is restricted to approximately US$ 100,000 for the solar PV system with its components (batteries, control system, installation, etc), which corresponds to options 1 and 2. However, a different budget of US$ 101,000 is allocated to the backup generator set needed to provide the system with sufficient power when solar power is not enough. As option 3 will provide a whole integrated system including PV system and generators, a sum of both values can be considered as the budget for this option. This last option is possible to consider because it does not include batteries, which would be the most expensive component of options 1 and 2. As previously mentioned, the three options will be simulated in HOMER to obtain the optimal size of the components in terms of techno-economic performance, thus the optimal system would be the one that maximizes the renewable fraction while making sense in an engineering point of view being adjusted to the budget. The results will be presented to the country office to choose among the options.

3.4.1. HOMER Inputs

In this section, a more detailed definition of the common data used to run the HOMER simulations for the three options will be defined. This will include Irradiance and Temperature Data, Unit Costs of Components and, finally, Other Specifications worth considering. The load data entered in the software will be different for each of the options, and thus it will be described in the following section.

3.4.1.1. Irradiance and Temperature Data

The first important input in HOMER is the irradiance and temperature data, obtained directly from the software, which uses the NASA Surface meteorology and Solar Energy database to obtain the relevant parameters [41]. The values are obtained in an annual basis for the projects' location (Malakal, South Sudan) and are especially important for the performance analysis of the solar PV generation. ***Figure 3.10*** shows the monthly average solar global horizontal irradiance data in Malakal, while in ***Figure 3.11*** the monthly average temperature data can be found.

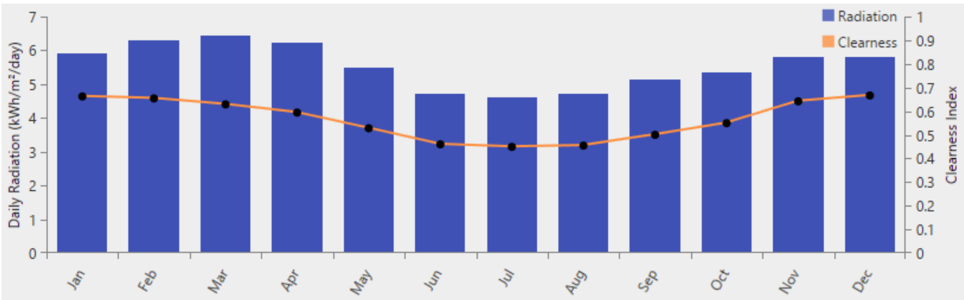

Figure 3.10*.Malakal Monthly Average Solar Global Horizontal Irradiance [39].*

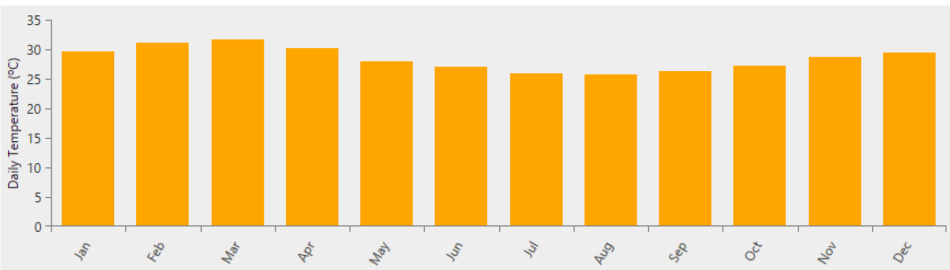

Figure 3.11*.Malakal Monthly Average Temperature Data [39].*

As observed in both figures, from June to August both the solar irradiance and temperature slightly decrease in Malakal, corresponding to the rainy season of the region. This can be confirmed by the decrease in the clearness index, which is a factor that expresses the amount of sky clearness (absence of clouds) at a given time. However, this index is not important for the calculation of solar PV energy production, it is mainly used for solar thermal, which is not applicable in this case.

Both datasets concerning environmental data on site are extremely important to calculate both PV power production, from irradiance data, and PV module efficiency, from temperature data.

3.4.1.2. Unit Costs of Components

The cost per unit of the components of the power systems will be similar for the three options considered, with small changes for the third system or mini grid. These costs will be entered in HOMER as stated in ***Table 3.8*** below:

Table 3.8*. Unit Costs as input in HOMER simulations.*

Cost Definition	Option 1	Option 2	Option 3
PV Unit Cost (US$/kWp)	410	410	377
Batteries Unit Cost (US$/kWh)	546	546	-
Inverter Unit Cost (US$/kW)	351	351	439
Genset Unit Cost (US$/kW)	250	250	250
Fuel Price (US$/L)	1.92	1.92	1.92

The fuel price value will be taken from the Preliminary Site Survey, filled by the country office in South Sudan. However, the fuel costs in the region are not only high but also extremely volatile (see section 3.1), so an average value of 1.92 US$/L will be considered, in agreement with the customer.

The diesel generator cost will also be taken from the information provided by the CO. As they considered a preliminary budget of US$61,000 for a 300-kW genset, a safe assumption of 250 US$/kW will be used in HOMER.

The other unit cost values will be calculated according to the OIMT Green Energy Project Cost database, including real costs of previous systems implemented by the GES team. More information on the content of this database can be found in Annex B. The unit cost of the different components will be the average values of final quotations of similar projects, in terms of location, PV and battery size and year of implementation. Most recent projects will logically be prioritized, as to consider the market price trends of the different components. ***Figure 3.12*** below graphically shows the comparison of the projects in the database considered for the Upper Nile University first and second options, which components will be considered to have the same price as for load similarity. In ***Figure 3.13***, the same comparison is shown but for option 3, characterized by a bigger load, as it includes the whole university compound, and by the lack of batteries to be included in the system. The letters in the x axis represent each of the projects, where the first three letters represent the country of the projects (SSD would be South Sudan, NGR as Nigeria, and GHA as Ghana).

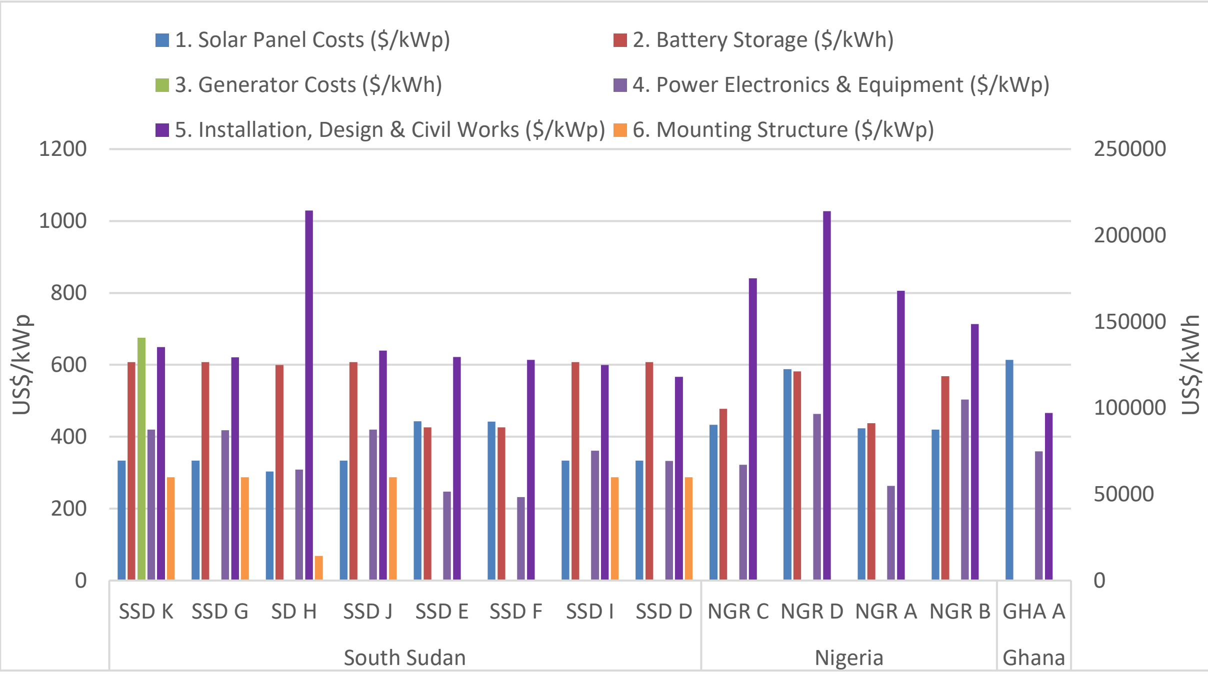

Figure 3.12*.OIMT Project Database Analysis for options 1and 2 in the Upper Nile University project.*

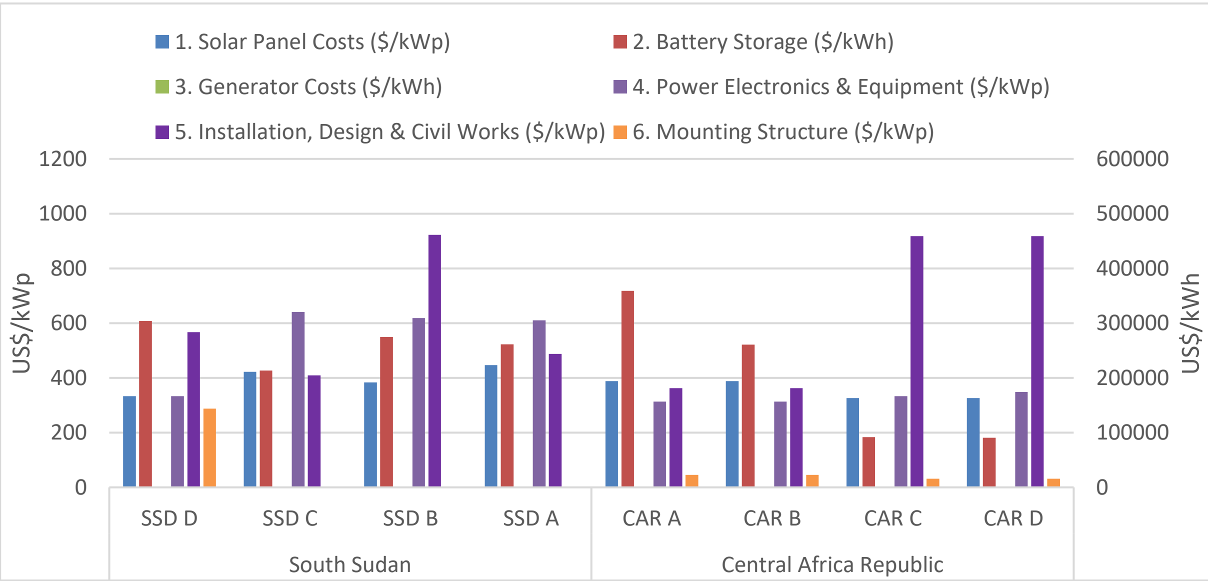

Figure 3.13*.OIMT Project Database Analysis for option 3 in the Upper Nile University project.*

From the same database, fixed costs applied to the system such as installation or civil works can also be extracted. However, these will not be included in HOMER simulations, but will be added to the final CAPEX of the project at a later stage.

3.4.1.3. Other Specifications

Finally, other important parameters set in the software include lifetime of the different components simulated and lifetime of the project. For the PV equipment, a value of 20 years has been considered, typically conservative as it usually lays closer to the 25 years. Additionally, 10 and 15 years have been set for the battery bank and converter, respectively. For the diesel generator, the lifetime will depend on its operating hours, which will be set to a maximum of 15,000 hours as the default value in the software. All these values have been obtained from similar recent projects carried out by the GES team. To add simplicity to the financial evaluation of the project, a cash flow of 20 years has been set in HOMER, as it involves a single battery bank and converter replacement, as well as it corresponds to the whole lifetime of the PV system. The replacement costs of the selected components have been considered as the same as their purchase cost.

3.4.2. HOMER Results for each of the Scenarios

This section will include the specific characteristics of each of the options simulated in HOMER, including the load entered for the different simulations, as well as the results obtained in system configuration and sizing, including main technical and economic parameters for each of the options. As the final system for each of the options will be the one adjusted to the budget with a maximum renewable capacity that makes sense in an engineering point of view, a lot of attention will be given to the hourly system response for the worst-case scenario, being this during the rainy season, when the solar production is minimum. Thus, the graphs focusing on hourly PV production compared to the load, the generator production and the battery state of charge will be closely examined. Additionally, as it will be seen in the deeper analysis of each of the options, the generator has been set with the possibility to charge the batteries in the simulations. This can be useful as it can prevent the noise of the generator running all night.

3.4.2.1. Base Case: Diesel Generator Sized as Peak Load

The three options considered for the hybrid system in the university, and simulated in HOMER, will be compared to a base case. This will consist of a single diesel generator powering the electrical load corresponding to each of the options, sized as its peak power. For example, for the first option, accounting the lecturers' office building, the base case will be a 25-kW diesel generator, which would be able to cover the load in any situation. The same happens in the second option, for the VC office excluding the AC loads, where a 28-kW diesel genset will be used instead as the base case. However, as the daily load varies considerably, especially during the night and weekends, the base case will be highly disadvantageous, as the generator would be forced to work in non-recommended minimum load ratios, which limit has been set as 25% in the software for all the options. Nevertheless, the same gensets will not be only considered for the base case but also as to provide backup power in all the options. More details on the specifications of the diesel generators can be found in the following sections, where a more in-depth analysis of each of the simulations is performed.

3.4.2.2. Off-grid PV-Diesel Hybrid System Powering the Lecturers' Building Loads

The first HOMER simulation will correspond to option 1. The schematic of the components presented in the simulations of options 1 and 2 can be seen in ***Figure 3.8***. For this option, as the data for all the components has been properly set in the software, the daily load profile of the Lecturers' Office Building will be introduced as well. A commercial load profile is chosen for the simulation, as it better represents the load of an office building. The corresponding curve created by the software can be seen in ***Figure 3.14***, and the main load representative values, in ***Table 3.9***.

Figure 3.15 shows the seasonal load profile of the simulation, created by the software from an input random variability value of 20%. This will add reality to the simulation as, even if there is a lack of data in monthly load variability, the electricity consumption of the compound will not be exactly equal throughout the year.

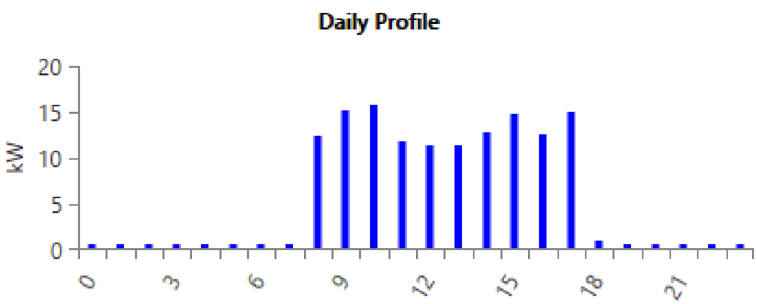

Figure 3.14*.Upper Nile University Lecturers' Office Daily Load Profile.*

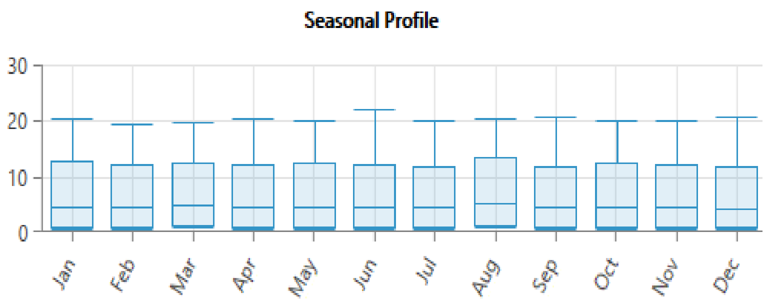

Figure 3.15*.Upper Nile University Lecturers' Office Seasonal Load Profile.*

Table 3.9 shows the optimal size of the system in option 1, extracted from HOMER's results dashboard. Economic parameters such as NPC, LCOE and capital investment have not been included in the table, as they still need to be revised. As a matter of fact, the variable O&M value per component that HOMER uses will be replaced by fixed yearly values extracted from the OIMT Project Database, and thus new economic parameters will be obtained. Additionally, to obtain the values of generator's reduced consumption and operating time, the results of this configuration have been compared to the ones obtained in the base case, where 100% of the load is supplied by a single 25-kW generator. Finally, the backup generator of 25 kW considered in this configuration will be, in reality, a connection to the system that will power the remaining loads of the compound, which will probably be a set of diesel generators of similar conditions.

Table 3.9. Summary of Upper Nile University HOMER results for Option 1.

Description	Option 1 – Lecturers' Office	Unit
Peak Load	22.2	kW
Daily average load	112.4	kWh/day
Solar PV Capacity	30	kW_p
Battery Size	64	kWh
Inverter Size	20.9	kW
Generator Size	25	kW
Estimated Battery Autonomy	10.8	hours
Reduced Generator Operation Time	8,321	hours/year
Reduction in Diesel Consumption	27,084	litres/year
Renewable Fraction	81.4	%
Excess Electricity	23.5	%

Figure 3.16 shows how the monthly load of the Lecturers' Office is distributed among the two electricity generation sources, where it is clearly defined the dominance of PV generation throughout the year. Additionally, it can be observed that the PV production is slightly reduced from June to August, as it corresponds to the rainy season in Malakal.

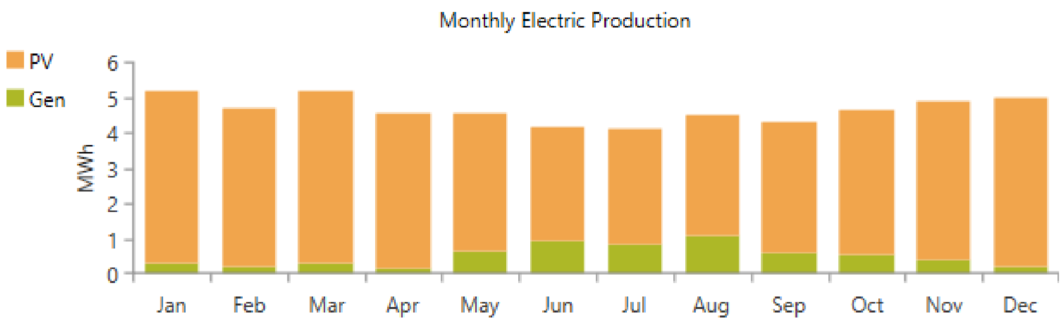

Figure 3.16*.Monthly Electricity Production by Source in Option 1.*

Figure 3.17 represents the behaviour of all the components in the optimal system along a timeframe of one week. End of July has been selected as the study period because it happens during the rainy season in Malakal, when the solar irradiance is minimum and thus the worst-case scenario in terms of PV production takes place. The graph on the top shows the load served, and the genset and PV production. The graph below shows the State of Charge (SOC), as a percentual value, of the battery bank. As observed, the PV production is low for several days. Consequently, the battery bank reaches its minimum value of 20% and is unable to charge completely during the respective days, and thus the genset supplies an increasing share of the load throughout the week. As a matter of fact, on July 27th, the generator even turns on early in the morning to charge the batteries, seen as a small orange peak in the graph. However, during the weekend, as the load decreases, the PV system can charge completely the batteries and the genset is not needed anymore at the beginning of the following week. Again, this is one of the worst weeks throughout the year in terms of diesel consumption, as the solar production is usually higher, and the battery bank can complete a full cycle of discharging and charging in a single day, while the genset is used some days at the morning/evening to complement the battery bank.

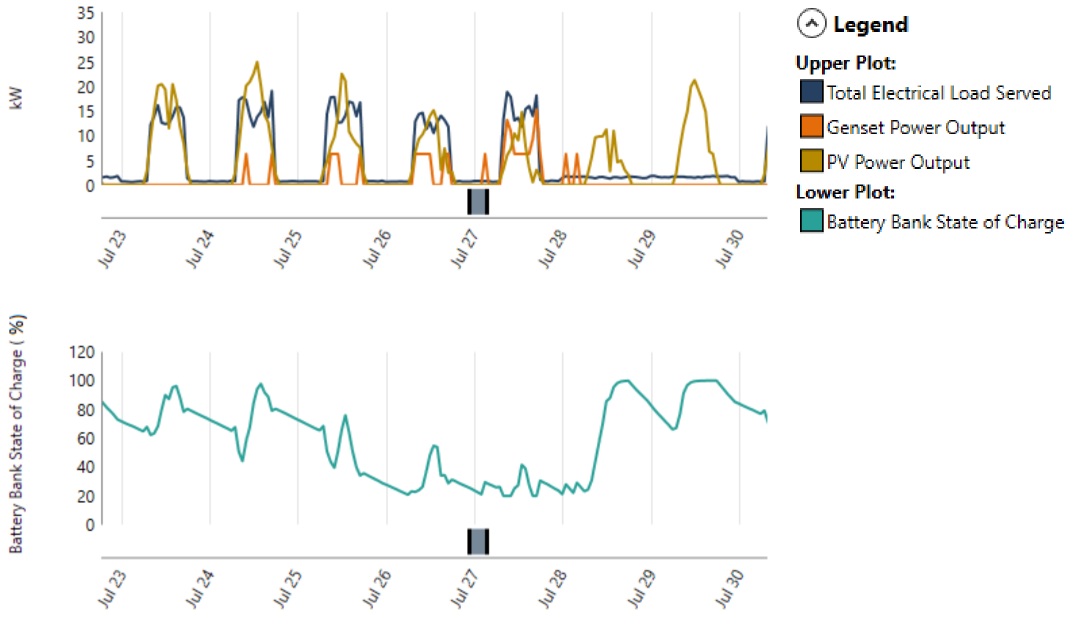

Figure 3.17*.Electrical System Analysis per component for one week in Option 1.*

3.4.2.3. Off-grid PV-Diesel System for the VC's Building Loads, excluding ACs

In the HOMER simulation corresponding to option 2, the daily load profile of the Vice-Chancellor's Office Building excluding the load of the AC units will be introduced. A commercial load profile is again chosen for the simulation. The corresponding curve created by the software can be seen in ***Figure 3.18***, and the main load representative values, in ***Table 3.10***.

Figure 3.19 shows the seasonal load profile of the simulation, created by HOMER in the same way as for option 1. As both loads are very similar, their load profiles, either daily or seasonal, are also similar for options 1 and 2.

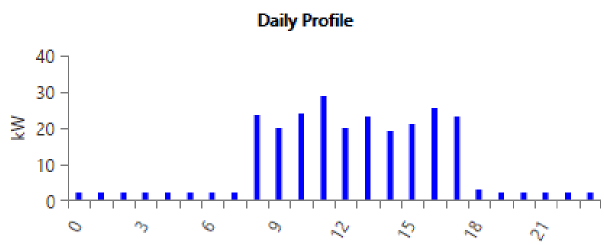

Figure 3.18*.Upper Nile University VC's Office Daily Load Profile.*

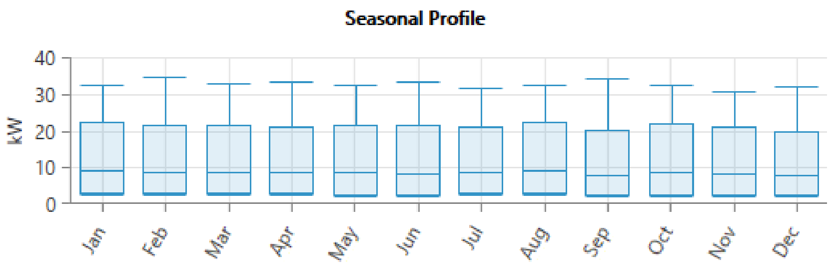

Figure 3.19.*Upper Nile University VC's Office Seasonal Load Profile.*

Table 3.10 shows the optimal size of the system in option 2, extracted again from HOMER's results dashboard. As the electrical load is slightly higher, the base case is represented by a 28-kW diesel generator instead, which operating time and diesel consumption values will be used for the calculation of both reduced parameters. Additionally, a higher load implies a lower renewable fraction in this case, even if the total solar production is higher and thus the reduction in diesel consumption is also higher than in option 1. As in the previous case, the backup generator of 28 kW considered in this configuration will be, in reality, a connection to the set of generators that will power the remaining loads of the compound. Finally, it can be observed that in this option the battery is slightly undersized compared to option 1, as the autonomy of this system is slightly lower and, the excess of electricity, higher. This can be expected as the supplied load is now higher for the same available budget.

Table 3.10. *Summary of Upper Nile University HOMER results for Option 2.*

Description	Option 2 – VC's Office	Unit
Peak Load	25.2	kW
Daily average load	150	kWh/day
Solar PV Capacity	40	kW_p
Battery Size	74	kWh
Inverter Size	26.7	kW
Generator Size	28	kW
Estimated Battery Autonomy	9.5	hours
Reduced Generator Operation Time	8,189	hours/year
Reduction in Diesel Consumption	30,537	litres/year
Renewable Fraction	78.9	%
Excess Electricity	24.8	%

Figure 3.20 shows how the monthly load of the VC's Office is distributed among the two electricity generation sources. Similar as option 1, the PV production is still the main source of load supply.

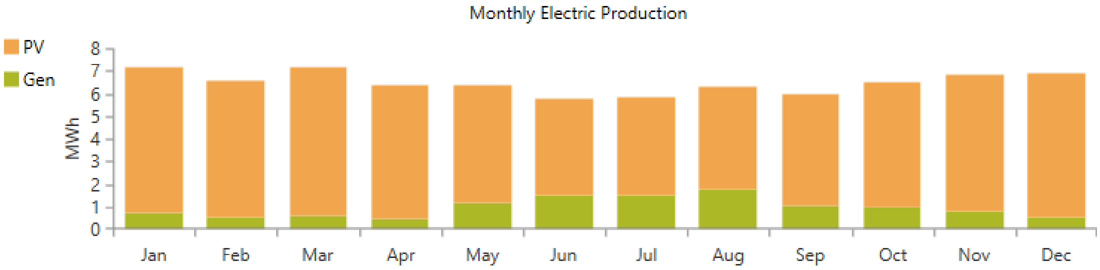

Figure 3.20*.Monthly Electricity Production by Source in Option 2.*

Figure 3.21 represents the behaviour of all the components in the optimal system along a timeframe of one week. End of July has been again selected as the study period, representing the rainy period in Malakal and hence the worst-case scenario. As observed, in general terms the battery bank does not have enough capacity to cover the load in the morning, as it slowly gets discharged during the night. As a matter of fact, when the PV production is low, the battery is discharged several times a day, and the genset needs to operate more frequently. During the weekend, as the load decreases, the PV system can charge completely the batteries and the genset is not needed anymore at the beginning of the following week.

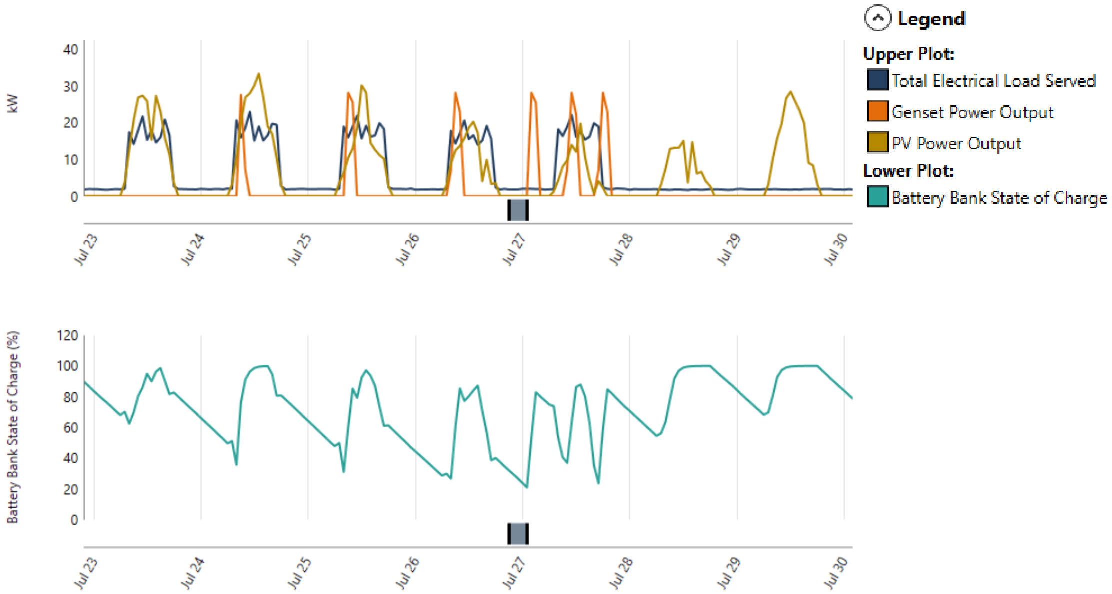

Figure 3.21*.Electrical System Analysis per component for one week in Option 2.*

3.4.2.4. Off-grid PV-Diesel Hybrid System as a Mini grid for the whole Compound

In the HOMER simulation corresponding to option 3, the daily load profile of the whole compound is considered. However, in this case, the components considered for the simulation change, as an additional small backup generator is considered, replacing the battery bank. The schematics of the simulation components for option 3 can be found in ***Figure 3.22***. A commercial load profile is again chosen for the simulation, as most of the load comes from office buildings. The corresponding curve created by the software can be seen in ***Figure 3.23***, and the main load representative values, in ***Table 3.11***.

Figure 3.24 shows the seasonal load profile of the simulation, created by HOMER in the same way as for options 1 and 2. As previously stated, the seasonal variability of the load of the university compound is very limited, and not enough data is available to better adjust each of the simulations.

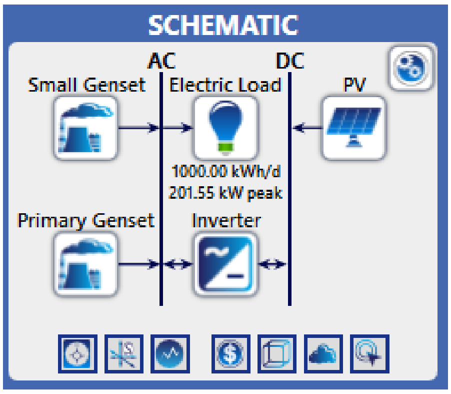

Figure 3.22.*HOMER schematic of components of the simulation of option 3.*

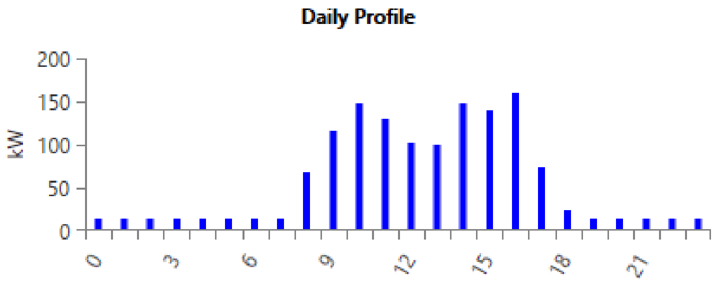

Figure 3.23.*Upper Nile University Daily Load Profile.*

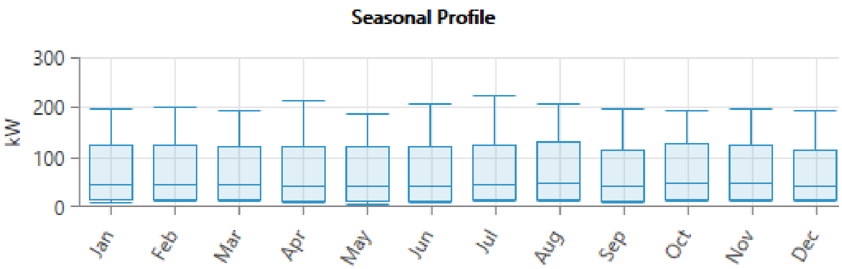

Figure 3.24.*Upper Nile University Seasonal Load Profile.*

Table 3.11 shows the optimal size of the system in option 3, extracted again from HOMER's results dashboard. The base case now is represented by a single 230-kW diesel generator, capable of supplying the peak load of the whole university by itself. Additionally, in this simulation, the battery bank is replaced by two diesel generators, one equal to the one representing the base case (230 kW), as to provide backup power to the PV system during working hours when the load is maximum, and a smaller one (25 kW), sized as to be able to supply the load outside working hours. The small genset has been introduced as to avoid the main generator to be operating during a long time in its minimum load ratio, which would be highly inefficient, and it would considerably reduce the lifetime of the device. However, even if batteries are not considered in this option and either one of the generators will be operating a 100% of the time, the reduced fuel consumption is now much higher than for the other options, as the load to be supplied in this option includes the whole compound, and the comparison against one single genset for the total load shows the big advantage of this solution. The renewable penetration refers to the percentage of PV generation compared to the load, and in this case, it has an average value of 36.21%. However, as to guarantee the system stability, its value at a given instant should not exceed 40%, otherwise the PV power would need to be bypassed.

Table 3.11. *Summary of Upper Nile University HOMER results for Option 3.*

Description		Option 3 – Mini grid	Unit
Peak Load		201.6	kW
Daily average load		1,000	kWh/day
Solar PV Capacity		80	kW_p
Inverter Size		58.4	kW
Generator Sizes	**Working Hours**	230	kW
	Night and Weekends	25	
Reduction in Diesel Consumption		120,721	litres/year
Renewable Fraction		21.6	%
Excess Electricity		11.7	%
Renewable Penetration		30 – 40	%

Figure 3.25 shows how the monthly load of the university compound is distributed among the two electricity generation sources. However, in this case the gensets are divided into the small one, meant to supply the night and weekend load, and the primary one, which will operate during working hours. The PV system is, in this case, the second source of electricity supply after the primary genset, although its peak production months are still corresponding to the dry season (October to March, approximately).

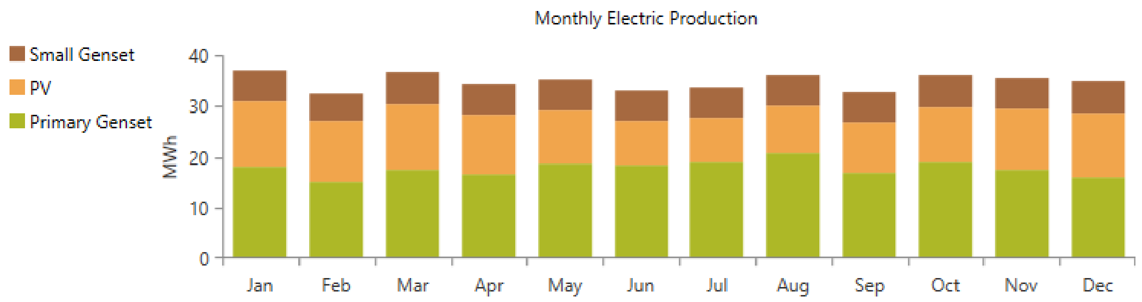

Figure 3.25.*Monthly Electricity Production by Source in Option 3.*

Figure 3.26 represents the behaviour of all the components in the optimal system along a timeframe of one week. End of July has been again selected as the study period, representing the rainy period in Malakal and hence the worst-case scenario. As observed, the primary generator complements the PV capacity when the load is high, thus during working hours. The small generator, on the other hand, is usually forced to supply the whole load during the rest of the hours, as the minimum load corresponds to hours without solar irradiation. Finally, during weekends, as the load is minimum, the small generator just complements the PV capacity as the primary one does during weekdays. In this option, as the battery bank is replaced by generators which will be operating alternatively a 100% of the time, the difference between the rainy season and periods with higher solar irradiance is not as different as in the other options, as the generators will be just providing more or less power to the system, not switched on and off depending on the PV production.

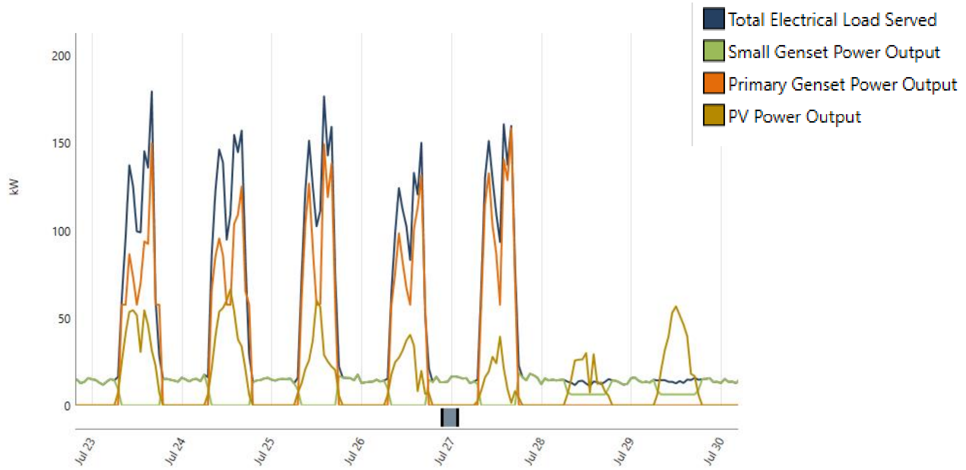

Figure 3.26.*Electrical System Analysis per component for one week in Option 3.*

3.5. Environmental Analysis

With the use of internally developed tools, the OIMT GES team calculates the CO_2 emissions savings achieved by the implementation of green energy solutions in each of the options considered. As to perform the calculations, the team uses CO_2 emission factors estimated by the United Nations Environmental Programme (UNEP), applied to the national grid for each country and/or to the fuel consumption of generators. In the case of the Upper Nile University project, only the emission factor for the use of diesel generators will be considered, as the options are all implemented off-grid. Consequently, the emission factor used to calculate the CO_2 emission savings for all the options will be equivalent to 2.6908 kg CO_2eq/litre for diesel fuel [42].

The results obtained of CO_2 emissions savings for the three options are shown in ***Table 3.12.***

3.6. Financial Analysis

The objective of the financial analysis of the project is to obtain the following information for the three options presented: Initial Capital, Annual Operating Costs of both base case and green energy solution, as to be able to compare them, Annual Maintenance Cost and PV Replacement Cost. With this information, a cash flow of 20 years is built comparing the new case with the base case, and thus the Payback Time and the Annual Monetary Savings of the three options is obtained.

To begin with, the initial capital of each of the options will be the CAPEX value obtained in HOMER, subtracting the generators CAPEX for options 1 and 2. For option 3, all the components of the system will be in the scope of the project, and thus included in the CAPEX, but for the first two options, as previously stated, the generators will be provided by the country office in a separate budget, as to power the remaining loads of the campus. Other values such as freight costs, installation costs, and civil works will be included in the CAPEX of the three options as well, calculated from the OIMT Project Database (see ***Figure 3.12***, ***Figure 3.13*** and Annex B). The OIMT GES team professional service fee of 5% of the project CAPEX will be included too. The initial capital values obtained for the three options can be found in ***Table 3.12.***

The Operating Costs for both the base case and the solutions provided by the GES team will be directly obtained from HOMER results. However, the annual O&M value provided by the software will be subtracted, as it will be included later as a fixed annual cost, which value will be also extracted from the OIMT Project Database. Finally, the PV Replacement Cost will be extracted from HOMER's new system for all the options considered.

The Cash Flow including all the values described in this section will be available in the Business Case document, and in Annex C of the thesis. The values obtained for Capital Investment, Simple Payback Time and Annual Monetary Savings can be also found in ***Table 3.12.***

3.7. Comparison of the Results for the three Options

Table 3.12. shows the main results obtained for each of the options, which will be presented to South Sudan's country office so that they can choose the most suitable solution according to their expectations.

For a clearer analysis of the three solutions, it is important to notice that options 1 and 2 have similar characteristics, as they are both isolated systems covering the load of a single building. However, as the load supplied in option 2 is slightly bigger, the renewable fraction is lower even if the annual PV production is higher. As both PV size and battery size are higher in option 2, the system is also more expensive, although the annual monetary savings are more beneficial in this case. As a matter of fact, the fuel price in South Sudan is so expensive that the more energy covered by the PV system, the more beneficial is the economic analysis of the solution, in terms of annual monetary savings and payback time. However, the three solutions are highly economically beneficial.

A big disadvantage encountered in options 1 and 2 and presented to the country office is the difficulty in the future expansion of both options. As they cover the load of a single building, which is limited, the system can expand to a maximum of a 100% renewable fraction of each of the building loads, which is not far from the actual value. On the other hand, option 3 covers the whole load of the compound and thus the expansion possibilities are high, as it is very far to achieve a 100% renewable fraction of the load supplied. As a matter of fact, another way of understanding the advantages of the mini grid with respect to options 1 and 2 can be that the lack of a battery bank in the mini grid is replaced by a higher load, which means that most of the electricity excess, instead of being stored to be used later, it is consumed by other loads of other buildings in the compound, which would be free of cost. However, options 1 and 2 have other advantages, as they are more compact and simpler and they include batteries, which makes the system highly efficient if only the load of the corresponding building is considered.

Table 3.12. *Summary of Upper Nile University project.*

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
Estimated Battery Autonomy	10.8	9.5	-	hours
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 reduction in diesel consumption has been calculated as in comparison to the base case, in which one single diesel generator powers the corresponding load. As both simple payback time and annual monetary savings values depend on the diesel cost in Malakal, which has been set as 1.92 US$/L as in the HOMER simulations, it is important to mention that those values can drastically change in the near future, as for the high volatility of fuel costs in the region. However, as both values are highly beneficial, a decrease in fuel costs would hardly affect the high positive impact of the investment.

In conclusion, the most recommended system would be 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.

3.8. Final System Description to be implemented in the Upper Nile University

The three options obtained in the design phase of the Upper Nile University power system were presented to the South Sudan UNDP Country Office. Finally, as for the clear advantages in front of the other options, option 3 or the mini grid solution was selected by the country office, and thus it will become soon the power system solution implemented in the compound.

Once the CO makes the decision, the RfQ document is released to start the Step 3 or Procurement phase, in order to find the most suitable vendor in charge of the implementation of the selected solution. However, in the scope of the RfQ, the big diesel generator (230 kW) will not be included, as the CO decided to procure it locally to cut costs. Consequently, the vendor will be in charge of providing the mini grid system including PV system, the small generator (25 kW) and the control system, among other services that will be specified below.

The first element in the scope of the vendor will be the creation of the final design of the system, which will be finalized after the vendor performs an energy audit on site represented by its local partner in the country. The final design shall include the grid forming strategy, which shall be prescribed to the characteristics of the mini grid. As for its expected low to medium renewable penetration of 30 to 40% (see ***Table 3.11***), a genset dominated architecture should be expected, where either one of the gensets will be in charge of setting the voltage and the frequency levels of the mini grid (see ***section 2.5.2*** for further details). Consequently, the control system provided shall regulate the gensets operation as to make sure they are able to maintain the grid stability inside predefined limiting values, a 100% of the time. As one of the gensets would be operating during the low-load periods and the other during the high-load ones, the control system shall guarantee an automatic switch from one generator to the other depending on the load ratio, making sure either one of them is operating. The control system shall also guarantee the optimal economic performance of the system, prioritizing PV generation as to maximize fuel savings. However, it shall also prevent the gensets to operate below the recommended minimum load ratios, of about 25% to 30% of their nominal power, and thus the system will prioritize the genset safe operation above fuel savings in case the load decreases and/or the PV irradiance increases drastically.

The vendor shall also provide an online monitoring system for the OIMT GES team to visualize in a user-friendly platform the system control features and main parameters. An example of an online monitoring system used by the GES team to remotely track the currently operating green energy system in Tanzania Country Office can be seen in ***Figure 3.27***.

Figure 3.27*.Online monitoring portal of Tanzania CO Green Energy System [1].*

On the other hand, ***Figure 3.28*** shows in a graphical way an example of a power system configuration, with PV and battery bank, in which the diesel generator (G1) is the master component in charge of the grid forming. A similar configuration should be expected for the Upper Nile University mini grid, although the battery bank will not be included in this case. Additionally, the same figure also shows the modularity of the addition of components in such structure, where if only additional PV panels where to be included in the future, an additional unidirectional inverter would be needed to connect them to the mini grid. However, if a battery bank wants to be added in the future, a bidirectional inverter would need to be used instead to connect it to the mini grid.

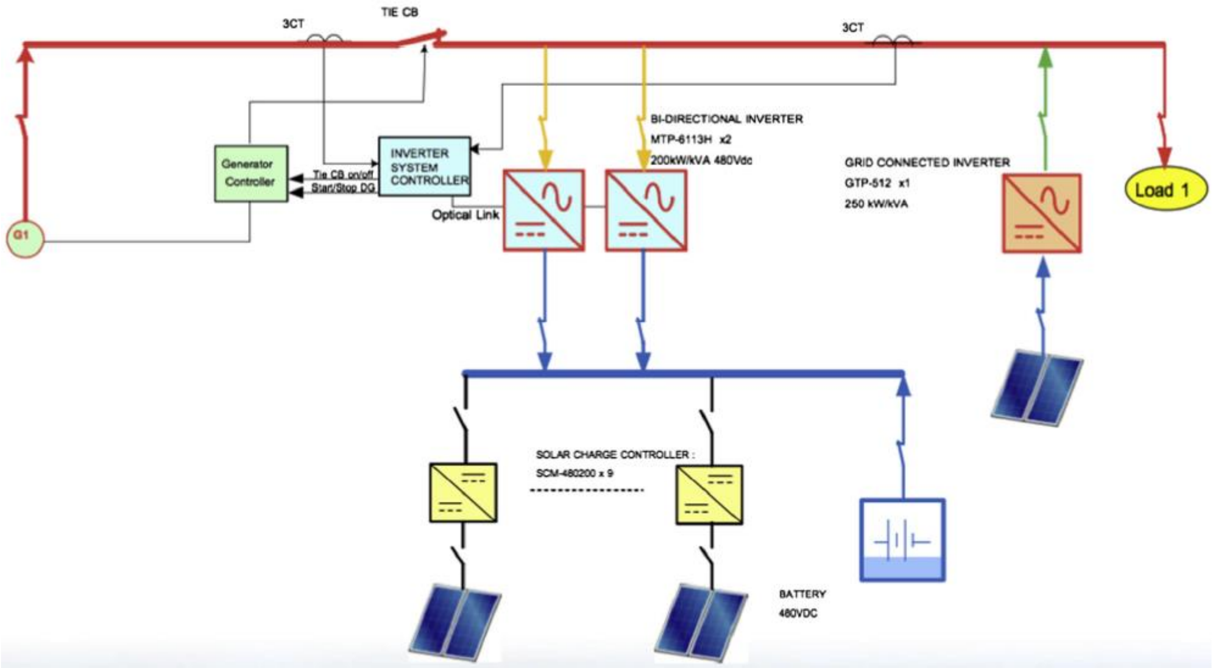

Figure 3.28*.Configuration in which the diesel generator is the master of the system* [22].

Finally, the vendor will also be required to provide, besides the final system design, installation, and commissioning, a testing period of 6 months after the system commissioning, as well as simple training to the end users in basic management of the system. An O&M period of 3 years, provided by the vendor and its local partner will also be required, which includes biannual preventive maintenance and cleaning of the PV panels. However, in the case of the Upper Nile University mini grid, a more frequent cleaning will be expected as for the climatic conditions in Malakal, which region is considered to be dust intense in a level 4 out of 4 (see ***Figure 3.29***), usually experiencing several dust storms per year.

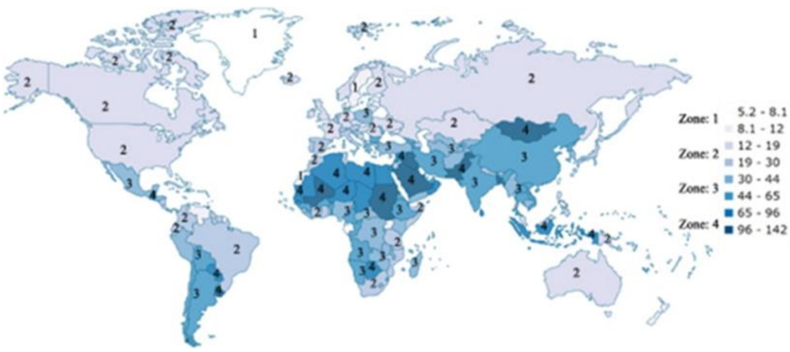

Figure 3.29*.Dust intensity around the world* [43].

Chapter 4

Mini grid Expansion Opportunities in Upper Nile University

This chapter briefly explores further opportunities of improvement and expansion of the Upper Nile University Power System, which will be implemented by the OIMT GES team in the terms stated in the previous chapter.

4.1. Opportunities for the Increase in Renewable Fraction of the System

As the South Sudan UNDP Country Office has decided to implement a power system in the Upper Nile University that will supply the whole load of the compound, a big window of opportunities is now open in terms of expanding the system and obtaining even higher benefits out of it. As the designed mini grid is undersized because of previous budget constraints (characterized by only 21.6% of renewable fraction), in this section several options for increasing the PV electricity consumption of the loads in the mini grid, by adding PV or battery capacity, will be proposed. This would allow the end user to increase the annual monetary savings of the power system, by adding a second investment round in the project timeline. The expansion would take place after the first investment has been recovered, which would happen in about 2 years after the system inauguration, and only if the mini grid is proved to be operating as expected. As a matter of fact, the OIMT GES team in charge of the first system implementation is aware of the possibilities of the country office to obtain more funds for this project in the near future and has therefore been careful in designing and executing a system that can be easily expanded with more PV panels or adding a battery bank.

Consequently, a techno-economic analysis of three expansion possibilities for the Upper Nile University has been performed, which can be seen summarized in ***Table 4.1***, showing the resulting systems after the addition of new components during the expansion. Again, HOMER has been used to simulate the different configurations, which resulted on the corresponding values.

***Table 4.1**. Expansion Possibilities for the Upper Nile University mini grid.*

Description	Current System	Recommended System	Addition of Batteries	Addition of PV panels	Unit
Solar PV Capacity	80	250	80	170	kWp
Battery Size	0	145	66	0	kWh
Inverter Size	58.4	142	58.4	90	kW
Renewable Fraction	21.6	63.8	26.8	32	%
Excess Electricity	11.7	30	6.8	30	%
Diesel Consumption	96,112	48,572	90,873	86,355	litres/year

As to obtain the three expansion configurations above, the same specifications have been used in the software than for the mini grid design. However, several assumptions have been made in this case, as there is a high uncertainty associated to each of the components' costs and diesel price. The main concern comes from the fuel cost, as for the high volatility linked to this value in South Sudan, especially as the expansion would be implemented in minimum two years from now. As for the missing reliable data, this section will be considered as an opportunity analysis more than a proper system design as the previous chapter. Consequently, simple financial statements concerning the expansion possibilities have been included in ***Table 4.2***, as to analyse the financial benefits associated to each of the expansion options. Nevertheless, for the calculation of the estimated annual savings, only the savings in fuel cost have been considered, as not enough reliable data is available to create a proper cash flow, considering the market price variability of the components and O&M services. As a matter of fact, for the investment value of each of the configurations, only the cost of the added components has been included as well.

Table 4.2*. Financial Results of Expansion Possibilities for the Upper Nile University mini grid.*

Description	Recommended System	Addition of Batteries	Addition of PV panels	Unit
Expansion Investment	143,260	36,036	33,930	US$
Reduction in Diesel Consumption	47,540	5,239	9,757	litres/year
Estimated Annual Monetary Savings	91,276.8	10,058.9	18,733.4	US$/year
Simple Payback Time	1.6	3.6	1.8	years

Comparing all the configurations resulting from the addition of components during the expansion, it is clear that the single addition of a battery bank to the system is the least beneficial option. The main reason is that the excess of electricity of the mini grid, which mainly comes from solar production, is not sufficient to charge a big battery bank, which would release the excess energy during the night and reduce the fuel consumption. Therefore, a small difference in terms of system performance is noticed when a small battery bank is added to the mini grid if more PV capacity is not added as well. Consequently, the recommended system for a minimum budget would involve the addition of 90 kWp of PV capacity, reaching a system of 170 kWp and 32% renewable fraction, although the excess PV electricity would increase up to a 30% in this case. Therefore, the most recommended option of the ones considered would include both the addition of PV capacity and a battery bank, resulting on a system of 250 kWp and 145 kWh of battery. This system is highly beneficial as with a considerably lower second investment compared to the first one, the renewable fraction of the system is almost tripled. The annual savings coming from this expansion would also increase more than US$ 90,000, resulting in a total value of US$ 366,465 in annual savings with the implementation and expansion of the mini grid.

In conclusion, even if it has been proved that the recommended system expansion would be highly beneficial in financial terms, the new configuration would be also beneficial in the technical point of view of the mini grid performance. Even if the grid forming strategy is still part of the functionalities of the diesel generators, the battery bank adds an extra layer of reliability to the system. However, a higher economic benefit would be obtained if the grid forming responsibility was transferred to the inverters, which may be possible with the addition of the battery bank, as in this way one of the gensets would not be forced to operate a 100% of the time, decreasing considerably the fuel consumption of the mini grid.

4.2. Opportunities for Mini Grid Expansion outside the University Compound

According to [44], in 2009 a 35.9% of the population in South Sudan had access to electricity, corresponding to the latest data available. Although there is no specific data regarding the particular situation of the electricity sector in the city of Malakal, the same report stated in 2018 that for those connected to the national grid, the average frequency of outages was estimated as 19 days per year, hence most of the commercial and industrial users relied on private diesel generators for electricity supply. However, this approach is extremely disadvantageous for private households, small businesses, or community buildings, which may not have the financial resources to invest in individual diesel generators to power their homes or facilities. Consequently, this section focuses on opportunities to take advantage of the mini grid implemented in the Upper Nile University for powering communities in Malakal near the compound.

4.2.1. Innovative Business Models for Mini Grid Profitability

The implementation of diesel hybrid mini grids in similar settings than the city of Malakal has been proved to be highly advantageous, as it reduces the cost of electricity for the end users while increasing the reliability of the power supply. However, the high investment costs and low electricity demand in rural or poor areas makes it unappealing for private companies to invest, and thus the dependence on public subsidies, added to the low scalability of the solutions, slower down the spread of such systems. The study of Safdar on business models for mini grids [45] suggests three innovative approaches directed to implement economically viable mini grids in areas of low electricity demand. The first one, named the franchise approach, relies on economies of scale to obtain relevant benefits, expanding until obtaining a high number of customers. In this way, each customer can pay minimum management costs and the projects can still be viable. Husk Power Systems in India is a good example of a company adopting this business model.

The ‘clustering approach’ is the second innovative model stated by Sadfar. The concept aims to benefit from the ‘clustering’ or connection of neighbouring mini grids as a low-cost technique to expand the customer segment of the corresponding systems. This model is worth to consider in the specific case of the Upper Nile University mini grid. As a matter of fact, less than four kilometres far from the university, the Internally Displaced Persons (IDP) camp in Malakal is located, run by various humanitarian NGOs and UN agencies [46]. The camp has been recently electrified with the commissioning of a 700-kWp PV and 1368-kWh battery mini grid, which has been partially integrated to the power distribution grid.

Consequently, this could be an opportunity to merge both mini grids and provide a big part of the local population of Malakal with a more reliable and sustainable electricity supply. As the merged mini grid grows, additional PV, battery capacity or diesel generators could be connected to the system with the revenues obtained by its end users. However, an entity should be responsible for the management and collection of revenues of the mini grid, which could involve the private sector, community-driven organizations or other public or humanitarian entities. Even if not directly, the public sector should be involved in providing a policy framework, to avoid private companies to take advantage of the local population with unaffordable tariffs and bad management.

The last innovative business model mentioned by Sadfar and with positive implications to this specific project is the 'ABS' approach, characterized by the beneficial relationship between 'Anchors, Businesses and Consumers'. This model aims to benefit from 'Anchor' customers that will 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 will provide the required investment for the implementation of the mini grid and will 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. 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.

As to consider an 'ABS' approach applied to the Upper Nile University mini grid in Malakal, an analysis of the connection of different community members to the system has been performed. However, the base system is too limited to consider additional loads to supply, and therefore the configuration obtained by the recommended expansion will be used instead for the analysis (see ***Table 4.1*** in Recommended System), with a PV capacity of 250 kWp and battery bank of 145 kWh. Hence, if the mini grid was to be expanded until reaching these configuration parameters, the option of letting external users to benefit from its power supply could be safely considered.

To begin with the expansion analysis, the load characteristics of possible external end users of the mini grid have been estimated. A summary of load approximations for a small household and a classroom can be seen in ***Table 4.3***. However, the results are assumed to be conservative, especially as the average electric power consumption in 2014 in South Sudan (latest data available) was estimated as 44 kWh per capita, according to the World Bank Database [47], resulting in an average of 120 Wh/day. Therefore, a household consuming 1.4 kWh/day seems an optimistic average, even considering the limited number of appliances that have been included in the study. Cooking appliances such as stoves or refrigerators have not been considered, as the residential load would be even further from the average and as to consider that the most popular Pay-as-you-go off-grid solar systems in such areas usually power access to communications and lighting (50W to 200W) [15]. The nominal power value of the appliances used in this study have been extracted from the compound equipment list provided by the South Sudan UNDP Country Office, for the design of the university power system (see section 3.1). The load profile obtained for both types of facilities will be used to analyse how the connection of the corresponding end users would impact the mini grid operation.

Table 4.3. *Simulation of Small Household and Classroom list of appliances.*

Facility	Electrical Equipment	Units	Operating Time (Hours/day)	Nominal Power (W)	Electricity Consumed (Wh/day)
Small Household	Lights	5	4	36	720
	Mobile charges	2	2	10	40
	TV 17”	1	3	75	225
	Fan	1	3	80	240
	Laptop	1	2	80	160
	TOTAL			**435**	**1,385**
Classroom	Lights	20	6	36	4,320
	Mobile charges	20	2	10	400
	Fans	6	6	80	2,880
	TV 17”	1	3	75	225
	Laptop	5	3	80	1,200
	TOTAL			**1,875**	**9,025**

The objective of ***Table 4.4*** is to study the impact of the addition of electric loads, corresponding to new users, on the main parameters of the mini grid. The results have been obtained by simulating in HOMER the Recommended System expansion mini grid configuration, of 250 kWp PV and 145 kWh battery bank, supplying both the load of the university compound and the one corresponding to each of the groups identified in the table. The first group is represented by a small community of 20 small households, the second by a bigger community of 50 small households and the last a small school has been considered as the additional load besides the university. As to simplify the study, the power losses in the mini grid as result of the distribution of the electricity among the end users have not been considered, as data regarding distances to the compound would have had to be approximated.

The results show that the impact on the renewable fraction of the mini grid, as a result of the addition of the corresponding loads, is minimal. As a matter of fact, the set of diesel generators of the mini grid alone is capable of supporting the worst-case scenario possible, which is very unlikely to occur, of all the appliances being operating at the same time, both in the university buildings and in the new end users’ facilities, when no PV power is available. However, in the case of the medium community, both generators would have to be operating at the same time if the worst-case scenario described above occurs.

On the other hand, while the mini grid is barely affected by the addition of the new loads, the economic benefits to the new end users compared to the power consumption from individual generators is considerable. In the cases concerning communities of small households benefitting from the mini grid power supply, the monetary savings per each household raises to almost US$ 400 per year compared to a base scenario where they would pay for the same system powered by diesel generators. Although this value may seem only slightly positive, it corresponds to more than a 30% of the Gross Domestic Product (GDP) per capita in South Sudan, which is possible due to the high fuel costs for the population in the country. Consequently, the socio-economic benefits of such power system to be available for the community in Malakal is worth considering by the stakeholders in charge of its management.

Table 4.4*. Financial Results of Expansion Possibilities.*

Description	Base Case (Recommended Expansion)	Small Community	Medium Community	Small School
Facilities Connected	Only University Compound	University Compound and 20 Small Households	University Compound and 50 Small Households	University Compound and 1 Small School (5 Classrooms)
Extra Load	0	27.7 kWh/day	69.3 kWh/day	45.1 kWh/day
Renewable Fraction	63.8%	62.8%	61.2%	62.4%
Excess Electricity	30%	29.1%	27.8%	28.4%
Fuel Savings of Community/School (compared to using only generators)	-	3,809 litres/year	9,924 litres/year	5,011 litres/year
Monetary Savings Community/School	-	7,313 US$/year (366 per household)	19,054 US$/year (381 per household)	9,621 US$/year

Several assumptions have been used in this case to simplify the complexity of the simulations, as the daily load profiles of the small household and classroom were unknown (only average estimated values of consumption were available). Consequently, pre-defined HOMER daily profiles have been used and adjusted to the value of average daily electricity consumption, which was obtained from the calculations seen in ***Table 4.3***. A commercial shape for the school and a residential shape for the small household were used for the pre-defined HOMER profiles.

Additionally, distribution energy losses, due to the electricity transportation through cables, were not considered. Although in the mini grid powering only the university compound they can be assumed as meaningless, due to the small distances among loads and power sources, in the case of the expansion outside the compound, through the village of Malakal, they can become important. As a matter of fact, from the university to the furthest house of the village there can be more than 7 km. However, a preliminary assessment of the corresponding power loss results in quite low values (less than 3 kW for a peak load of 220 kW, the maximum in the worst-case scenario) considering that the cabling is sized with an appropriate section with respect to the maximum current it would handle.

Finally, it is important to remember that the study described in this section has been performed using important assumptions and approximations of data, and thus its reliability is limited, far from the accuracy of the design of the mini grid seen in Chapter 3, which will be implemented in the near future with the supervision of the OIMT GES team. However, this part of the study, although less accurate, it has been considered to be a useful tool, as it helps to understand the further beneficial impacts that can be obtained from the implementation of a mini grid, in the city of Malakal, with the possibility of expansion to the neighboring communities.

Chapter 5

Discussion of Results

This chapter discusses the limits of the approach, the results, boundaries and limitations of the project and potential opportunities to be considered in future thesis and projects.

5.1. Boundaries and Limitations of the Project

The main boundaries encountered during the development of this project by the student in the scope of the UNDP OIMT GES Team can be summarized in the points below:

I. Budget restrictions. The available budget of this project is restricted to approximately US$ 100,000 for the solar PV system with its components (batteries, control system, installation, etc), which is very limited compared to the total load of the university compound to be covered. However, a different budget of US$ 101,000 is allocated to the backup generator set needed to provide the system with sufficient power when solar power is not enough. Consequently, an option combining both features will be proposed, with a total CAPEX of US$ 201,000.

II. Data availability. The data regarding the electrical load to be covered by the hybrid system is insufficient to guarantee the optimal design of the mini grid. This is because the electrical equipment of the university has yet to be installed, as the compound is under renovation works, and thus power monitoring devices could not be installed to obtain reliable electrical consumption data.

III. The last constraint is the time and team resources to consider all the options available. As certain urgency has been put in the development of this project, only renewable energy technologies including solar PV with batteries and fuel generators as the backup energy source have been evaluated. Other green energy sources such as wind power or biomass could have been included in the analysis, but the lack of team´s expertise in such technologies did not allow their inclusion in the design in such tight timelines. The time constraint also prevented the design process to include a proper sensitivity analysis. As many of the preliminary data that the project relies on can be extremely volatile, as the fuel costs, and change easily, as the electrical appliances to be connected, a sensitivity analysis would have allowed the study to determine the risk level on relying on the results obtained, which would have been very valuable data for UNDP Country Office to undertake an informed decision.

5.2. Limits of the Approach

Clearly, the system to recommend to the CO 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. According to further simulations with HOMER, which have been described in section 4.1, 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 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, and reducing the excess electricity up to 30%.

On the other hand, as the electrical consumption data which has been the base of the simulations comes from a list of electrical appliances which are yet to be installed, it is important to evaluate the risk of these data to result to be different from the expected. As security margins for the load data has been considered in the simulations up to +/- 20%, small variations should not be an issue. However, if the university starts to receive more students than expected in the future and thus the load is considerably increased, the expected operation of the diesel generators could change. While with the planned load the generators work in an alternate way depending on whether they are in high load operating hours (up to 230 kW) or night and weekends (up to 25 kW), with a highly increased load both gensets could start operating at the same time. In this case, it would be recommended to acquire a new generator to alternate with the others, as to reduce the operating time for each of them, which would improve their lifetime and operating quality.

Finally, the higher risk comes from the approximation on the investment cost of the project. While the monetary savings coming from the solar energy production are easier to estimate, the costs of the components highly depend on the present situation and the capability to find suitable vendors, as they are estimated from similar UNDP projects' data. This is especially critical in the case of the village of Malakal, which is highly isolated from suitable roads and transportation lines, which could increase unexpectedly transportation costs of the system components. Additionally, the COVID-19 pandemic has critically worsened the situation, as several delays are expected from Mombasa port to South Sudan for big trucks carrying goods, which are forced to wait in long queues in the border of Kenya to wait for their COVID-19 results.

5.3. Potential Opportunities to be considered in Future Thesis and Projects

As it has been seen in previous chapters of this thesis, the potential of renewable energy projects in South Sudan are considerable, especially regarding solar power. However, the lack of public incentives makes it difficult to find a profitable way to finance such projects, especially as at the beginning the returns will be low in rural areas. However, more research should be conducted regarding the benefits of electrifying such areas and methods to increase those benefits with innovative business models, as to reduce the amount of investment required, or to further attract actors in the private sector.

Additionally, a bigger amount of data and access to information would be extremely helpful to determine the impact of renewable energy projects in such environments. Data acquisition and analysis could be another impactful research area to further increase the incentives to promote beneficial developments in similar environments.

Finally, meaningful data and examples of several projects performed under similar conditions could help obtaining scalable energy solutions which would decrease costs and complexity.

Chapter 6

Conclusions

This chapter finalises this work, summarising conclusions and pointing out aspects to be developed in future work.

The first thing worth to mention is the methodology used to obtain the results showed in the thesis, the 7-Steps Green Energy Solutions. This, developed by the UNDP OIMT GES Team, is simple, clear, and concise, making any party with limited resources and knowledge on solar power systems capable of assessing their own electrical loads, pre-designing a solar system and executing the procurement, installation, and commissioning processes with limited effort, with the help of the GES Team. As a matter of fact, it has been specially designed as a way of simplifying the process for non-profit organizations and institutions working in developing countries with limited resources on the field, for them to be able to easily obtain the benefits of solar energy in countries where this resource is so abundant. Furthermore, such a useful methodology could have the potential to be furtherly used by private companies specialized in green energy and placed in areas with limited energy access, as a way of providing the same service to the population in a simple and scalable way. However, the target of the team which developed the 7-Steps methodology is not currently oriented towards the population but towards non-profit organizations and their own UNDP premises.

Secondly, regarding the electrical load of the university compound, this can be considered extremely limited with respect to the load of other universities analysed from the existing literature. As a matter of fact, the Upper Nile University load accounts for only 1% of the Stanford University load in the US [19]. This can be due to the fact that the resources available in a university compound placed in a highly conflicted area of a developing country are limited, due to restricted resources and involvement from the government in creating high-quality public educational institutions.

Additionally, while most of the projects have limited space available for placing the PV panels, only two building roofs have been considered for this project, as the available budget allows the addition of a limited amount of PV panels compared to the high amount of space available in the roofs of other buildings in the compound. This leads to the conclusion that the system designed is not the optimal but very restricted due to the budget, as it has been observed that using a higher portion of the available area for generating solar electricity would lead to an increase in annual savings, lower payback times and further environmental benefits.

Other conclusions extracted during the project development include the high benefits of including the total load of several buildings in the power system design instead of considering the load of a single building, even when the electricity generated is very limited. This adds flexibility to the system in terms of future expansion and increases the control level of the loads of the whole compound. The social benefits of implementing a mini grid instead of an isolated system are even higher, as it can lead to the incorporation of new users of the community, improving the affordability of energy access in the village.

Furthermore, the benefits of PV-diesel hybrid systems with respect to only fuel-powered systems are worth to highlight. Hybrid systems are not only more sustainable solutions as they significantly reduce the diesel consumption of the system, thus emitting less CO_2, but they also supply more affordable and reliable electricity, sometimes even avoiding the need of expensive components such as batteries. However, the diesel consumption can be extremely reduced by the use of grid forming technologies other than genset dominated (e.g., batteries), as otherwise the requirement of operating either one of the gensets all the time reduces the use of available solar energy. Therefore, the use of batteries is highly recommended in such systems.

In conclusion, it is expected that the final solution proposed and accepted as the system powering the Upper Nile University compound, summarized in ***Table 6.1***, will be highly advantageous for both the university end users and stakeholders involved in the project, and it will provide a sustainable example to the region while creating local capacity as well. Furthermore, if the expansion plans are followed as suggested in the thesis, even other members of the community may benefit from the sustainable, affordable, and reliable electricity supplied by the mini grid, originated at the university compound.

On the other hand, hopefully this will be only one more extremely meaningful project that the interns in the UNDP GES team will successfully develop, with the leadership of such professional experts which are their staff.

Table 6.1. *Summary of main results.*

Final Power System to be Implemented in the Upper Nile University	Mini Grid of 80 kWp, supplying the whole load with a renewable fraction of 21.6%. The PV panels will be placed either in the Lecturers' or in the Vice-Chancelor's Office building roof.
Best Recommendation for System Expansion	Up to 250 kWp and the addition of a 145-kWh battery bank, which system would reach a renewable fraction of 63.8%. The expanded system could even export electricity to more than 50 small households in the village keeping a renewable fraction of more than 60% and drastically reducing the diesel consumption in the village.

Finally, further thesis research work could be related to the analysis of the potential of distributed renewable energy projects in similar environments such as underdeveloped countries in sub-Saharan Africa. Other topics would include the impact of electrification in the level of development of a country and data acquisition and analysis for the development of similar projects.

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Annex A

University Electrical Load Data

The whole set of data corresponding to the electrical load of each of the buildings of the university compound can be found in this Annex, as well as the use of this data for the construction of the corresponding daily load profiles.

Dean Office

	Item	Floor	Device	Nominal power [W]	# of units	Total peak power [W]	Expected operating hours [hr]	Day time load/ Night time load	Variability	1	2	3	4	5	6	7
Weekdays	1	UNDP	Fans (ceiling mounted)	80	30	2400	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	UNDP	Lights	36	60	2160	8	Day time	Lights Pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	UNDP	External Lights	36	12	432	16	Night time	None	432.00	432.00	432.00	432.00	432.00	432.00	432.00
	4	UNDP	Desktop Computer	200	20	4000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	UNDP	MFP Printer	500	2	1000	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	UNDP	Phone Chargers	10	50	500	3	Day time	Random Working pattern (Low)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	UNDP	Projector (LCD)	350	1	350	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weekends	8	UNDP	External Lights	36	12	432	24	Base load	None	432.00	432.00	432.00	432.00	432.00	432.00	432.00

Load curve Weekdays

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	518.40	518.40	518.40	518.40	518.40	518.40	518.40	9523.20	6584.40	7420.80	9020.40	7189.20	7893.60	7206.00	7970.40
kWh	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	9.5232	6.5844	7.4208	9.0204	7.1892	7.8936	7.206	7.9704
Peak load (kWh)	9.5232														
Average (kWh)	3.6248														

Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40
kWh	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184
Peak load (kWh)	0.5184														
Average (kWh)	0.5184														

Lecture Halls (x9)

	Item	Floor	Device	Nominal power [W]	# of units	Total peak power [W]	Expected operating hours [hr]	Day time load/ Night time load	Variability	1	2	3	4	5	6	7
Weekdays	1	UNDP	Fans (ceiling mounted)	80	200	16000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	UNDP	Lights	36	150	5400	8	Day time	Lights Pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	UNDP	External Lights	36	65	2340	16	Night time	None	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00
	4	UNDP	Phone Chargers	10	50	500	3	Day time	Random Working pattern (Low)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	UNDP	Projector (LCD)	350	9	3150	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weekends	6	UNDP	External Lights	36	65	2340	24	Base load	None	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00

Load curve Weekdays

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	23808.00	16218.00	17976.00	22182.00	17658.00	19284.00	17790.00	19404.00
kWh	2.808	2.808	2.808	2.808	2.808	2.808	2.808	23.808	16.218	17.976	22.182	17.658	19.284	17.79	19.404
Peak load (kWh)	23.808														
Average (kWh)	9.749														

Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00
kWh	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808
Peak load (kWh)	2.808														
Average (kWh)	2.808														

Library (x2)

	Item	Floor	Device	Nominal power [W]	# of units	Total peak power [W]	Expected operating hours [hr]	Day time load/ Night time load	Variability	1	2	3	4	5	6	7
Weekdays	1	UNDP	Fans (ceiling mounted)	80	25	2000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	UNDP	Lights	36	70	2520	8	Day time	Lights Pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	UNDP	External Lights	36	20	720	16	Night time	None	720.00	720.00	720.00	720.00	720.00	720.00	720.00
	4	UNDP	Desktop Computer	200	10	2000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	UNDP	MFP Printer	500	1	500	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	UNDP	Phone Chargers	10	50	500	3	Day time	Random Working pattern (Low)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	UNDP	Projector (LCD)	350	2	700	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weekends	8	UNDP	External Lights	36	20	720	24	Base load	None	720.00	720.00	720.00	720.00	720.00	720.00	720.00

Dean Office

	Item	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			
Weekdays	1	2328.00	1440.00	1488.00	2112.00	1776.00	1968.00	1800.00	1752.00	1944.00	1728.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18336.00	19200	96%
	2	1728.00	1512.00	1296.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1728.00	0.00	0.00	0.00	0.00	0.00	0.00	13824.00	17280	80%
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	432.00	432.00	432.00	432.00	432.00	432.00	5616.00	6912	81%
	4	3880.00	2400.00	2480.00	3520.00	2960.00	3280.00	3000.00	2920.00	3240.00	2880.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30560.00	32000	96%
	5	0.00	0.00	500.00	500.00	0.00	0.00	0.00	500.00	500.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2000.00	2000	100%
	6	0.00	135.00	245.00	130.00	175.00	250.00	125.00	215.00	185.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1460.00	1500	97%
	7	0.00	0.00	175.00	175.00	0.00	0.00	0.00	175.00	175.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	700.00	700	100%
Weekends	8	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	432.00	10368.00	10368	100%

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	8548.80	6825.60	2073.60	518.40	518.40	518.40	518.40	518.40	518.40
kWh	8.5488	6.8256	2.0736	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184
Peak load (kWh)									
Average (kWh)									

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40
kWh	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184	0.5184
Peak load (kWh)									
Average (kWh)									

Lecture Halls (x9)

	Item	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			
Weekdays	1	15520.00	9600.00	9920.00	14080.00	11840.00	#######	12000.00	11680.00	12960.00	11520.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	122240.00	128000	96%
	2	4320.00	3780.00	3240.00	2700.00	2700.00	2700.00	2700.00	2700.00	2700.00	2700.00	4320.00	0.00	0.00	0.00	0.00	0.00	0.00	34560.00	43200	80%
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	30420.00	37440	81%
	4	0.00	135.00	245.00	130.00	175.00	250.00	125.00	215.00	185.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1460.00	1500	97%
	5	0.00	0.00	1575.00	1575.00	0.00	0.00	0.00	1575.00	1575.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6300.00	6300	100%
Weekends	6	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	2340.00	56160.00	56160	100%

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	20904.00	17064.00	5184.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00
kWh	20.904	17.064	5.184	2.808	2.808	2.808	2.808	2.808	2.808
Peak load (kWh)									
Average (kWh)									

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00
kWh	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808	2.808
Peak load (kWh)									
Average (kWh)									

Library (x2)

	Item	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			
Weekdays	1	1940.00	1200.00	1240.00	1760.00	1480.00	1640.00	1500.00	1460.00	1620.00	1440.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15280.00	16000	96%
	2	2016.00	1764.00	1512.00	1260.00	1260.00	1260.00	1260.00	1260.00	1260.00	1260.00	2016.00	0.00	0.00	0.00	0.00	0.00	0.00	16128.00	20160	80%
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	720.00	720.00	720.00	720.00	720.00	720.00	9360.00	11520	81%
	4	1940.00	1200.00	1240.00	1760.00	1480.00	1640.00	1500.00	1460.00	1620.00	1440.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15280.00	16000	96%
	5	0.00	0.00	250.00	250.00	0.00	0.00	0.00	250.00	250.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000.00	1000	100%
	6	0.00	135.00	245.00	130.00	175.00	250.00	125.00	215.00	185.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1460.00	1500	97%
	7	0.00	0.00	350.00	350.00	0.00	0.00	0.00	350.00	350.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1400.00	1400	100%
Weekends	8	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	17280.00	17280	100%

Load curve Weekdays

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	864.00	864.00	864.00	864.00	864.00	864.00	864.00	7075.20	5158.80	5804.40	6612.00	5274.00	5748.00	5262.00	5994.00
kWh	0.864	0.864	0.864	0.864	0.864	0.864	0.864	7.0752	5.1588	5.8044	6.612	5.274	5.748	5.262	5.994
Peak load (kWh)	**7.0752**														
Average (kWh)	**2.9954**														

Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00
kWh	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864
Peak load (kWh)	**0.864**														
Average (kWh)	**0.864**														

Hostel (x2)

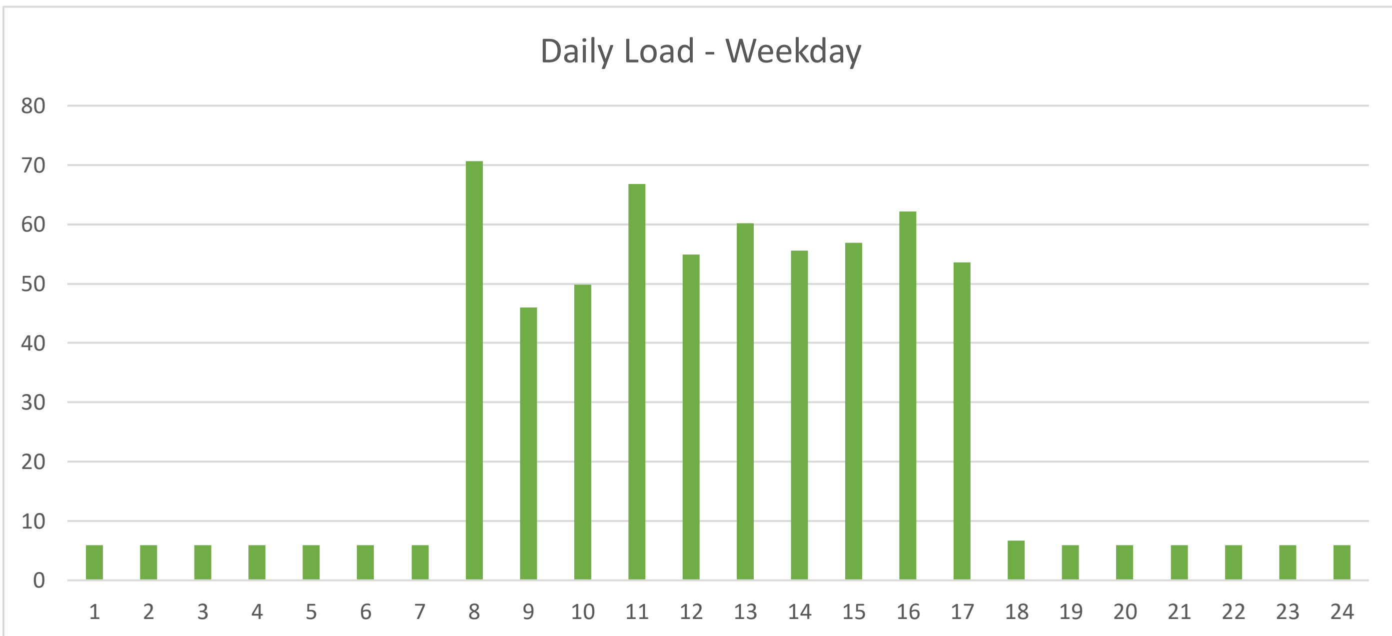
	Item	Floor	Device	Nominal power [W]	# of units	Total peak power [W]	Expected operating hours [hr]	Day time load/ Night time load	Variability	1	2	3	4	5	6	7
Weekdays	1	UNDP	Fans (ceiling mounted)	80	30	2400	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	UNDP	Lights	36	70	2520	8	Day time	Lights Pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	UNDP	External Lights	36	30	1080	16	Night time	None	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00
	4	UNDP	Phone Chargers	10	50	500	3	Day time	Random Working pattern (Low)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weekends	5	UNDP	External Lights	36	30	1080	24	Base load	None	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00

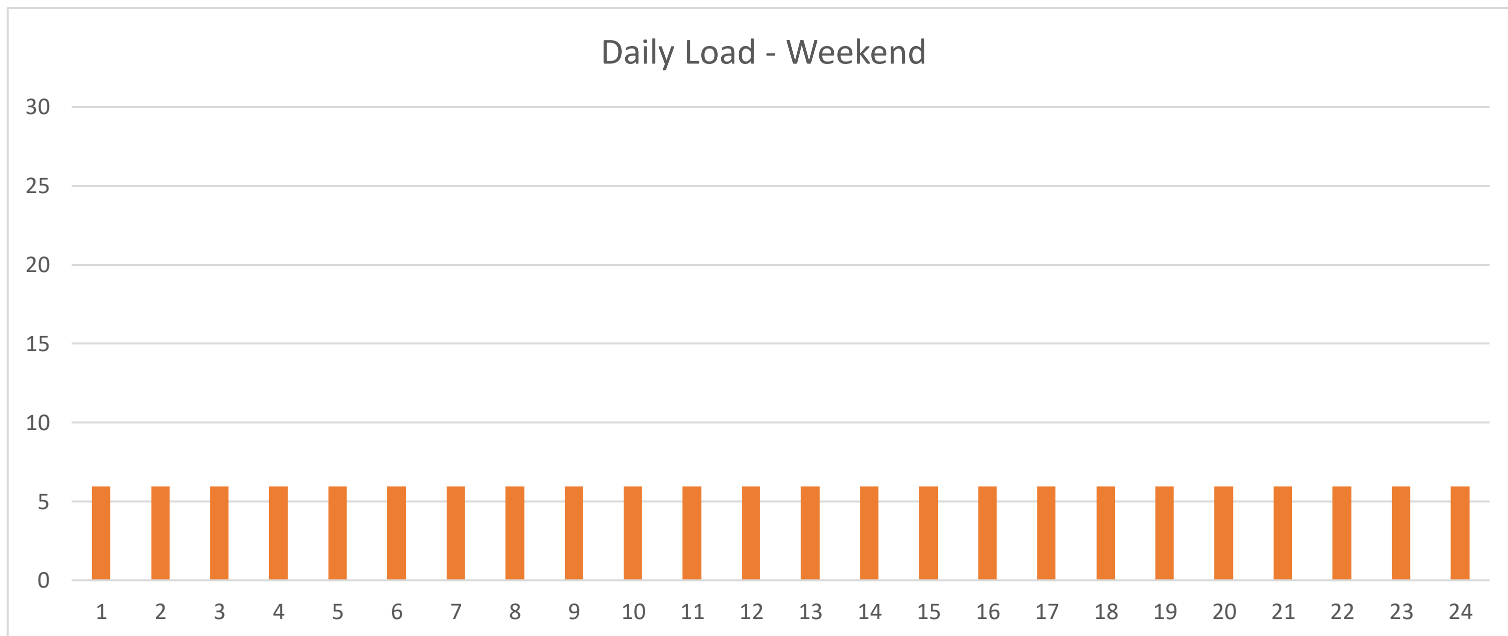
Load curve Weekdays

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	5212.80	4006.80	3894.00	4202.40	3853.20	4173.60	3822.00	3872.40
kWh	1.296	1.296	1.296	1.296	1.296	1.296	1.296	5.2128	4.0068	3.894	4.2024	3.8532	4.1736	3.822	3.8724
Peak load (kWh)	**5.2128**	**Peak load (kW)**	7.8												
Average (kWh)	**2.4982**														

Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00
kWh	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296
Peak load (kWh)	**1.296**	**Peak load (kW)**	1.296												
Average (kWh)	**1.296**														





	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	6342.00	4968.00	2419.20	864.00	864.00	864.00	864.00	864.00	864.00
kWh	6.342	4.968	2.4192	0.864	0.864	0.864	0.864	0.864	0.864
Peak load (kWh)									
Average (kWh)									

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00	864.00
kWh	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864
Peak load (kWh)									
Average (kWh)									

Hostel (x2)

	Item	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			
Weekdays	1	2328.00	1440.00	1488.00	2112.00	1776.00	1968.00	1800.00	1752.00	1944.00	1728.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18336.00	19200	**96%**
	2	2016.00	1764.00	1512.00	1260.00	1260.00	1260.00	1260.00	1260.00	1260.00	1260.00	2016.00	0.00	0.00	0.00	0.00	0.00	0.00	16128.00	20160	**80%**
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	14040.00	17280	**81%**
	4	0.00	135.00	245.00	130.00	175.00	250.00	125.00	215.00	185.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1460.00	1500	**97%**
Weekends	5	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	1080.00	25920.00	25920	**100%**

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	4066.80	3585.60	2419.20	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00
kWh	4.0668	3.5856	2.4192	1.296	1.296	1.296	1.296	1.296	1.296
Peak load (kWh)									
Average (kWh)									

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00	1296.00
kWh	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296	1.296
Peak load (kWh)									
Average (kWh)									

VC's Office

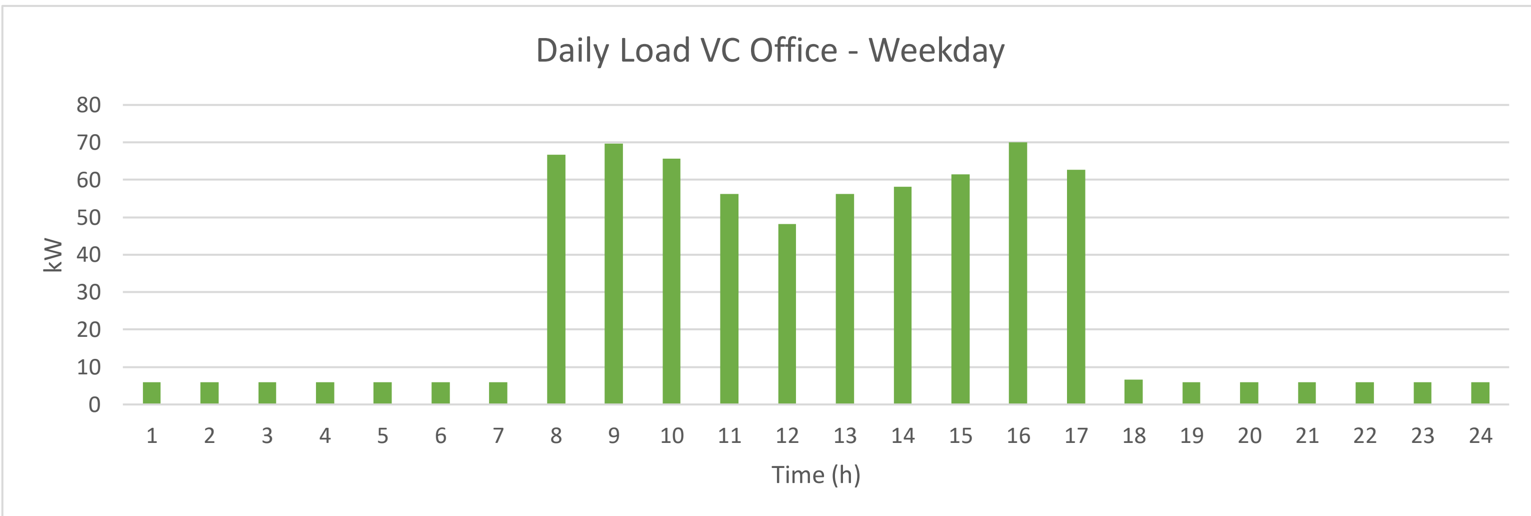
	Item	Floor	Device	Nominal power [W]	# of units	Total peak power [W]	Expected operating hours [hr]	Day time load/ Night time load	Variability	1	2	3	4	5	6	7
Weekdays	1	UNDP	Fans (ceiling mounted)	80	40	3200	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	UNDP	Lights	36	46	1656	8	Day time	Lights Pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	UNDP	External Lights	36	20	720	16	Night time	None	720.00	720.00	720.00	720.00	720.00	720.00	720.00
	4	UNDP	Laptops	80	9	720	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	UNDP	Desktop Computer	200	45	9000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	UNDP	MFP Printer	500	2	1000	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	UNDP	Phone	10	35	350	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	UNDP	Projector (LCD)	350	9	3150	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	UNDP	AC	3500	12	42000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	10	UNDP	AC server room	3500	1	3500	24	Base load	None	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00
	11	UNDP	Server/VSAT/switches	750	1	750	24	Base load	None	750.00	750.00	750.00	750.00	750.00	750.00	750.00
Weekends	12	UNDP	Lights	36	20	720	24	Base load	None	720.00	720.00	720.00	720.00	720.00	720.00	720.00
	13	UNDP	Server/VSAT/switches	750	1	750	24	Base load	None	750.00	750.00	750.00	750.00	750.00	750.00	750.00
	14	UNDP	AC server room	3500	1	3500	24	Base load	None	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00

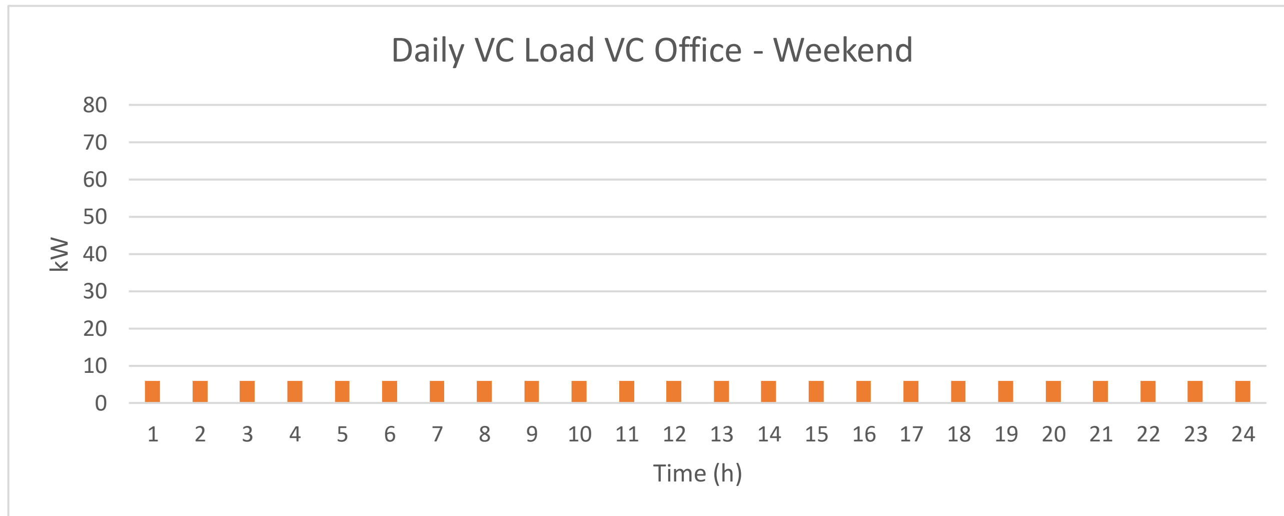
Load curve Weekdays

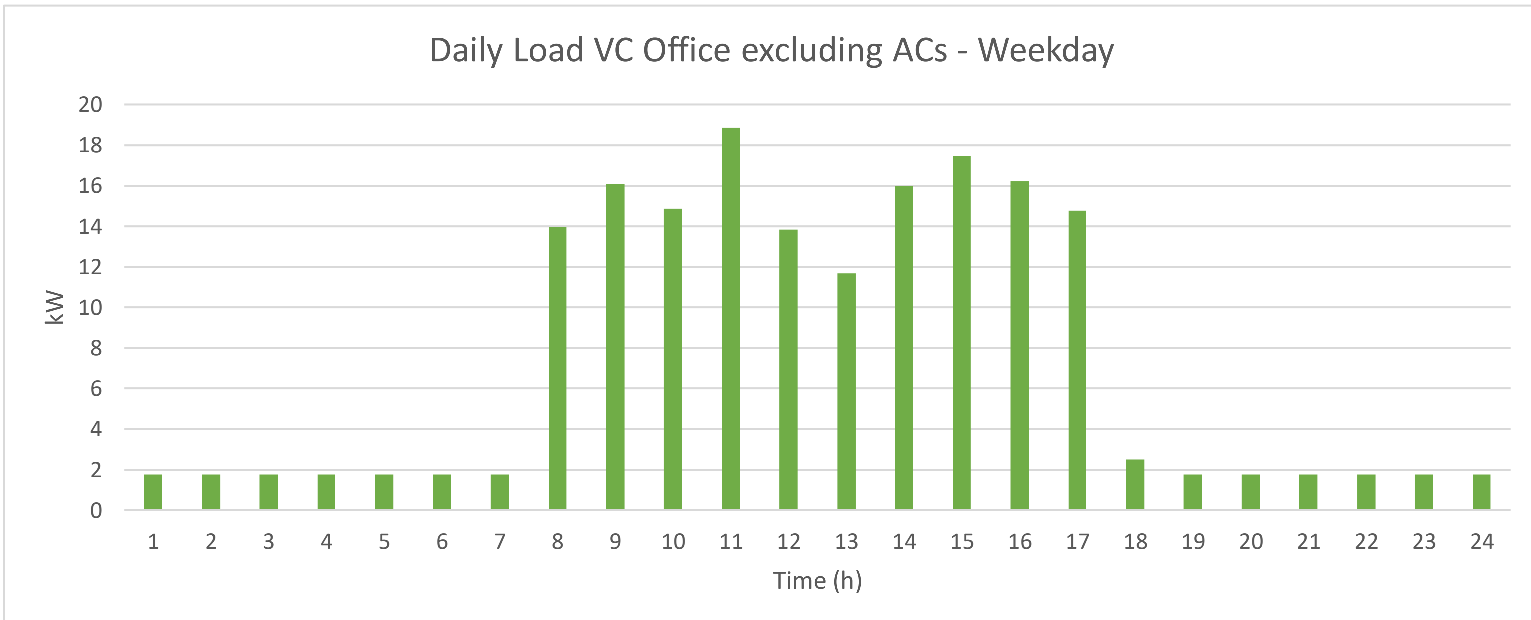
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	66662.40	69758.88	65669.76	56244.48	48272.16	56180.64	58157.76	61516.80
kWh	5.964	5.964	5.964	5.964	5.964	5.964	5.964	66.6624	69.75888	65.66976	56.24448	48.27216	56.18064	58.15776	61.5168
Peak load (kWh)	**70.08432**														
Average (kWh)	**29.1475**														

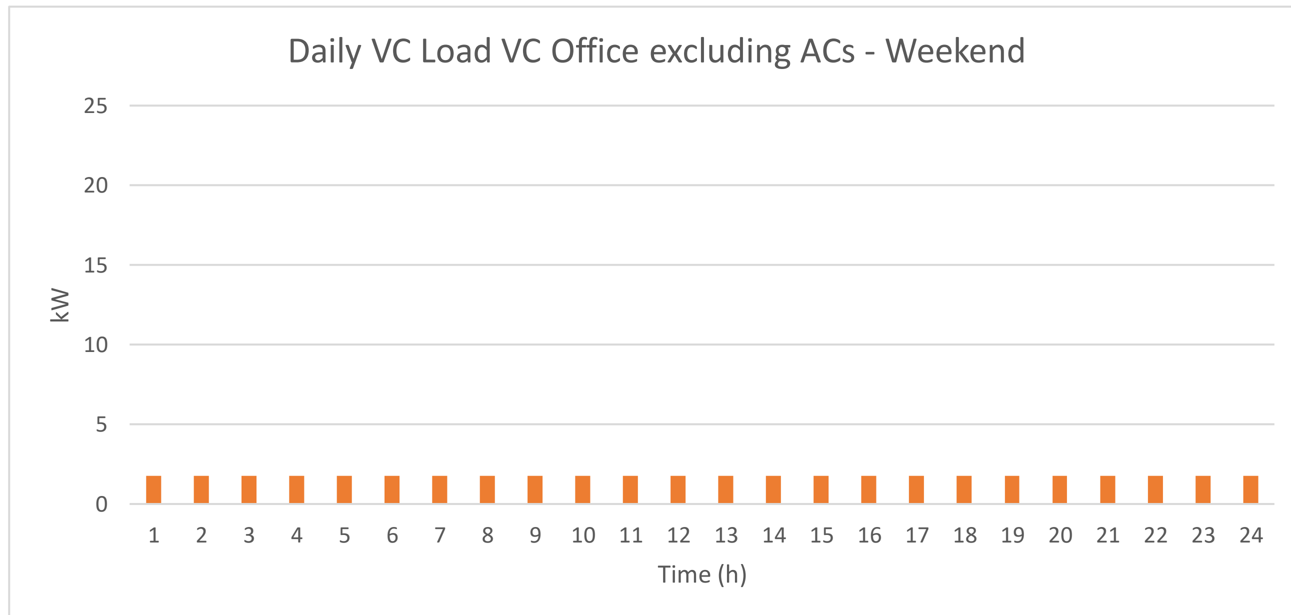
Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00
kWh	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964
Peak load (kWh)	**5.964**														
Average (kWh)	**5.964**														









VC's Office

	Item	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			
Weekdays	1	2912.00	3072.00	2752.00	2304.00	2048.00	2432.00	2528.00	2560.00	2976.00	2752.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	26336.00	25600	103%
	2	1324.80	1159.20	993.60	828.00	828.00	828.00	828.00	828.00	828.00	828.00	1324.80	0.00	0.00	0.00	0.00	0.00	0.00	10598.40	13248	80%
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	720.00	720.00	720.00	720.00	720.00	720.00	9360.00	11520	81%
	4	655.20	691.20	619.20	518.40	460.80	547.20	568.80	576.00	669.60	619.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5925.60	5760	103%
	5	8190.00	8640.00	7740.00	6480.00	5760.00	6840.00	7110.00	7200.00	8370.00	7740.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	74070.00	72000	103%
	6	0.00	0.00	500.00	500.00	0.00	0.00	0.00	500.00	500.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2000.00	2000	100%
	7	0.00	0.00	175.00	175.00	0.00	0.00	0.00	175.00	175.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	700.00	700	100%
	8	0.00	0.00	1575.00	1575.00	0.00	0.00	0.00	1575.00	1575.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6300.00	6300	100%
	9	38220.00	40320.00	36120.00	30240.00	26880.00	31920.00	33180.00	33600.00	39060.00	36120.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	345660.00	336000	103%
	10	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	84000.00	84000	100%
	11	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	18000.00	18000	100%
Weekends	12	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	17280.00	17280	100%
	13	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	18000.00	18000	100%
	14	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	3500.00	84000.00	84000	100%

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	70084.32	62771.04	6689.76	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00
kWh	70.08432	62.77104	6.68976	5.964	5.964	5.964	5.964	5.964	5.964
Peak load (kWh)									
Average (kWh)									

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00	5964.00
kWh	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964	5.964
Peak load (kWh)									
Average (kWh)									

VC's Office - Excluding ACs

Weekdays - Daily Profile

Time	Consum (kWh)
1	1.76
2	1.76
3	1.76
4	1.76
5	1.76
6	1.76
7	1.76
8	13.96
9	16.09
10	14.87
11	18.86
12	13.83
13	11.66
14	16.00
15	17.46
16	16.22
17	14.76
18	2.49
19	1.76
20	1.76
21	1.76
22	1.76
23	1.76
24	1.76
TOTAL	179.14
HOURLY AVG	7.46
THEORETICAL	6.46
COMPARISON	115%
PEAK (KW)	24.66

Weekends - Daily Profile

Time	Consum (kWh)
1	1.76
2	1.76
3	1.76
4	1.76
5	1.76
6	1.76
7	1.76
8	1.76
9	1.76
10	1.76
11	1.76
12	1.76
13	1.76
14	1.76
15	1.76
16	1.76
17	1.76
18	1.76
19	1.76
20	1.76
21	1.76
22	1.76
23	1.76
24	1.76
TOTAL	42.34
HOURLY AVG	1.76
THEORETICAL	1.47
COMPARISON	120%
PEAK (KW)	1.76

AVG ANNUAL CONSUMPTION	51119.86	kWh/year	AVG DAILY CONSUMPTION	140.05	kWh/day

Lecturers' Office

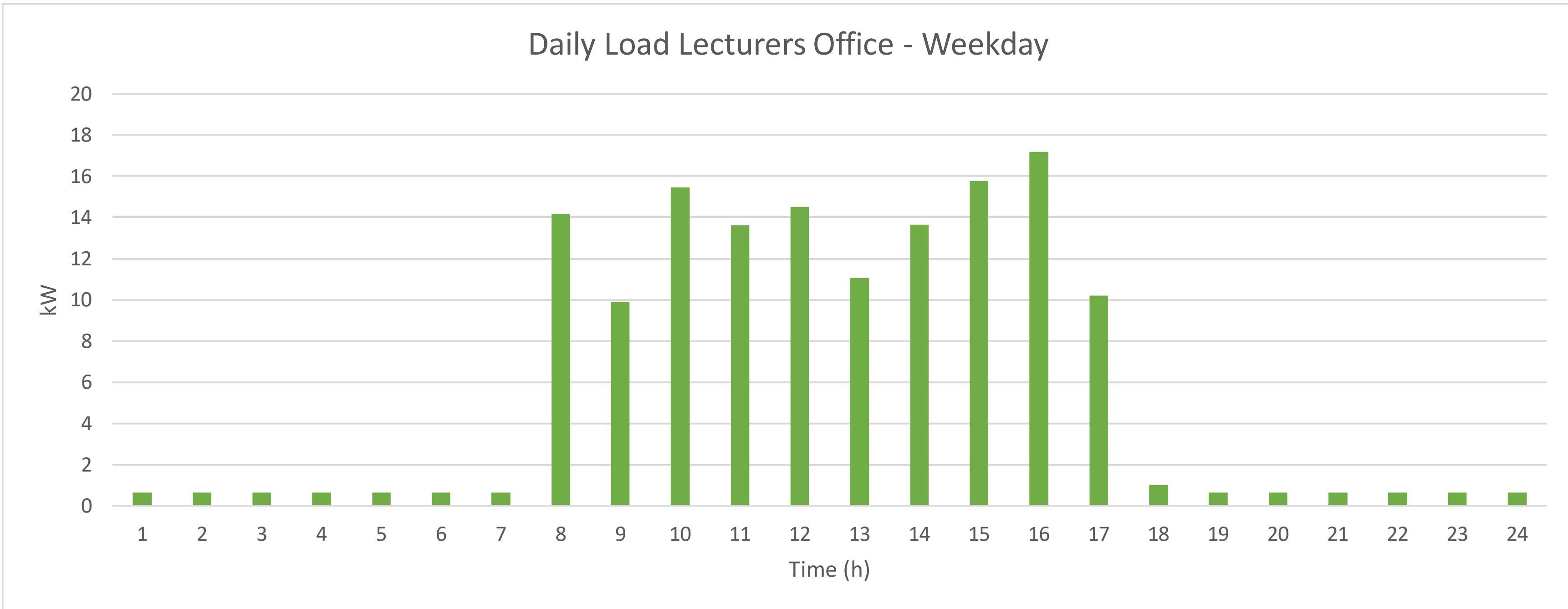
	Item	Floor	Device	Nominal power [W]	# of units	Total peak power [W]	Expected operating hours [hr]	Day time load/ Night time load	Variability	1	2	3	4	5	6	7
Weekdays	1	UNDP	Fans (ceiling mounted)	80	40	3200	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	UNDP	Lights	36	29	1044	8	Day time	Lights Pattern	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	UNDP	External Lights	36	15	540	16	Night time	None	540.00	540.00	540.00	540.00	540.00	540.00	540.00
	4	UNDP	Laptops	80	9	720	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	UNDP	Desktop Computer	200	40	8000	8	Day time	Random Working pattern (intense)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	UNDP	MFP Printer	500	1	500	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	UNDP	Phone	10	35	350	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	UNDP	Projector (LCD)	350	9	3150	2	Day time	Small printers 4h	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	UNDP	Server/VSAT/switches	750	1	750	24	Base load	None	750.00	750.00	750.00	750.00	750.00	750.00	750.00
Weekends	10	UNDP	Lights	36	15	540	24	Base load	None	540.00	540.00	540.00	540.00	540.00	540.00	540.00
	11	UNDP	Server/VSAT/switches	750	1	750	24	Base load	None	750.00	750.00	750.00	750.00	750.00	750.00	750.00

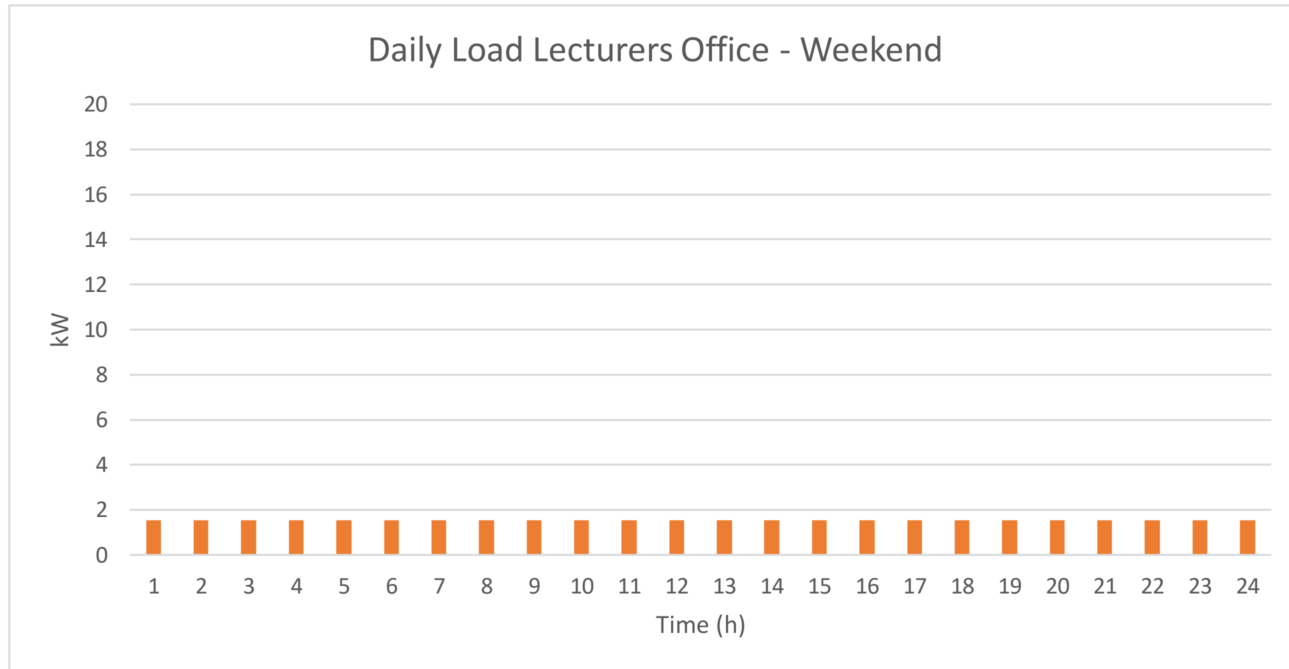
Load curve Weekdays

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	648.00	648.00	648.00	648.00	648.00	648.00	648.00	14161.92	9888.48	15453.12	13611.36	14501.28	11068.32	13643.04	15756.96
kWh	0.648	0.648	0.648	0.648	0.648	0.648	0.648	14.16192	9.88848	15.45312	13.61136	14.50128	11.06832	13.64304	15.75696
Peak load	**17.18736**														
Average	**6.03784**														

Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Variable curve (Wh)	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00
kWh	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548
Peak load	**1.548**														
Average	**1.548**														





Lecturers' Office

	Item	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			
Weekdays	1	2944.00	2016.00	2752.00	2368.00	3104.00	2336.00	2912.00	2848.00	3168.00	2144.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	26592.00	25600	104%
	2	835.20	730.80	626.40	522.00	522.00	522.00	522.00	522.00	522.00	522.00	835.20	0.00	0.00	0.00	0.00	0.00	0.00	6681.60	8352	80%
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	540.00	540.00	540.00	540.00	540.00	540.00	7020.00	8640	81%
	4	662.40	453.60	619.20	532.80	698.40	525.60	655.20	640.80	712.80	482.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5983.20	5760	104%
	5	7360.00	5040.00	6880.00	5920.00	7760.00	5840.00	7280.00	7120.00	7920.00	5360.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66480.00	64000	104%
	6	0.00	0.00	250.00	250.00	0.00	0.00	0.00	250.00	250.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000.00	1000	100%
	7	0.00	0.00	175.00	175.00	0.00	0.00	0.00	175.00	175.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	700.00	700	100%
	8	0.00	0.00	1575.00	1575.00	0.00	0.00	0.00	1575.00	1575.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6300.00	6300	100%
	9	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	18000.00	18000	100%
Weekends	10	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	540.00	12960.00	12960	100%
	11	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	750.00	18000.00	18000	100%

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	17187.36	10210.08	1002.24	648.00	648.00	648.00	648.00	648.00	648.00
kWh	17.18736	10.21008	1.00224	0.648	0.648	0.648	0.648	0.648	0.648
Peak load									
Average									

	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00	1548.00
kWh	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548	1.548
Peak load									
Average									

Total Load - Including Hostels

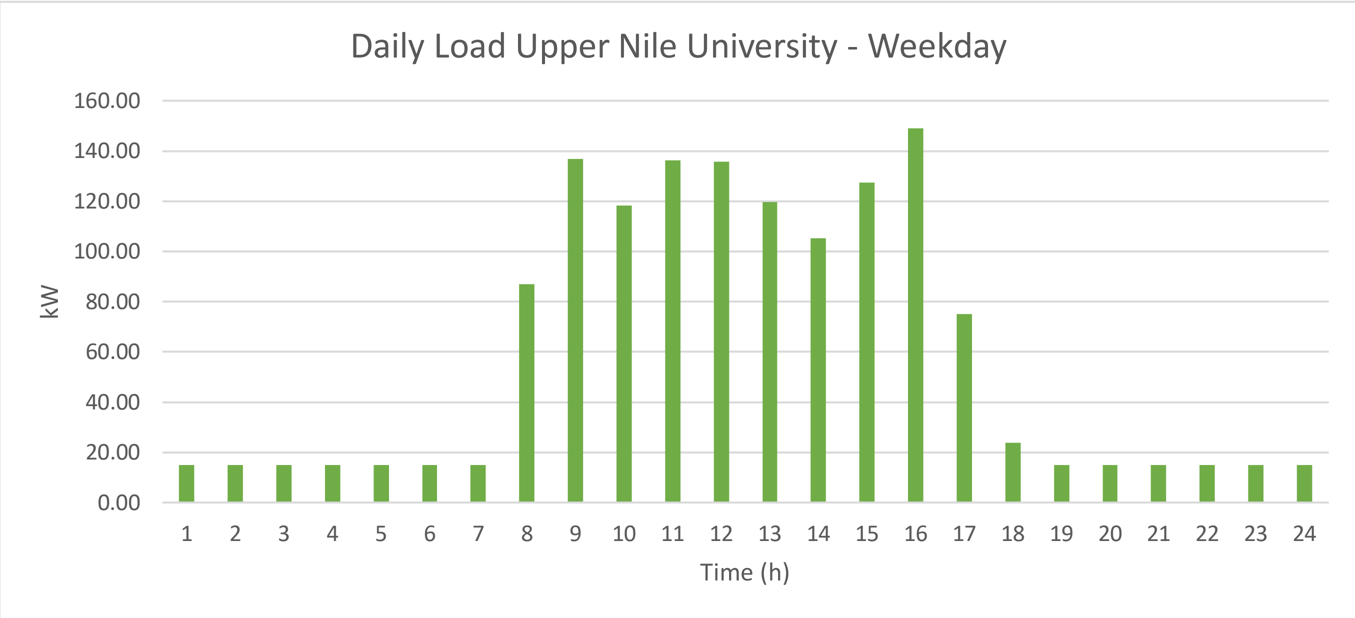
Load curve Weekdays

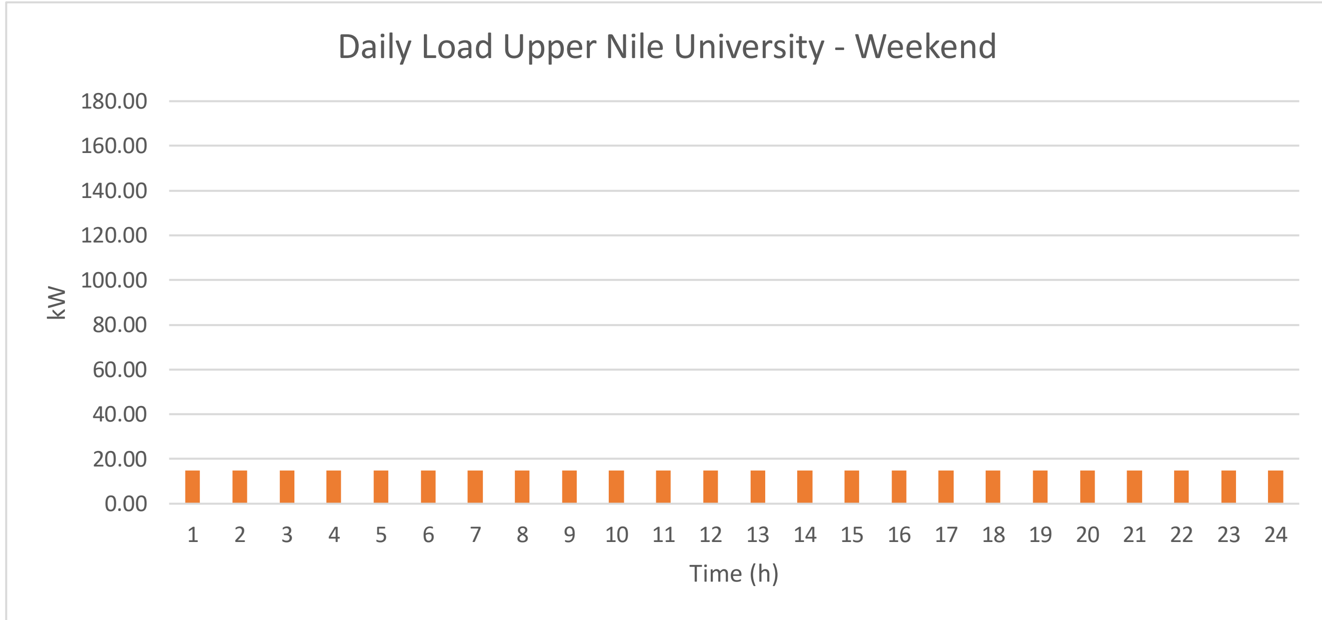
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	87081.00	136695.20	118325.60	136164.80	########	119666.40	105175.60	127544.80	149120.80	74998.20	23732.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80
kWh	14.95	14.95	14.95	14.95	14.95	14.95	14.95	87.08	136.70	118.33	136.16	135.77	119.67	105.18	127.54	149.12	75.00	23.73	14.95	14.95	14.95	14.95	14.95	14.95
Peak load (kWh)	**149.12**	**Peak load (kW)**	189.84	227.81																				
Average (kWh)	**58.69**																							

Load curve Weekends

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Variable curve (Wh)	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80	14948.80
kWh	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95	14.95
Peak load (kWh)	**14.95**	**Peak load (kW)**	14.95																					
Average (kWh)	**14.95**																							

Average (kW)	46.19	**Average (kWh/day)**	1108.65	**Average (kWh/year)**	404658.21





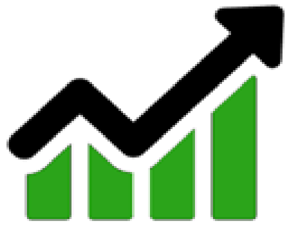
Variability Pattern	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Regular working Pattern	0	0	0	0	0	0	0	0.3	0.31	0.88	0.98	0.85	0.63	0.7	0.76	0.9	0.39	0	0	0	0	0	0	0
Random Working pattern (intense)	0	0	0	0	0	0	0	0.65	0.96	0.86	0.84	0.94	0.8	0.7	0.73	0.93	0.97	0	0	0	0	0	0	0
Random Working pattern (Medium)	0	0	0	0	0	0	0	0.7	0.53	0.49	0.61	0.45	0.5	0.68	0.41	0.68	0.61	0	0	0	0	0	0	0
Random Working pattern (Low)	0	0	0	0	0	0	0	0.37	0.43	0.32	0.38	0.4	0.26	0.23	0.25	0.49	0.21	0	0	0	0	0	0	0
Tcontrol	0.41	0.53	0.6	0.5	0.43	0.6	0.45	0.8	0.88	0.75	0.89	0.89	0.68	0.66	0.81	0.72	0.74	0.77	0.57	0.47	0.5	0.45	0.54	0.47
Lights Pattern	1	1	1	1	1	1	0.9	0.8	0.7	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.8	0.9	1	1	1	1	1
Meal Pattern	0	0	0	0	0	0	0.4	0.8	0.5	0	0	0.5	0.8	0.5	0	0	0	0	0	0	0	0	0	0
Toilet Pattern	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.9	0.9	0.8	0.7	0.7	0.6	0.5	0.2	0.2	0.2	0.2	0.2
Boileres Pattern	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	0.4	0.3	0.2	0.2	0.2	0.1	0.1	0.2	0.4	0.6	0.1	0.1	0.1	0.1	0.1	0.1
Printers 5 h heavy	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0
Small printers 4h	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0
Lunch Pattern Load	0	0	0	0	0	0	0	0	0	0	0	0.3	1	0.2	0	0	0	0	0	0	0	0	0	0
None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Annex B

OIMT Project Database

The OIMT Project database contains the quotation data of all the projects implemented by the OIMT Green Energy Services team, including the main characteristics of each of the projects and categorized by components and year of implementation. It is used to estimate the unit costs of the components of the power systems to be designed, such as price per kWp of PV in a specific country.

GREEN TEAM BUSINESS CASE COST ESTIMATE TOOL



2. Business Case

Participant: GIA unit

This step serves to provide essential information and data for decision-making. With the information gathered during Self Assessment (step 1) through the PCMM and CO schematics, OIMT/GIA compiles a load profile of the energy consumption for the respective Country Office. This enables an analysis resulting in drafting of a business case which presents a potential green energy solution (solar and/or wind) for the CO. Among other things, the business case provides the following information:

- an overview of the planned solution,
- risk assessment
- environmental impact from CO2 reduction
- a budget estimate for the proposed solution
- annual savings
- initial bill of material
- approximate return on investment (ROI)
- OIMT recommendation on way forward

*** PLEASE ALWAYS CREATE A COPY OF THIS EXCEL FILE WHEN USING FOR A BUSINESS CASE**

	Excel Spreadsheet	Category	Use	Explained
1	OneNoteRFQ	**OUTPUT** for OneNotes	Admin Only	OneNote spreadsheets for Green Team OneNote (**7-step Procedures ==> 7.Solar Installations**). Admin to update spreadsheets, then copy them and paste in OneNote
2	OneNoteBC	**OUTPUT** for OneNotes	Admin Only	
3	RFQs	**INPUT** RFQ Database	Admin Only	Contains financial information from all **vendor bids received by Green Team**
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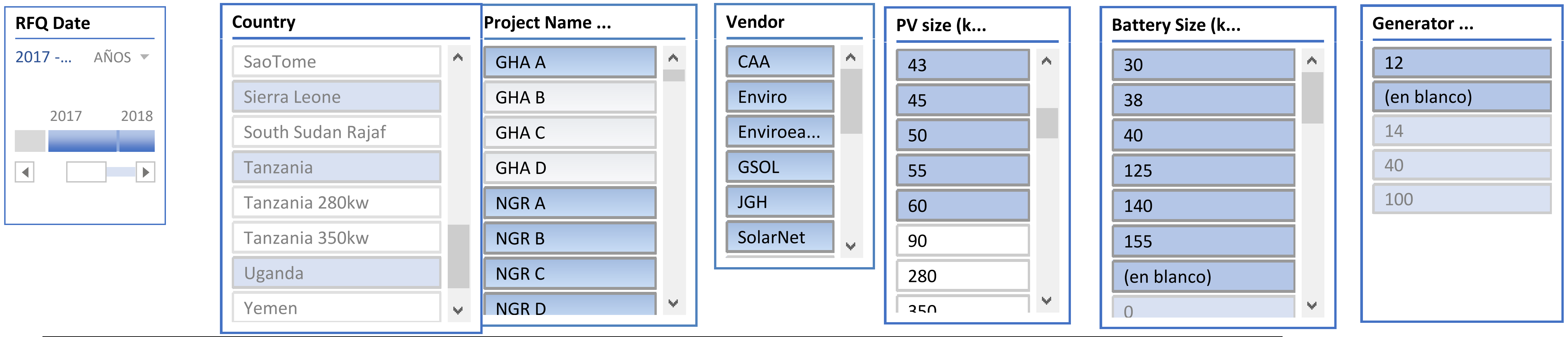
5	Project Comparison	**COST INPUT FOR CURRENT PROJECT**	Green Team	Pivot tables and charts for new Green Team project cost estimation
6	Cost Table	**OUTPUT** for HOMER	Green Team	Project cost breakdown and outputs for HOMER software
7	ALL	**GRAPHS**	Green Team	TOTAL PROJECT COSTS (all projects // PV projects without battery // projects with PV and battery)
8	PV Only	**GRAPHS**	Green Team	
9	PV&Bat	**GRAPHS**	Green Team	
10	ALL <90kW	**GRAPHS**	Green Team	TOTAL PROJECT COSTS FOR PROJECTS WITH **PV SIZE BELOW 90kW** (all projects // PV projects without battery // projects with PV and battery)
11	PV Only <90kW	**GRAPHS**	Green Team	
12	PV&Bat <90kW	**GRAPHS**	Green Team	
13	ALL ($ kWp)	**GRAPHS**	Green Team	TOTAL PROJECTS COSTS **per kWp** (all projects // PV projects without battery // projects with PV and battery)
14	PV Only ($ kWp)	**GRAPHS**	Green Team	
15	PV&Bat ($ kWp)	**GRAPHS**	Green Team	
16	Battery Costs	**GRAPHS**	Green Team	TOTAL BATTERY COSTS (all projects with battery)
17	O&M	**GRAPHS**	Green Team	TOTAL O&M COSTS (all projects)
18	Freight	**GRAPHS**	Green Team	TOTAL FREIGHT COSTS (all projects)

NOTES:

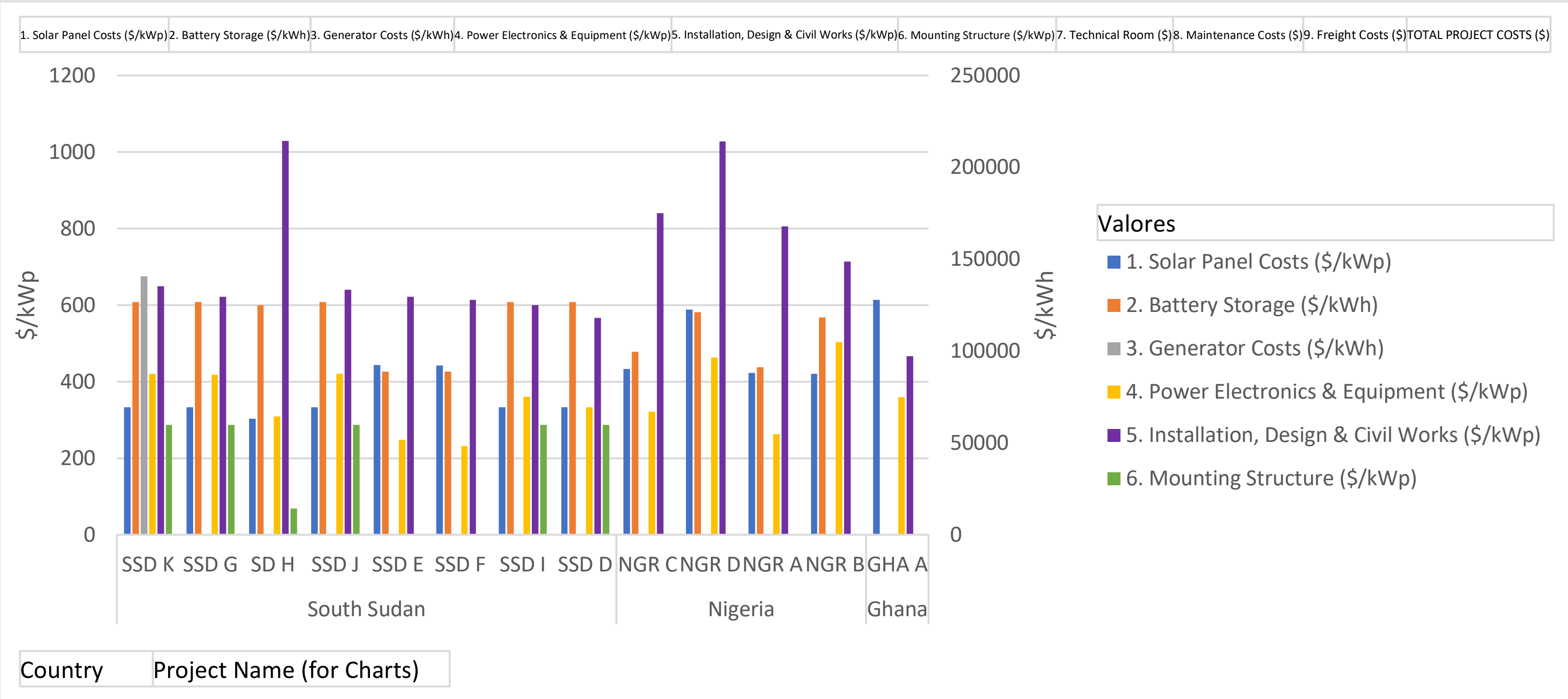
VERSION 5:
- Fixed the issue with the ZERO for Yemen
- Calculations for Guinea (and Guinea only) were changed since it's just a system with battery. Instead of dividing per kWp, it's being divided per kWh - No more mistakes when considering Guinea for the comparison.

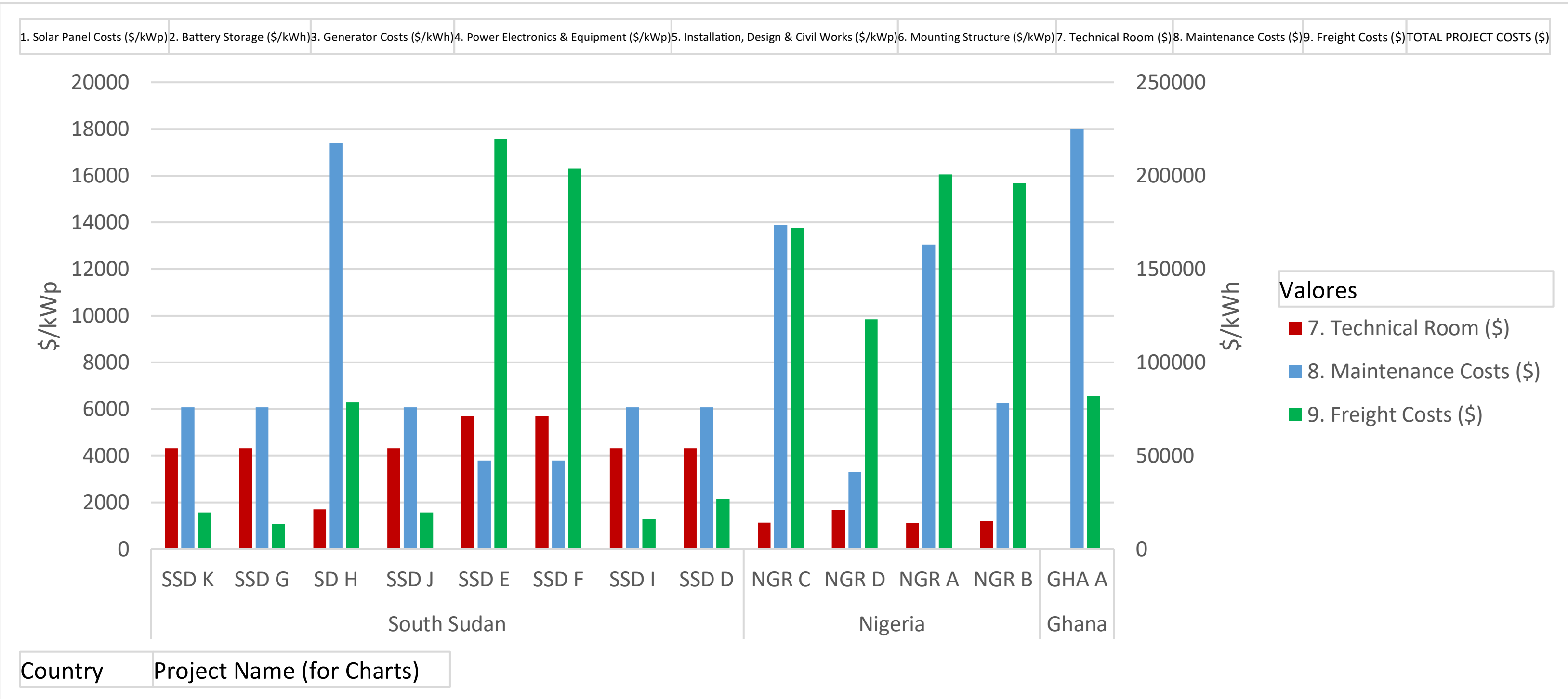
- Prices are now also filtered by Generator size, and broken down by Generator Size and Mounting Structure.
- Costs that are "included" in other costs in the offers (starting from FAO UGANDA) are now being split by average ratio from previous projects, or similar offers for that specific project
- For UNICEF Nepal: Elevated mounting structure was set as All Other, and only regular mounting structure considered as mounting structure itself

PROJECT COMPARISON



Etiquetas de fila	1. Solar Panel Costs ($/kWp)	2. Battery Storage ($/kWh)	3. Generator Costs ($/kWh)	4. Power Electronics & Equipment ($/kWp)	5. Installation, Design & Civil Works ($/kWp)	6. Mounting Structure ($/kWp)	7. Technical Room ($)	8. Maintenance Costs ($)	9. Freight Costs ($)	TOTAL PROJECT COSTS ($)
South Sudan	**357**	**561**	**675**	**343**	**668**	**251**	**4337**	**6920**	**5980**	**101593**
SSD K	333	608	675	420	649	287	4320	6075	1580	80373
SSD G	333	608		418	621	287	4320	6075	1080	76958
SD H	303	600		309	1029	68	1707	17393	6283	98623
SSD J	333	608		420	640	287	4320	6075	1580	72003
SSD E	443	426		248	622		5696	3797	17586	132562
SSD F	442	426		232	613		5696	3797	16292	147184
SSD I	333	608		361	600	287	4320	6075	1280	94210
SSD D	333	608		333	567	287	4320	6075	2160	110837
Nigeria	**466**	**516**		**388**	**847**		**1289**	**9125**	**13833**	**150981**
NGR C	433	478		322	840		1140	13882	13747	110750
NGR D	588	582		463	1028		1690	3315	9845	118907
NGR A	423	437		263	806		1110	13052	16056	194975
NGR B	420	568		503	713		1215	6250	15685	179290
Ghana	**614**			**359**	**466**			**18000**	**6570**	**103382**
GHA A	614			359	466			18000	6570	103382
Total general	**410**	**546**	**675**	**358**	**707**	**251**	**3321**	**8451**	**8442**	**116927**


1. Solar Panel Costs ($/kWp) 2. Battery Storage ($/kWh) 3. Generator Costs ($/kWh) 4. Power Electronics & Equipment ($/kWp) 5. Installation, Design & Civil Works ($/kWp) 6. Mounting Structure ($/kWp) 7. Technical Room ($) 8. Maintenance Costs ($) 9. Freight Costs ($) TOTAL PROJECT COSTS ($)
$/kWp
$/kWh
Valores
1. Solar Panel Costs ($/kWp)
2. Battery Storage ($/kWh)
3. Generator Costs ($/kWh)
4. Power Electronics & Equipment ($/kWp)
5. Installation, Design & Civil Works ($/kWp)
6. Mounting Structure ($/kWp)
SSD K SSD G SD H SSD J SSD E SSD F SSD I SSD D NGR C NGR D NGR A NGR B GHA A
South Sudan
Nigeria
Ghana
Country
Project Name (for Charts)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$/kWp
$/kWh
Valores
7. Technical Room ($)
8. Maintenance Costs ($)
9. Freight Costs ($)
SSD K SSD G SD H SSD J SSD E SSD F SSD I SSD D NGR C NGR D NGR A NGR B GHA A
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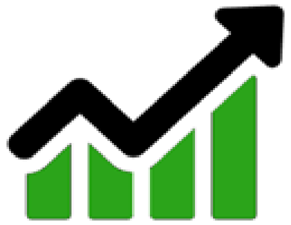
GREEN TEAM BUSINESS CASE COST ESTIMATE TOOL



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11	PV Only <90kW	**GRAPHS**	Green Team	TOTAL PROJECT COSTS FOR PROJECTS WITH **PV SIZE BELOW 90kW**
12	PV&Bat <90kW	**GRAPHS**	Green Team	
13	ALL ($ kWp)	**GRAPHS**	Green Team	
14	PV Only ($ kWp)	**GRAPHS**	Green Team	TOTAL PROJECTS COSTS **per kWp** (all projects // PV projects without battery // projects with PV and battery)
15	PV&Bat ($ kWp)	**GRAPHS**	Green Team	
16	Battery Costs	**GRAPHS**	Green Team	TOTAL BATTERY COSTS (all projects with battery)
17	O&M	**GRAPHS**	Green Team	TOTAL O&M COSTS (all projects)
18	Freight	**GRAPHS**	Green Team	TOTAL FREIGHT COSTS (all projects)

NOTES:

VERSION 5:
- Fixed the issue with the ZERO for Yemen
- Calculations for Guinea (and Guinea only) were changed since it's just a system with battery. Instead of dividing per kWp, it's being divided per kWh - No more mistakes when considering Guinea for the comparison.

- Prices are now also filtered by Generator size, and broken down by Generator Size and Mounting Structure.
- Costs that are "included" in other costs in the offers (starting from FAO UGANDA) are now being split by average ratio from previous projects, or similar offers for that specific project
- For UNICEF Nepal: Elevated mounting structure was set as All Other, and only regular mounting structure considered as mounting structure itself

PROJECT COMPARISON

RFQ Date
2017 -... AÑOS
2016 2017

Country
- Central Africa Republic
- Ghana
- Guinea
- Guyana
- Haiti
- Nepal
- Nigeria
- South Sudan

Project Name ...
- CAR A
- CAR B
- CAR C
- CAR D
- SS UNDP EE
- SSD A
- SSD B
- SSD C

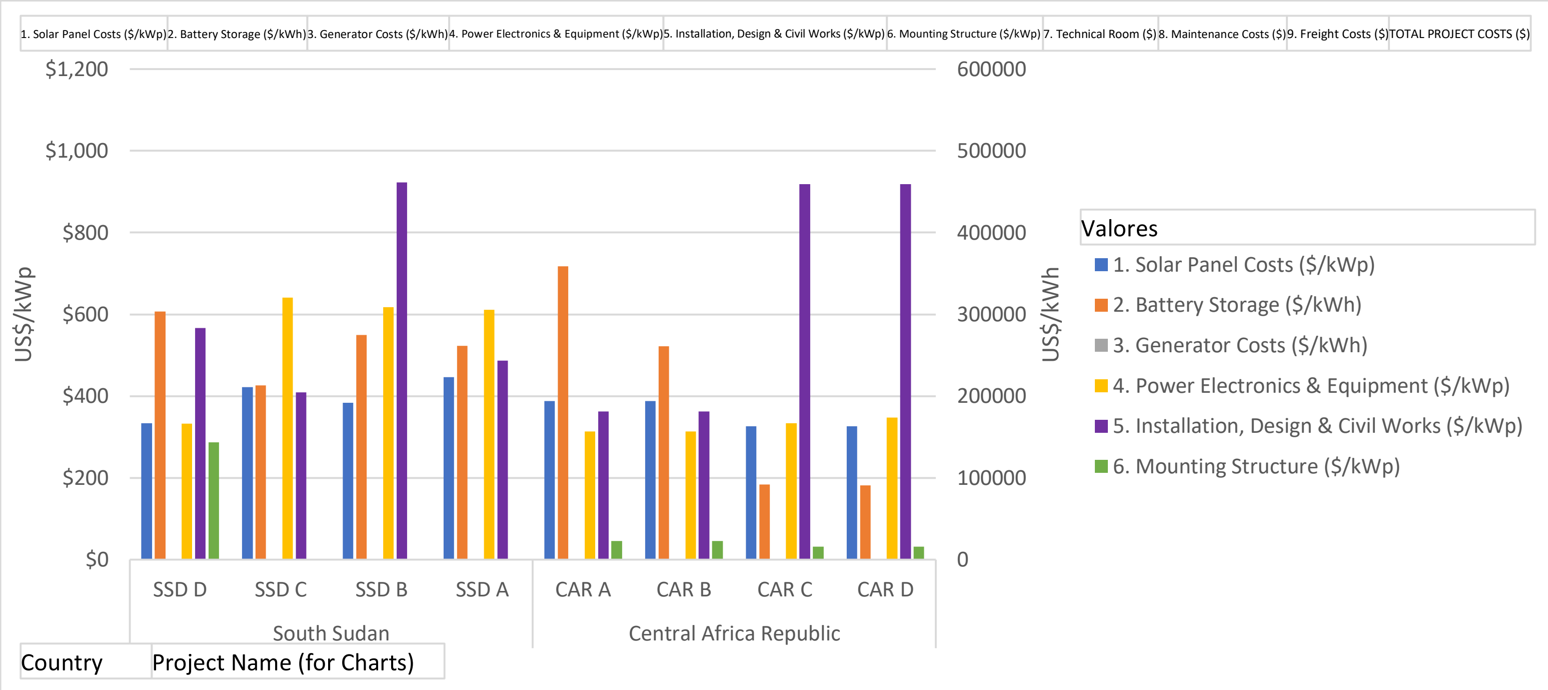
Vendor
- Enviro
- GSOL
- JGH
- Peak Int...
- Solar23
- Trama

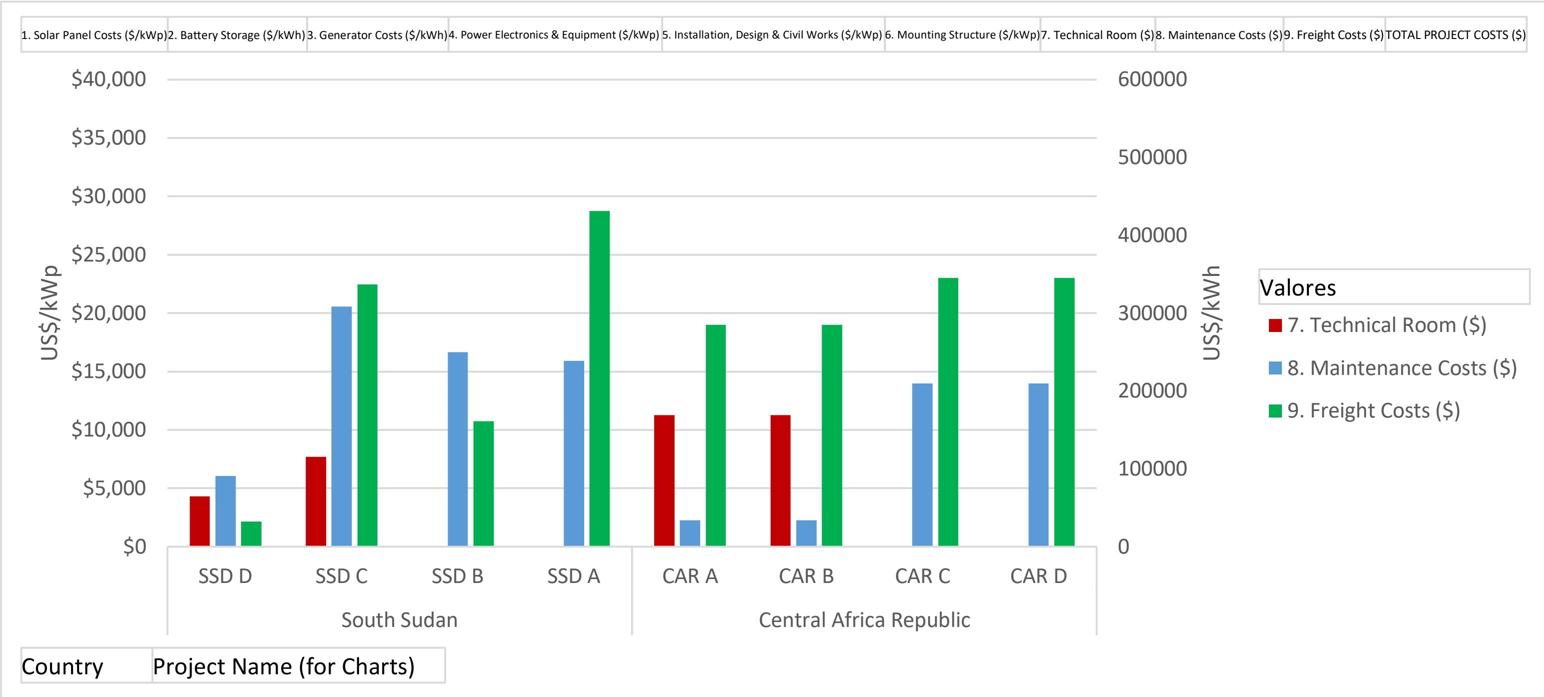
PV size (k...
- 162
- 163
- 164
- 165
- 167
- 200
- 0
- 38

Battery Size (k...
- 248
- 250
- 250
- 350
- 496
- 500
- (en blanco)

Generator ...
- (en blanco)
- 12
- 14
- 40
- 100

Etiquetas de fila	1. Solar Panel Costs ($/kWp)	2. Battery Storage ($/kWh)	3. Generator Costs ($/kWh)	4. Power Electronics & Equipment ($/kWp)	5. Installation, Design & Civil Works ($/kWp)	6. Mounting Structure ($/kWp)	7. Technical Room ($)	8. Maintenance Costs ($)	9. Freight Costs ($)	TOTAL PROJECT COSTS ($)
South Sudan	**396**	**527**		**551**	**597**	**287**	**6002**	**14808**	**16034**	**379356**
SSD D	333	608		333	567	287	4320	6075	2160	110837
SSD C	422	427		641	409		7685	20581	22478	407746
SSD B	384	550		618	923			16675	10745	490495
SSD A	446	523		611	487			15900	28754	508347
Central Africa Republic	**357**	**401**		**327**	**641**	**38**	**11250**	**8117**	**21010**	**174050**
CAR A	388	718		314	363	45	11250	2250	19000	157039
CAR B	388	522		314	363	45	11250	2250	19000	157039
CAR C	326	184		333	918	31		13984	23020	189110
CAR D	326	181		348	918	31		13984	23020	193010
Total general	**377**	**464**		**439**	**619**	**88**	**8626**	**11462**	**18522**	**276703**




1. Solar Panel Costs ($/kWp)
2. Battery Storage ($/kWh)
3. Generator Costs ($/kWh)
4. Power Electronics & Equipment ($/kWp)
5. Installation, Design & Civil Works ($/kWp)
6. Mounting Structure ($/kWp)
7. Technical Room ($)
8. Maintenance Costs ($)
9. Freight Costs ($)
TOTAL PROJECT COSTS ($)
US$/kWp
$40,000
$35,000
$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
$0
US$/kWh
600000
500000
400000
300000
200000
100000
0
SSD D
SSD C
SSD B
SSD A
CAR A
CAR B
CAR C
CAR D
South Sudan
Central Africa Republic
Valores
7. Technical Room ($)
8. Maintenance Costs ($)
9. Freight Costs ($)
Country
Project Name (for Charts)

Annex C

Project Cash Flow

The project detailed Cash Flow will be presented in this section, for the three options of Power System configuration presented to the client in South Sudan.

__Table C.1__. Nominal Cashflow for Option 1

Years	Capital	Replacement	O&M	Energy Savings	Yearly Totals	Cash Flow
0	-89,930	-	-		-89,930.0	-89,930.0
1		-	-	73,708.9	73,708.9	-16,221.1
2		-	-	73,708.9	73,708.9	57,487.9
3		-	-	73,708.9	73,708.9	131,196.8
4		-	-10,938	73,708.9	62,770.9	193,967.8
5		-	-10,938	73,708.9	62,770.9	256,738.7
6		-	-10,938	73,708.9	62,770.9	319,509.6
7		-	-10,938	73,708.9	62,770.9	382,280.6
8		-	-10,938	73,708.9	62,770.9	445,051.5
9		-	-10,938	73,708.9	62,770.9	507,822.5
10		-19,257.9	-10,938	73,708.9	43,513.0	551,335.5
11		-	-10,938	73,708.9	62,770.9	614,106.4
12		-	-10,938	73,708.9	62,770.9	676,877.4
13		-	-10,938	73,708.9	62,770.9	739,648.3
14		-	-10,938	73,708.9	62,770.9	802,419.3
15		-	-10,938	73,708.9	62,770.9	865,190.2
16		-	-10,938	73,708.9	62,770.9	927,961.1
17		-	-10,938	73,708.9	62,770.9	990,732.1
18		-	-10,938	73,708.9	62,770.9	1,053,503.0
19		-	-10,938	73,708.9	62,770.9	1,116,274.0
20		-19,257.9	-10,938	73,708.9	43,513.0	1,159,787.

Table C.2. *Nominal Cashflow for Option 2*

Years	Capital	Replacement	O&M	Energy Savings	Yearly Totals	Cash Flow
0	-101,103	-	-		-101,103	-101,103.0
1		-	-	83,555	70,351.2	-17,547.8
2		-	-	83,555	70,351.2	66,007.4
3		-	-	83,555	70,351.2	149,562.6
4		-	-13,204	83,555	70,351.2	219,913.8
5		-	-13,204	83,555	70,351.2	290,265.0
6		-	-13,204	83,555	70,351.2	360,616.1
7		-	-13,204	83,555	70,351.2	430,967.3
8		-	-13,204	83,555	70,351.2	501,318.5
9		-	-13,204	83,555	70,351.2	571,669.7
10		-22,470	-13,204	83,555	47,881.5	619,551.2
11		-	-13,204	83,555	70,351.2	689,902.4
12		-	-13,204	83,555	70,351.2	760,253.6
13		-	-13,204	83,555	70,351.2	830,604.8
14		-	-13,204	83,555	70,351.2	900,956.0
15		-	-13,204	83,555	70,351.2	971,307.2
16		-	-13,204	83,555	70,351.2	1,041,658.4
17		-	-13,204	83,555	70,351.2	1,112,009.5
18		-	-13,204	83,555	70,351.2	1,182,360.7
19		-	-13,204	83,555	70,351.2	1,252,711.9
20		-22,470	-13,204	83,555	47,881.5	1,300,593.4

Table C.3. Nominal Cashflow for Option 3

Year	Capital	Replacement	O&M	Energy Savings	Yearly Totals	Cash Flow
0	-211,729	-	-		-211,729	-211,729.0
1		-	-	288,387.8	288,387.8	76,658.8
2		-	-	288,387.8	288,387.8	365,046.6
3		-	-	288,387.8	288,387.8	653,434.4
4		-	-13,204	288,387.8	275,183.8	928,618.2
5		-	-13,204	288,387.8	275,183.8	1,203,802.0
6		-	-13,204	288,387.8	275,183.8	1,478,985.8
7		-	-13,204	288,387.8	275,183.8	1,754,169.6
8		-	-13,204	288,387.8	275,183.8	2,029,353.4
9		-	-13,204	288,387.8	275,183.8	2,304,537.2
10		-135,949.8	-13,204	288,387.8	139,234.0	2,443,771.2
11		-	-13,204	288,387.8	275,183.8	2,718,955.0
12		-	-13,204	288,387.8	275,183.8	2,994,138.8
13		-	-13,204	288,387.8	275,183.8	3,269,322.6
14		-	-13,204	288,387.8	275,183.8	3,544,506.4
15		-	-13,204	288,387.8	275,183.8	3,819,690.2
16		-	-13,204	288,387.8	275,183.8	4,094,874.0
17		-	-13,204	288,387.8	275,183.8	4,370,057.8
18		-	-13,204	288,387.8	275,183.8	4,645,241.6
19		-	-13,204	288,387.8	275,183.8	4,920,425.4
20		-135,949.8	-13,204	288,387.8	139,234.0	5,059,659.4