POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Design and Feasibility Assessment of Hybrid System for Adulis Archaeological Research center

Tesi di Laurea Magistrale in
Energy Engineering - Ingegneria Energetica

Author: **Abdelmagid A. A. Elamin**

Student ID: 10618363
Advisor: Prof. Riccardo Mereu
Academic Year: 2020-2021

Abstract

Access to clean and sustainable energy is critical in African developing countries. The goal of this project is to construct a hybrid system based on a PV solar system and a diesel generator for the Adulis Research Center in Eritrea, thereby enabling cultural, social, and economic development and fostering self-sufficiency.

This research also emphasizes the hybrid system's economic, environmental, and social consequences. The design and sizing of the power system address the unpredictability of energy consumption and the fluctuation of renewable sources through five scenarios models, identifying the consistent scenario's techno-economic and environmental reliability.

The analysis is carried out in order to identify the best energy demand projection for the center and build an appropriate PV system. The economic, environmental, and social outcomes, on the other hand, reveal that renewable-source-based systems are commercially viable while significantly reducing CO_2 emissions and ensuring the reliability of the energy supply for the social surrounds.

The lack of on-site information threatens to undermine the design's accuracy; therefore, more precise and additional research is needed for future work investigation.

Keywords: Off-Grid, Hybrid, Sustainability, PV Solar Energy, Environmental, Economic, Social Impact Analysis

Abstract in lingua italiana

L'accesso all'energia pulita e sostenibile è fondamentale nei paesi africani in via di sviluppo. L'obiettivo di questo progetto è costruire un sistema ibrido basato su un impianto solare fotovoltaico e un generatore diesel per il Centro di ricerca Adulis in Eritrea, consentendo così lo sviluppo culturale, sociale ed economico e favorendo l'autosufficienza.

Inoltre, questa ricerca sottolinea le conseguenze economiche, ambientali e sociali del sistema ibrido. La progettazione e il dimensionamento del sistema elettrico affrontano l'imprevedibilità dei consumi energetici e la fluttuazione delle fonti rinnovabili attraverso cinque modelli di scenari, individuando l'affidabilità tecnico-economica dello scenario corrispondente.

L'analisi viene effettuata al fine di individuare la migliore proiezione del fabbisogno energetico per il centro e realizzare un adeguato impianto fotovoltaico. I risultati economici, ambientali e sociali, d'altra parte, rivelano che i sistemi basati su fonti rinnovabili sono commercialmente fattibili, riducendo significativamente le emissioni di CO_2 e garantendo l'affidabilità della fornitura di energia per i dintorni.

La mancanza di informazioni in loco minaccia di minare l'accuratezza del progetto; pertanto, sono necessarie ricerche più precise e supplementari per future indagini di lavoro.

Parole chiave: Off-Grid, Ibrido, Sostenibilità, Energia fotovoltaica, Analisi di impatto ambientale, economico, sociale

Contents

1 | Introduction

1.1. Background

The world is concentrating its efforts on developing solutions and alternatives to the world's tremendous energy concerns while balancing three critical factors: sustainability, affordability, and reliability [1]. Developing countries are not only complicit in this predicament, but also have extra accessibility challenges, most notably access to electricity.

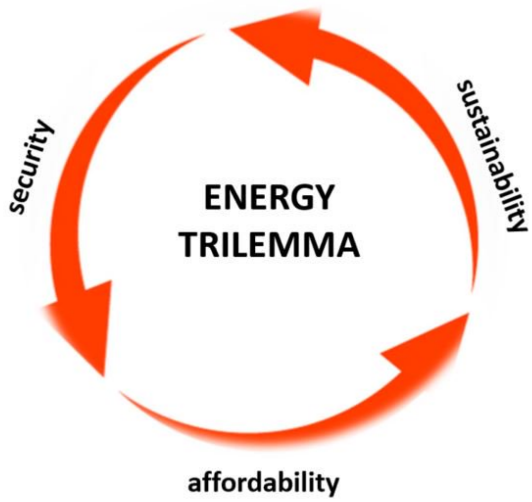

Figure 1.1: Energy Trilemma

- **Sustainability**: Energy production, distribution, and consumption are capable of meeting current and future needs without compromising people's quality of life or resource availability, thereby promoting social equality and economic efficiency.
- **Affordability**: Possibility of acquiring energy required for consumers' end-uses on the market (at market price).
- **Security**: Capacity to provide the quantities of energy required to meet final needs, either locally or via imported energy corridors and internal distribution systems.

The seventh Sustainable Development Goal (SDG) is "Affordable and clean energy for all [2]. It underscores the critical nature of energy access as a requirement for accomplishing the other SDGs' challenges and the three-dimensional potential of sustainable energy in supporting economic, social, and environmental sectors.

In Africa, the number of people with access to electricity more than doubled from 9 million in 2000 to 20 million in 2014 to 2019, outpacing population growth. As a result, the number of people without access to electricity has reduced progressively from 610 million in 2013 to approximately 580 million in 2019. A significant portion of the recent dynamism can be credited to a small number of countries, especially Kenya, Senegal, Rwanda, Ghana, and Ethiopia. The majority of progress in Africa during the previous decade has occurred as a result of grid connections, however the deployment of off-grid systems has increased significantly[3].

Nonetheless, the Covid-19 virus outbreak in 2020 exacerbated governments' efforts to address energy scarcity and expand access, pushing nations further away from universal access. Government objectives have shifted, supply chain issues have arisen, and societal distancing has hindered access projects and restricted activities in the decentralized energy access field.

Sub-Saharan Africa, which is home to three-quarters of the world's population without access to electricity, has been particularly hard hit, and recent progress in the region is being reversed by the pandemic's effects: preliminary estimates from the International Energy Agency "IEA" indicate that the population without access to electricity may increase for the first time since 2013 in 2020.

1.2. Project Objective

The purpose of this project is to determine the energy, economic, and environmental sustainability of a hybrid system comprised of solar panels and a backup diesel generator in Adulis, Eritrea, primarily for the Adulis Archaeological Research Centre. The referred project, which is being funded by international cooperation, aims to establish an energy-self-sufficient archaeological center, thereby facilitating the publication of research on the Adulis archaeological site and promoting the area as a tourist destination, thereby benefiting the local population.

The site is currently being excavated as a result of collaboration between the Italian and Eritrean governments. As a result of this collaboration, a proposal has been made to create a research center and housing for the researchers, with a portion of it acting as a gallery to draw people to the site and learn about its history and current activity.

Researchers and archaeologists are increasingly staying in caravan camps or tents throughout their expeditions, despite the region's complete lack of energy infrastructure. There, researchers and residents create electricity using gas and smaller diesel generators to power their gadgets and other electrical equipment. Additionally, neither the region nor the surrounding towns have a medical facility or easy access to clean water.

As a result of this, the proposed initiative could have a significant impact on the development of sustainable energy solutions. The project's ultimate goal is for Adulis to be energy self-sufficient. A variety of potential scenarios for the facility's operations will be explored in order to establish the facility's electricity usage. Following that, the project's economic and environmental viability will be discussed.

Throughout the thesis's development, numerous limits in terms of data availability existed, most notably economic data pertaining to Eritrea in general and the center's location in particular. Additionally, the absence of a realistic case scenario including the activities that users would perform at the center facilitated the establishment and development of many hypotheses. It was extremely difficult to design or compute anything precisely, given Eritrea is one of the countries with the least amount of available information.

1.3. Structural Outline

Chapter one discussed the general investigations conducted on Adulis. The research's objectives and aims have been specified, as well as the research's value. Chapter Two explains the concepts relevant to the thesis found in the literature, mainly related to energy assessment and solar energy system components. Moreover it highlights current Eritrean initiatives as well as analogous projects in countries with similarities to Eritrea in some way. In Chapter three the analysis's approach is defined to explain the methodology used to calculate the different parameters. All computations are presented in terms of meteorological, energy, environmental, and economic analyses. Furthermore, Chapter four provides all of the calculations and findings for the energy system design for the Adulis research center, as well as the project assessment studies. Finally, Chapter five includes a concise summary of the whole study along with suggestions for possible future enhancements.

2 | Adulis archaeological site

2.1. Overview

2.1.1. Eritrea

Eritrea is an East African nation with a Red Sea coastline. Eritrea is bounded on the west by Sudan, on the south by Ethiopia, and on the southeast by Djibouti. Additionally, the nation is bordered by the sea by Saudi Arabia and Yemen. In 1947, the former Italian colony joined a federation with Ethiopia; in 1952, Ethiopia seized Eritrea. In 1993, the nation declared independence. The geography of the nation is separated into three ecologically different ecoregions. There are three distinct regions in Eritrea: the Eritrean highlands, the northern extension of the Ethiopian Plateau that runs through the country's center, the hot and arid western lowlands, and the coastal plain. At 3,018 meters above sea level, Emba Soira is the highest peak. With an area of 117,000 km2, the nation is over four times the size of Belgium and somewhat bigger than the state of Pennsylvania in the United States of America. Asmara, Eritrea's capital and biggest city, is located on the northern edge of the Eritrean highlands. Other significant cities are Massawa and Assab. The country's 6 million inhabitants are composed of Tigrayans (55%), Tigre people (30%), and a few minor ethnic groups such as the Saho and Kunama. Tigrinya, Arabic, and English are the official languages. Around 50% of the population is Christian, while 48% is Muslim[4][5].

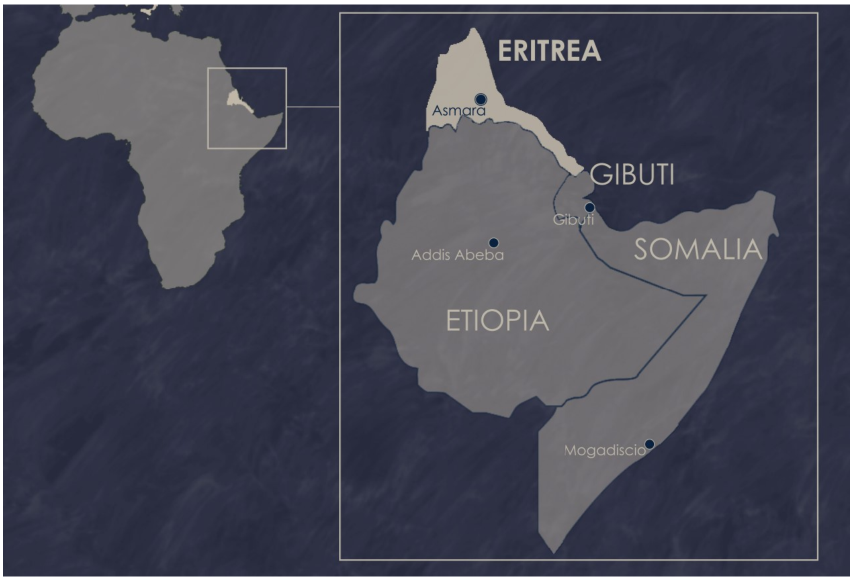

Figure 2.1: Eritrea[6]

2.1.2. Climate

Eritrea may be roughly classified into three primary climatic zones based on temperature variations: temperate zone, subtropical climate zone, and tropical climate zone. Eritrea's climate is determined by its unique geographical characteristics and tropical position. The varied landscapes and terrain of Eritrea's highlands and lowlands result in a varied climate across the nation. The highlands have a year-round moderate environment. The majority of lowland zones have an arid or semiarid climate. The rainfall distribution and plant types vary significantly throughout the nation. Eritrea's climate changes according to seasonal and altitudinal variations.

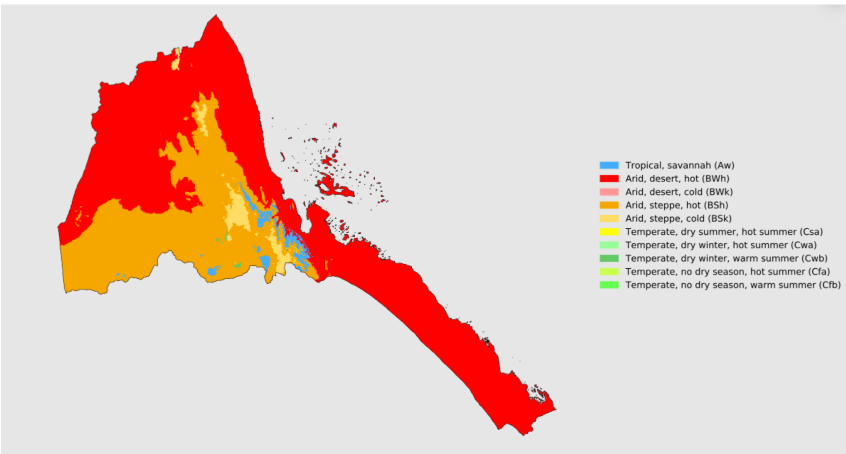

Figure 2.2: Climate classification map of Eritrea[7]

2.1.3. Economic

The IMF estimates Eritrea's GDP to be $2.1 billion in 2020, or $6.4 billion in purchasing power parity terms (PPP). Between 2010 and 2020, the economy expanded at a 3.9 percent annualized rate, an increase above the 1.3 percent annual rate between 2000 and 2010. The acceleration in growth has been linked to the start of full operations at the gold and silver Bisha mine, the manufacturing of cement at the Massawa cement factory, and Australian and Chinese mining firms' participation in Eritrea's copper, zinc, and Colluli potash mining activities. International worker remittances are expected to account for 32% of gross domestic product. Agriculture employs over 70% of the Eritrean labor and accounts for nearly one-third of the GDP. Sorghum, millet, barley, wheat, legumes, vegetables, fruits, sesame, linseed, cattle, sheep, goats, and camels are Eritrea's primary agricultural products. Tourism accounts for less than 1% of Eritrea's GDP[8].

2.2. Local case study

2.2.1. Project location

Prior going into the technical details, it is necessary to understand basic terms associated with the project's geographic location. Adulis is an ancient city on the Red Sea coast of Eritrea. It is mentioned, along with other Red Sea ports, in a number of Classical and Byzantine sources. For about seven centuries, the historic port-city served as a hub of commerce for Roman, Byzantine, and Indian traders. It is located 56 kilometers south of the town of Massawa. Locals call it Azuli, which literally translates as "white colored".[9][10]

Figure 2.3: Adulis Location

2.2.2. Archaeological site

According to a 2013 anthropological review, the port of Azuli was called after the first boat transshipped across the Red Sea Coast of the Gulf of Zula. As a result of these two historical versions, the name was created. In ancient times, Adulis was one of the world's most important commercial cities (ports). Numerous historians and merchants paid visits to the city and documented their observations, which have become key historical sources for illuminating various facets of its history. In 1907, an Italian archaeologist named Parabini conducted extensive excavations in roughly 20 areas in the northwest section, where he unearthed massive pillars indicating the presence of big structures such as churches and temples. He discovered extensive strata of cultural deposits that, according to Stuart Munroy-Hay, show that the site predates the first century AD and that it was possibly a self-contained community before upland inhabitants from Aksum arrived to rule them[10].

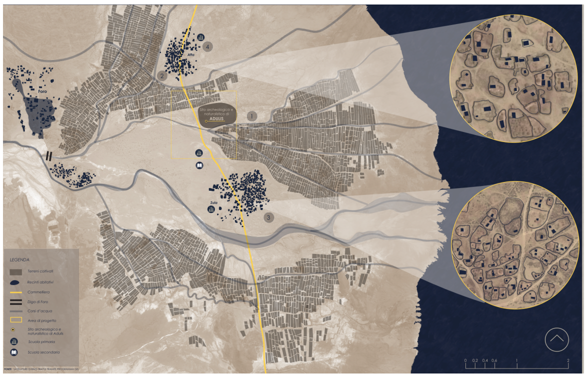

Figure 2.4: Adulis[6]

Figure 2.5: Archaeological site[6]

To address the current site's lack of a sustainable energy supply, this thesis will develop and identify viable resources for powering the archaeological center in Adulis, while also considering sustainability, economics, and the environment viability. To that purpose, an assessment of the center's energy resources will be conducted first, followed by an estimation of the center's hourly energy use. After developing an appropriate system, an overall economic and ecological evaluation of the system will be conducted.

3 | Literature Review

3.1. World

With rising energy consumption, rising energy prices, and increased efforts to combat global warming, hundreds of millions of people lack access to adequate energy. Measuring the proportion of individuals who have access to electricity is thus a critical social and economic indicator.

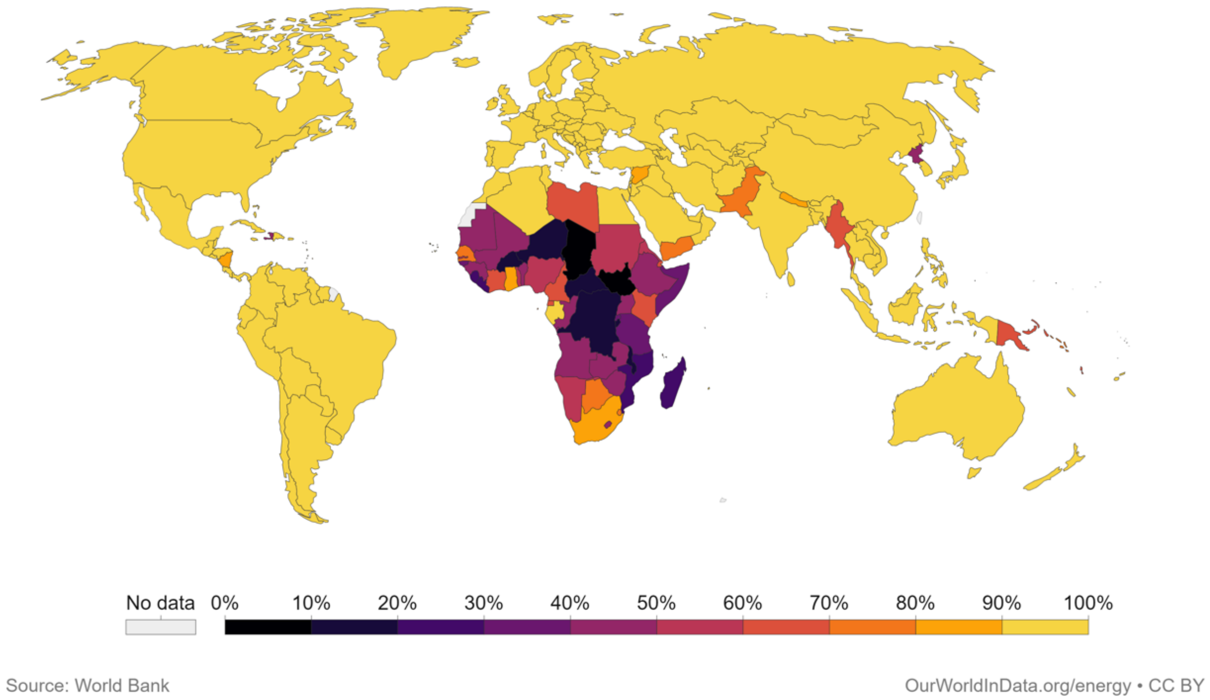

Figure 3.1: Share Of The Population With Access To Electricity [11]

There is no commonly accepted definition of what it means to have 'access to electricity.' However, the majority of definitions are oriented around the provision of power, proper cooking facilities, and a minimum amount of consumption. It is characterized as a power source capable of providing very rudimentary lights, charging a phone, or powering a radio for four hours per day. The International Energy Agency's (IEA) definition encompasses more than just household delivery. International statistics have an extremely low threshold for defining what it means to 'have access to electricity.' Additionally, it forces houses to maintain a defined minimum amount of electricity, which is determined by the household's rural or urban location and gradually grows over time. This minimum level is 250 kilowatt-hours (kWh) per year for rural households and 500 kWh per year for urban households [12].

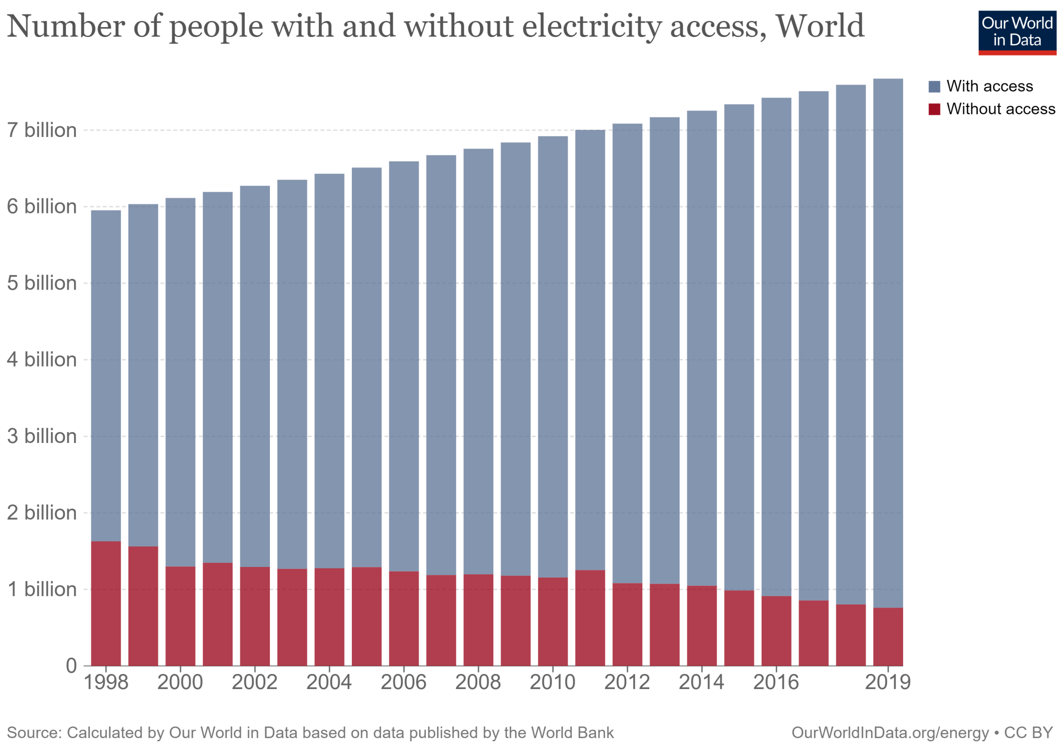

Figure 3.2: World Access to Electricity [13]

As illustrated in Figure 2.2, global access to electricity has continuously increased over the last few decades. In 1990, slightly more than 71% of the world's population had access; by 2016, this figure has climbed to more than 87%. This progress is also evident when we consider the total number of people without access to power. For the first time in decades, the total number of people without electricity dipped below one billion in 2015; very likely for the first time in our history of electricity production.

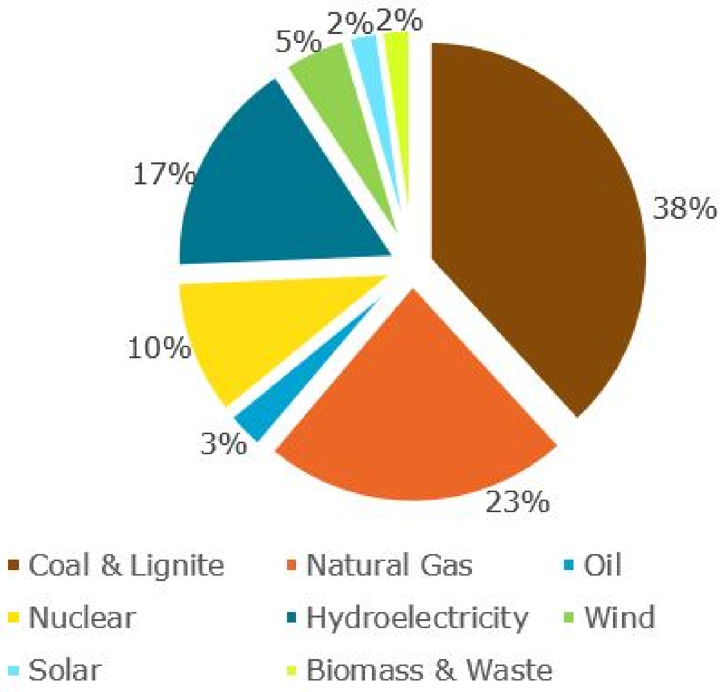

Figure 3.3: World Energy Resources in 2018 [14]

While global access to electricity has increased significantly in recent decades, the total energy balance continues to be dominated by fossil fuels, particularly coal. In 2018, the world's primary energy sources were oil, coal, and natural gas. The pie chart above illustrates the global distribution of energy resources.

3.2. Africa

According to the 2019 Tracking SDG7: The Energy Progress Report, Africa's continent is home to around 600 million people who now lack access to electricity and 900 million who lack access to clean cooking options. The International Energy Agency (IEA) released the Africa Energy Outlook 2019, which it describes as its "most extensive and detailed work on energy on the African continent to date, with a special emphasis on Sub-Saharan Africa." [15]

Energy is a more rare resource in Africa than it is in the developed world — annual consumption in Sub-Saharan Africa is 518 KWh [16], the same amount of energy consumed in 25 days by an individual in an Organization for Economic Cooperation and Development (OECD – example: the United States). Over 500 million people do not have access to power. Only 10% of people on the continent have access to the electrical grid, and 75%

of those who do come from the highest two quintiles of overall income. [17] Less than 2% of Malawi's rural population, Ethiopia's rural population, Niger's rural population, and Chad's rural population have access to electricity. According to the Forum of African Energy Ministers, the majority of agriculture continues to rely heavily on human and animal labor. The African electrical business faces an economic paradox: increasing costs will impede access to their services, but they cannot afford to expand infrastructure to drive down prices and boost access without extra cash.

Africa is suffering from severe grid infrastructure inadequacies. For instance, almost 600 million people in Sub-Saharan Africa lack access to grid electricity. African governments are aggressively investing in expanding their generation capacity: more than one-third of the continent's 800 active infrastructure projects in 2012 were dedicated to electricity infrastructure. However, with a required investment of $40 billion each year for the next decade, the African continent will struggle to cope. [18]

Nonetheless, Africa is endowed with an abundance of energy resources, including solar, wind, and hydro, which will be critical for expanding access to energy. The tremendous drop in the cost of solar photovoltaic (PV) and wind turbines has made such projects extremely cost-effective for off-grid energy access — particularly in distant rural locations where connecting to the central grid is difficult or expensive. Figures 2.4 and 2.5 depict the mean wind speed and solar Global Horizontal Irradiance for Sub-Saharan Africa, respectively.

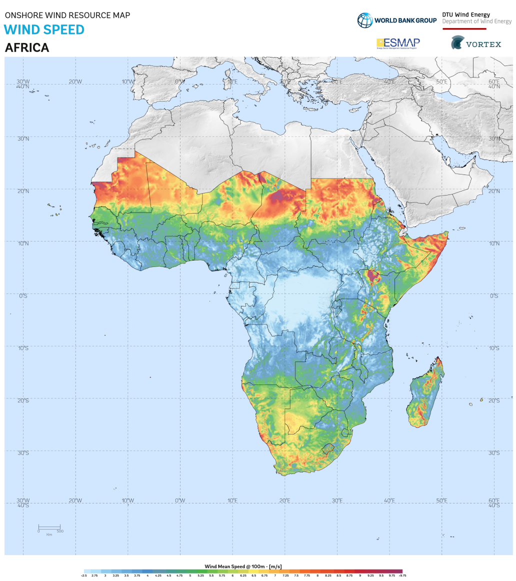

Figure 3.4: Mean Wind Speed [19]

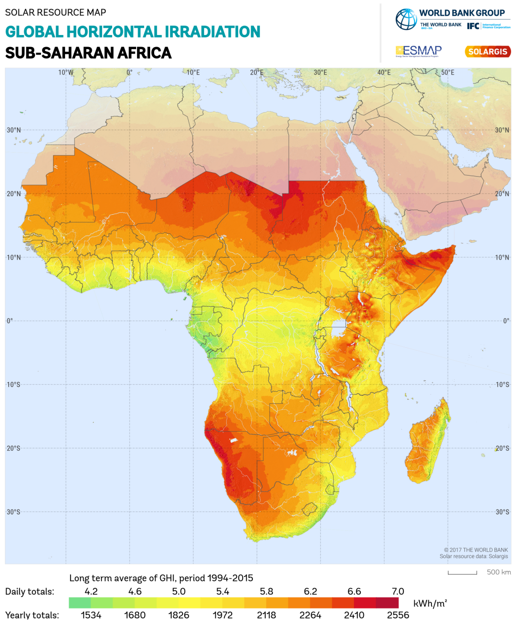

Figure 3.5: Solar Resource Map [20]

3.3. Eritrea

3.3.1. Energy Assessment and Development in Eritrea

As illustrated in Figure 2.6, Eritrea's primary energy source is biofuels and waste. In 2019, biofuels and wastes accounted for up to 70% of total energy generation. Eritrea's residual resources are mostly oil, with a small percentage of alternative energy sources such as solar and wind. Solar and wind energy provide for around 1% of overall energy supply.

In 1998, Eritrea had armed conflicts that involved the use of armed force in what is known as the Eritrean–Ethiopian War, one of the Horn of Africa's conflicts. As a result of this war, the enormous gap in energy supply from biofuels and wastes became apparent, as Eritrea spent hundreds of millions of dollars on the war and suffered tens of thousands of casualties as a direct result of the energy supply.

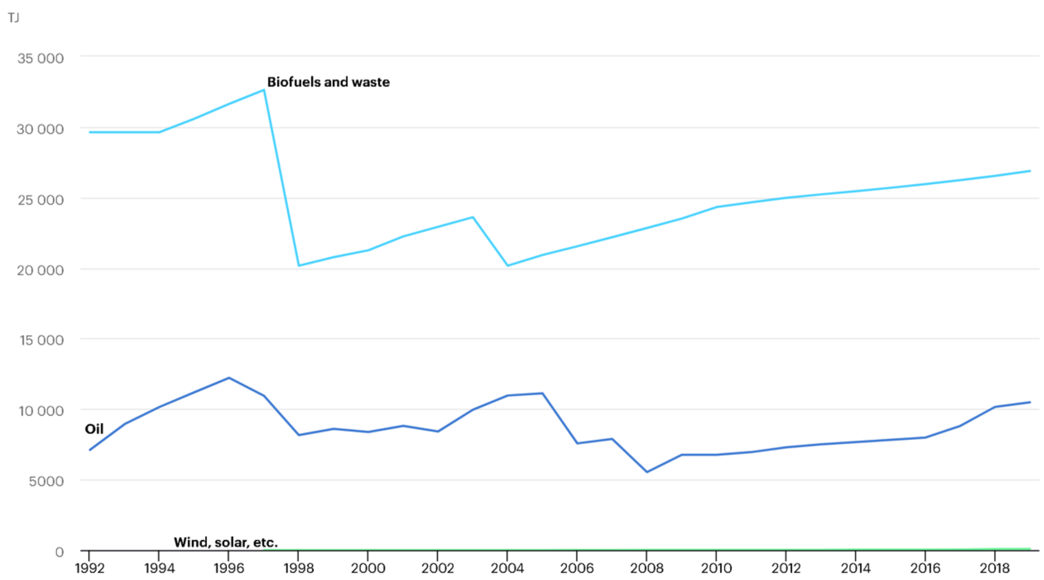

Figure 3.6: Energy Reliance by Resource in Eritrea

Around 88% of Eritrea's rural population lacks access to national grid power, forcing them to rely mostly on fuel gas or kerosene for cooking, heating, and lighting. It's essential to emphasize that biofuels and waste are considered renewable energy sources, high-carbon. According to the World Bank, less than 10% of the 73% renewable energy generated in 2019 is generated by so-called low-carbon electricity generation sources, such as solar and wind.

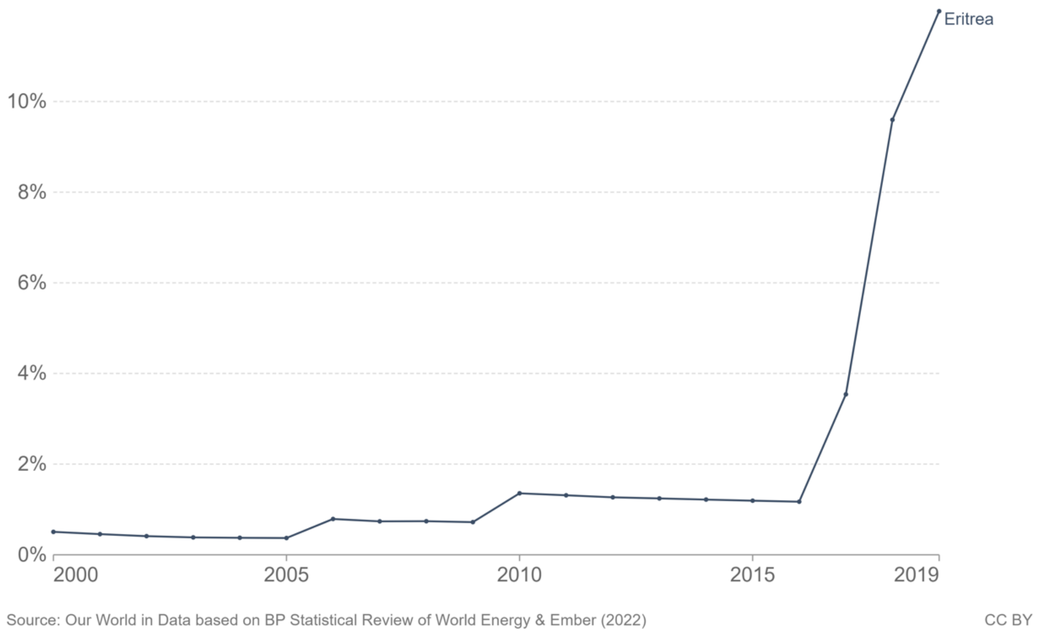

Figure 3.7: Low Carbon renewable

3.3.2. Electricity Situation in Eritrea

The major share of electricity production in Eritrea is produced from oil-fired power plants. The Eritrean Electricity Corporation (EEC), a transmission system operator and the only distributor in the country, is able to provide electricity in major cities only. The availability of electricity is limited, owing in part to the large number of rural villages that lack power. According to world bank statistics, Eritrea's national electrification rate was 49% of population. 86% of this electricity goes for the major cities while the 14% is the rural areas share [21].

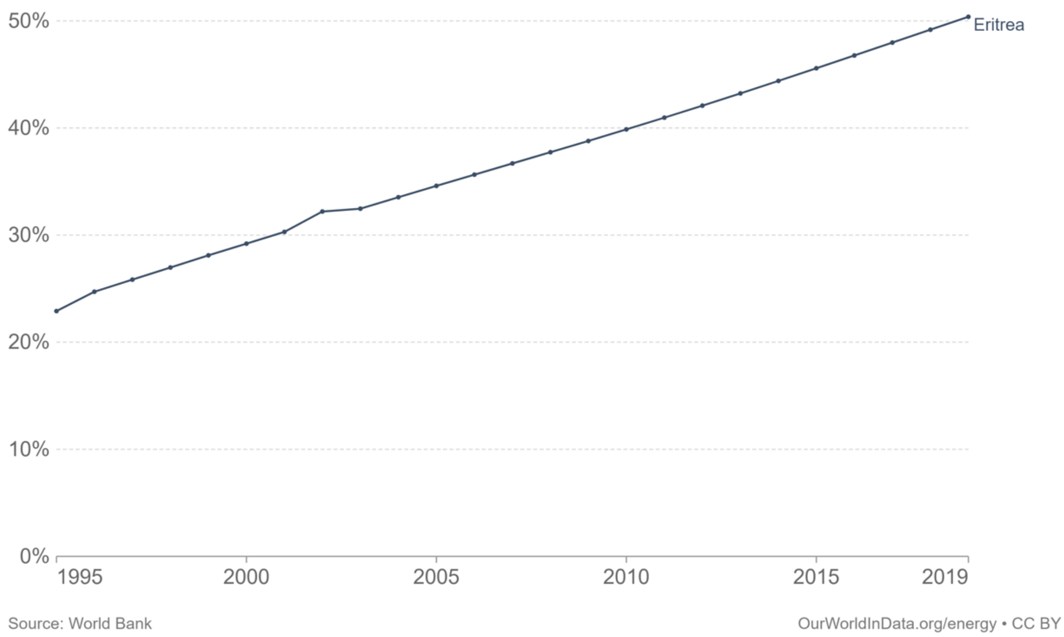

Figure 3.8: Electricity Access in Eritrea [21]

According to IRENA, Eritrea's non-renewable, diesel power plants have a combined capacity of around 205 MW, accounting for almost 90% of the country's installed generating capacity. While Eritrea also has solar power facilities with a combined capacity of 23 MW and wind power plants with a combined capacity of 1 MW. Solar and wind energy each account for 10% of total energy output, as illustrated in the figure 2.9 [22]

Capacity in 2020	MW	%
Non-renewable	205	90
Renewable	23	10
Hydro/marine	0	0
Solar	22	10
Wind	1	0
Bioenergy	0	0
Geothermal	0	0
Total	228	100

Figure 3.9: Electricity Capacity Eritrea

3.3.3. Renewable Energy Potential in Eritrea

As previously stated, Eritrea is experiencing an extreme energy crisis. A massive amount of effort should be done to close the gap between installed capacity and the number of individuals without access to energy. Given Eritrea's lack of fossil fuel output, it is critical to explore other methods of power generation. Eritrea's geographical location enables it to profit from abundant energy resources. Analyzing numerous renewable energy resources and comparing the various sorts of these potentials would aid in gaining a better knowledge of the country's energy situation.

Different available renewable energy sources in Eritrea will be investigated and compared to ensure consistency and to obtain more exact and accurate results. This portion of the report discusses Eritrea's renewable energy potential, specifically solar, wind, and geothermal energy.

Solar Energy

Eritrea's climate makes solar energy harvesting excellent. Solar monitoring data from stations established throughout Eritrea indicate that the country has a sizable solar energy potential, with an average of 6 kWh/m^2, according to Meteorological research undertaken by the Ministry of Energy and Mines (MEM). Solar energy is the principal source of renewable energy in Eritrea, according to IRENA. Solar energy has a bigger potential than other renewable energy sources since the yearly generation per unit of installed photovoltaic capacity between 1600 and 1900 (kwh/kWp/yr) covers more than 60% of Eritrea's landscape, as illustrated in figure 2.10 [22].

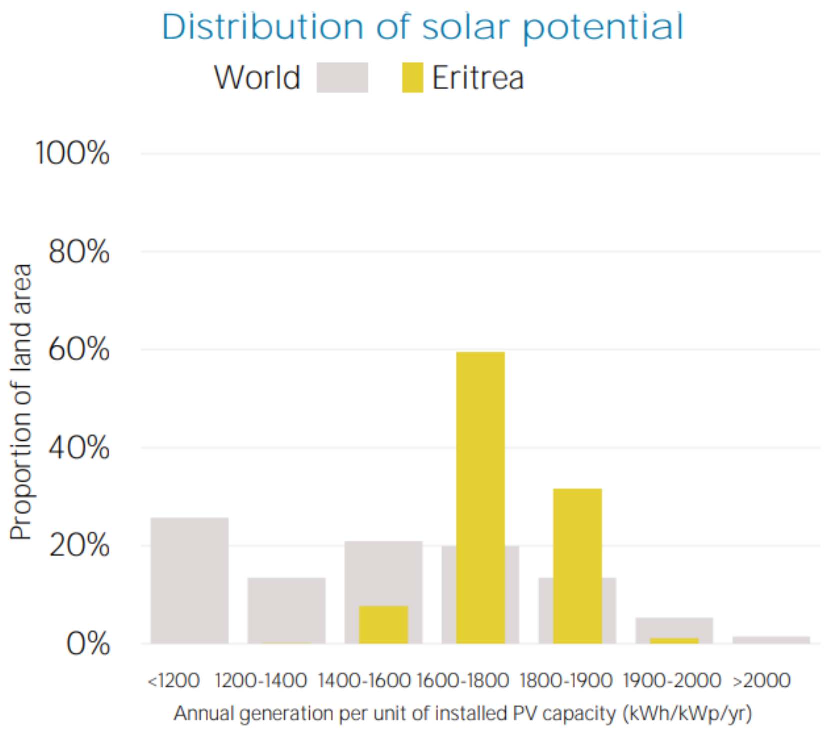

Figure 3.10: Distribution of Solar Energy Potential in Eritrea

The Ministry of Energy and Mines (MEM) has been trying to connect formerly off-grid villages and rural towns to modern, cost-effective, and long-term power. At the Logo and Misilam dams, solar energy plants have been developed, while a comparable facility is currently under development at Kerkebet. Around 40,000 individuals are involved in the campaign, which includes 40 villages, 513 small businesses, 15 schools, two kindergartens, two community hospitals, five health stations, and 80 organizations.

The MEM constructed a solar facility east of Asmara in April 2018 as part of its drive to promote the use of renewable energy sources. Each day, the plant generates an average of 11 MWh of electricity. Additionally, over 400 solar-powered lamps covering a 13-kilometer radius have been placed in Asmara [24]. Two power plants in Areza (1.5 acres) and Maidma (2.5 acres) demonstrate how solar hybrid power systems can be used to supply rural populations with uninterrupted power. The MEM wants to expand its capacity to generate electricity in the future by reducing its dependency on fossil fuels and increasing its efforts to develop sustainable alternative energy sources. Its short-term objective is to increase the quantity of solar energy produced, hence increasing national capacity.

On the same subject, Dekemhare will receive a 20-30 MW wind and solar hybrid power plant, Assab will receive a 10 MW wind power plant, Asmara, Adikeih, Debarwa, and

Barentu will receive a 10-20 MW solar power plant, Gerset will receive a 5 MW solar power plant, Kerkebet will receive a 5 MW wind and solar hybrid power plant, and Nakfa will receive a 2-3 MW [24]. Additionally, the MEM hopes to improve Eritrea's energy efficiency by expanding rural electrification through the implementation of extensive solar systems, rehabilitating Asmara's power distribution system, establishing a battery and other appliance assembly plant, and establishing facilities for in-house capacity building.

Wind Energy

Wind potential density (W/m^2) is depicted in the seven NREL-defined classes, measured at a height of 100m. In comparison to the global distribution of wind resources, Eritrea's wind power density is approximately 260 (W/m^2) per square kilometer of Eritrea's land area [22].

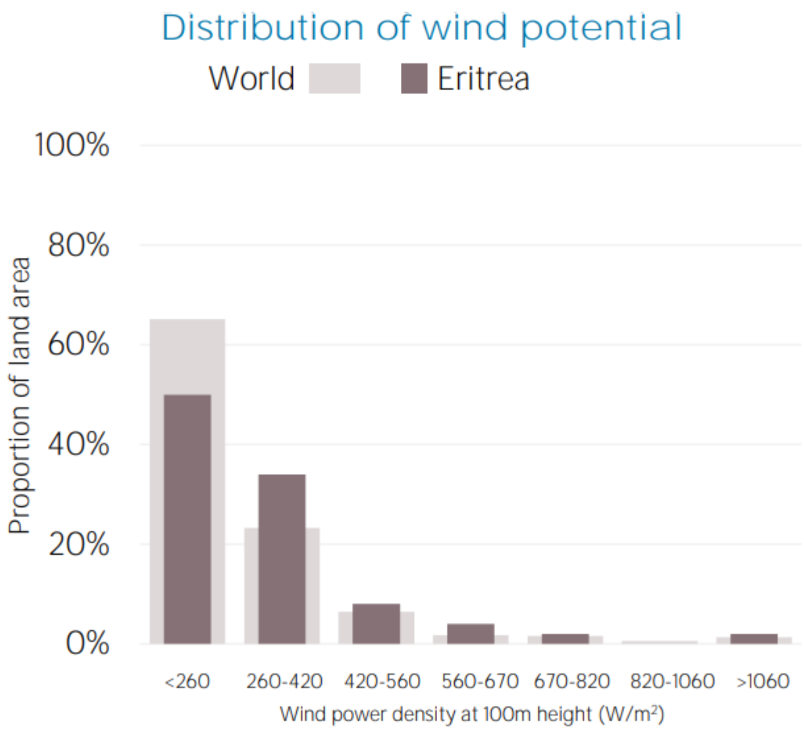

Figure 3.11: Distribution of Wind Energy Potential in Eritrea

Additional research on the wind resources in and around Eritrea have been conducted. The Red Sea and Gulf of Aden region's studies have yielded encouraging results, particularly for coastal areas (Elliott and Renne, 1987; Pallabazzer and Gabow, 1991; Radwan, 1987). Mulugetta and Drake (1996) assessed the wind potential of Ethiopia, which included Eritrea. Their fieldwork took them to four locations in Eritrea: three in the central highlands and one on the southern shore at Aseb.

The Eritrean coast, particularly in the Aseb region, has significant wind potential. The area around Aseb Airport appears to be the more promising of the two potential Aseb locations. Existing data sources indicate that the average annual wind speed at Aseb Airport is around 9.5 m/s at a height of 10 m [25]. Wind speeds of this scale can generate more energy than the Aseb power system can handle, while regulated development may provide Aseb with a less expensive alternative to the existing diesel supply. According to the Red Sea surface winds analysis provided, similar wind resource potential extends as far north as Aseb, 200 kilometers along the Eritrean coast.

In 2010, the United Nations Development Programme (UNDP) and the Eritrean government launched a wind energy project in the Southern Red Sea. The project entails the construction of a 750-kilowatt wind farm in Assab. Six small decentralized stand-alone wind turbines were installed in Rahayta, Gahro, Berasole, Edi, Beilul, and Dekemhare as a result of that initiative. Instantaneous results were obtained. Over 35,000 people now have direct access to affordable and reliable electricity. Wind energy has increased the electrical capacity of water systems, schools, hospitals, and small enterprises. Additionally, the project supplied lighting, ventilation, cooling, and fish preservation facilities, all of which benefited the region's small-scale fishermen [26].

Geothermal Energy

The geological characteristics of Eritrea's southern coastline zone indicate a significant potential for developing geothermal resources. During the Italian colony in 1902, the Italian Institute for Military Geography conducted a preliminary examination of Alid geothermal occurrences. Marini, Angel (Marini, 1938) [23]. However, no geothermal exploration study was conducted until 1973, when a team from the Geological Survey of Ethiopia conducted a reconnaissance survey under the auspices of the UNDP (UNDP, 1973).

Thermal springs were discovered for the first time along the Asmara-Massawa road and in the Gulf of Zula area south of Massawa. During the same year, a second thermal spring was discovered south of the fumaroles of Alid volcano. In 1992, Professor Giorgio Marinelli and a Department of Energy employee visited the Alid area and proposed a comprehensive research. The Ministry of Energy and Mines later improved this concept [23].

The hot springs discussed previously demonstrate a direct connection to magmatism. They are believed to be associated with high-volume, high-temperature fluid circulation at shallow depths. As a result, they are regarded to have the potential for large-scale commercial development in the energy sector.

Due to the estimated high reservoir temperature (more than $2200\,\deg C$) [23] from prior studies at Alid, hydrogeology and fracture analysis were conducted with the goal of selecting up-flow zones. From a hydrogeological standpoint, it is determined that Alid receives its water from highland water.

Unfortunately, there are insufficient geothermal energy research in Eritrea, despite the fact that all evidence indicate that Eritrea has significant geothermal energy potential. Additional investigations are required to map CO_2 and other gases (radon and mercury) on the Alid dome in order to determine the gas outflow zone and pick a viable drill site target. Additionally, gravity and microseismicity are critical factors to consider while defining the target on Mount Alid and its surroundings.

4 | Energy supply systems

4.1. System Connection

There are three primary options for solar system installation: off-grid, on-grid, and hybrid. Each of these configurations will be described in the following sections.

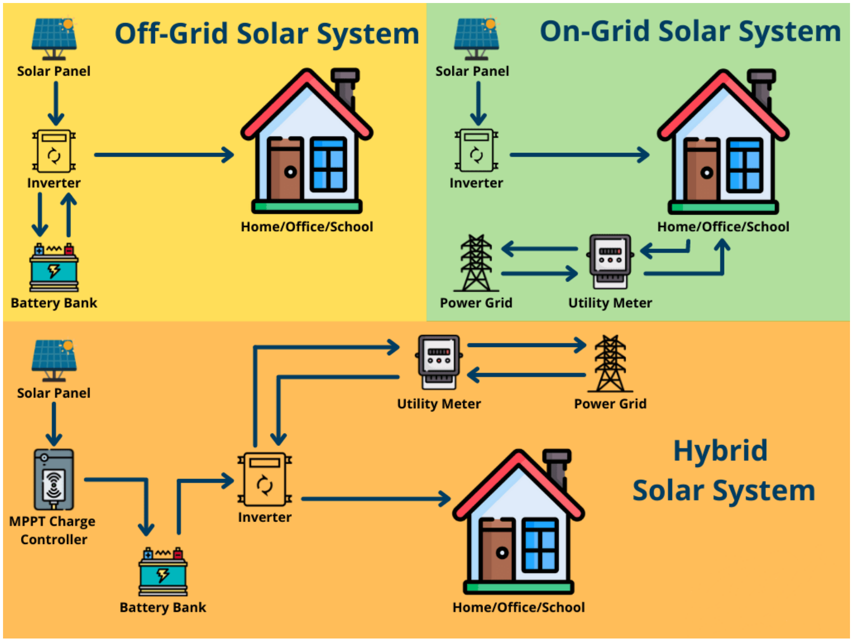

Figure 4.1: Solar system configurations

4.1.1. Off-Grid system

Off-grid solar power systems, sometimes referred to as standalone systems or mini-grids, are solar energy systems that are not linked to the utility grid and rely on a separate storage system. Typically, an off-grid system is meant to produce some extra power throughout the day and store it in battery systems. The energy stored in the batteries may then be utilised at night or during overcast conditions. Solar systems may be sized to produce enough energy to fulfill the user's energy needs around the clock based on the energy calculations. The primary benefit of off-grid solar panels is that the user is not reliant on grid electricity, which means that a power failure or outage would have no effect on the user. This configuration is well-suited for electrifying small towns. It is feasible for distant places in nations where there is little or no access to power due to the diverse living and dispersed people across a large area. On the flip-side, an off-grid solar system is completely reliant on solar radiation, and extended gloomy weather may have a substantial influence on power generation. Additionally, an extra battery system might increase the consumers' upfront installation expenses.

4.1.2. On-Grid system

By contrast, an on-grid system indicates that your solar system is linked to the grid of your utility provider. Between off-grid and on-grid systems, the latter is more common since consumers are protected by their utility provider in the event that their solar systems under-perform or fail. Additionally, if the user produces surplus energy, it may be sold back to the grid-power provider. In exchange, the user may accumulate credits that can be redeemed at the conclusion of the billing cycle. This is referred to as net metering. Being connected to the grid reduces upfront expenses by eliminating the need for the customer to acquire an expensive battery backup system for energy storage. However, the primary disadvantage of an on-grid system is that it fully shuts down in the event of a power outage. As a result, an on-grid power system may not provide enough output in locations exposed to utility power outages.

4.1.3. Hybrid system

Hybrid solar systems use the finest features of both grid-connected and off-grid solar systems. These systems may be classified as off-grid solar with backup power from the grid or as grid-tied solar with additional battery storage. Due to the potential of eliminating the backup generator, the hybrid system is less costly than off-grid solar systems. Additionally, the capacity of your battery bank may be reduced. Electricity purchased off-peak from the utility provider is less expensive than diesel. In the scenario of the Smart-grid, which enables two-way electricity exchange. Users may maximize their gains even more by selling extra power to the grid. Solar panels provide the maximum electrical power around midday, just before the energy price rises. It is possible to set the load demand to use energy during off-peak hours (or from solar panels). As a result, any extra power generated may be temporarily stored in batteries and then sold to the utility grid when the price per kWh is highest.

4.2. System Component

This section will describe the main features of solar panels and the Balance Of System. The term Balance Of System refer includes all the photovoltaic system components except for the photovoltaic panels. Four key components in solar PV system will be highlighted; DC-AC Inverter, Charge Controller & Maximum Power Point Tracking (MPPT), Batteries, and Diesel Generator.

4.2.1. Solar Panels

Solar cell technology is designed to convert solar radiation to electrical energy. The typical maximum theoretical efficiency of single solar cells are roughly about 33%. The efficiency of commercially available solar panels is now between 10% and 20% [27] and the prices have been decreased significantly from roughly $30/Wp to to $0.50/Wp as a result of the development of technology [28].

The major types of solar panels: mono-crystalline, polycrystalline, and thin-film. Polycrystalline solar cells are composed of fragments of silicon crystals that are melted together in a mold before being cut into wafers. Alternatively, Mono-crystalline solar cells are cut from a single, pure crystal of silicon. In thin-film solar panels, a substrate is covered in materials like copper, iridium, gallium, and selenium to create solar cells.

Crystalline solar panels have the highest efficiency out of all panels. In particular, mono-crystalline panels are between 15-22% efficient, making them the most efficient of all crystalline panels while the polycrystalline panels are between 13-15% efficient[29]. For this reason, mono-crystalline solar panel will be used in the project.

The advantages of mono-crystalline solar panels:

- They have the highest level of efficiency at 17-22%.
- Manufacturers state that this form of solar cell lasts the longest, with most giving them a 25-year warranty.
- They perform better in low levels of sunlight.

The disadvantages of mono-crystalline solar panels:

- They are the most expensive solar cells on the market.
- The performance levels tend to suffer from an increase in temperature.

4.2.2. Inverter

DC-AC inverter is used to convert direct current (DC) into an alternating current (AC) that can be fed into a commercial electrical grid or used by a local (AC) powered appliances.

From a commercial point of view, DC-AC inverters are broadly grouped into four types:

- **Stand-alone inverters** are used in isolated systems to pull DC electricity from batteries charged by solar panels. Many stand-alone inverters have inherent battery chargers to recharge the battery from an AC supply when one is available. These often do not interact with the power grid and, as a result, are not obliged to have anti-islanding protection.
- **Grid-tie inverters** which match phase with a sine wave provided by the utility. Grid-tied inverters are meant to shut down automatically in the event of a power outage for safety concerns. During power outages, they do not supply backup power.
- **Battery backup inverters** are types of inverters that take electricity from a battery, regulate the battery charge using an onboard charger, and export surplus energy to the utility grid. These inverters must include anti-islanding protection and are capable of delivering AC electricity to chosen loads during a power outage.
- **Hybrid inverters** control solar arrays, battery storage, and utility grids, all of which are directly tied to the unit. These current all-in-one systems are often quite adaptable and may be used for grid-tie, stand-alone, or backup applications, but their major role is self-consumption with storage.

Inverters have a quiet high efficiency in converting (DC) to (AC), usually more than 95% and in the recent year this conversion efficiency exceeded 98%. This inverter efficiency value depends on inverter load power capacity variation, as the efficiency increases and may reach to its max value at higher load power capacity in compare to lower loading power capacity.

4.2.3. Charge Controller and MPPT

An essiential part of a PV solar system is the charge controller and MPPT "maximum power point (MPP)". There are numerous techniques for tracking maximum power points (MPPT). They include simple approaches like finding Voltage at maximum power V_{mp} to be equal to the open circuit voltage V_{oc} or current at maximum power I_{mp} to be equal to short circuit current I_{sc}. There are more accurate ways; perturb and observe [PO], incremental conductance [IC], artificial neural networks, and fuzzy logic methods.

Each approach employs a DC–DC converter comprised of inductors and capacitors connected in parallel to determine the cell's operational point and to adjust the output voltage to V_{mp} using a control algorithm. Parallel circuits are composed of a DC/DC single ended primary inductor converter (SEPIC), a buck–boost converter, or a combination of these. By opening and shutting the switches, current may flow from the source to the inductor or capacitor and then to the load. The switching speed is what affects the output voltage that the load perceives.

The MPPT approaches vary in terms of how the V_{mp} is calculated. The simplest techniques determine it using a fixed constant "k" either from V_{oc} or I_{sc}. Both V_{oc} and I_{sc} vary with insolation and cell temperature, and so do not always provide the optimal values of V_{mp}.

The PO approach is much more accurate and widely used. The output voltage is raised or lowered (perturbed) in a PO algorithm, and the output power is compared to the power before the perturbation. When the power (dP/dV $>$ 0) rises, the voltage increases proportionately, and vice versa. If the insolation varies fast during a perturbation, the approach fails.

IC is a similar technique in which current I and voltage V are measured before and after a disturbance, and the ratio of dI/dV to I/V is compared. At MPP , (dI/dV + I/V) equals 0. If the MPP is to the right of the perturbed point, then (dI/dV + I/V) $>$ 0, and vice versa if the MPP is to the left of the perturbed point[30].

4.2.4. Batteries

Batteries, in general, may improve grid stability, boost the penetration of renewable energy sources, and improve the efficiency of energy systems, all while lowering their environmental effect. The literature review of battery will concentrate mainly on lithium-ion batteries while highlighting briefly the other technologies. Lithium-ion batteries are characterized by excellent performance and potential; they achieve high energy density between 100 and 250 Wh/kg, and their high power density, which ranges between 800 and 2000 W/kg[31]. The following are the primary criteria to consider while evaluating battery availability:

- **Capacity:** This is the greatest amount of electrical energy that a battery can store. Capacity may be enhanced by combining small units and it expressed in A-hours.
- **C-rate [1/h]:** Represents the rate at which a battery charges and discharges; this

number is not constant, which has an effect on the battery's efficiency.

- **Charge-discharge efficiency:** It is defined as the ratio of the discharge output of the batteries to the energy consumed to charge the batteries.
- **Depth of discharge:** this value represents the entire capacity of the battery and the maximum capacity within which the battery may operate. Indeed, 100% depth of discharge has a detrimental effect on the battery's life; normal values for Lithium-ion batteries are about 80%.
- **Life and cycling relationship:** aging has a detrimental effect on a battery's efficiency, diminishing its capacity to store energy. Increased cycle count depletes the battery's capacity.

Batteries' costs and advantages are critical in terms of size and design, especially given their high investment prices. Batteries often cost between $400 and $700 per kilowatt hour.

There are three primary battery technologies that may be used in conjunction with home solar systems. Each of these battery backup power systems is distinct in its own way. The main features of each kind of these batteries will be described below.

- Lead Acid

  Lead acid batteries are the solar battery industry's tried and reliable technology. These deep-cycle batteries have been used to store energy for a lengthy period of time - dating all the way back to the 1800's [32]. And they've survived due to their dependability. Lead acid batteries are classified into two types: flooded lead acid batteries and sealed lead acid batteries. in general, they have shallow depth of discharge, they also have a limited lifetime - between 5 and 10 years.

  Lead acid batteries are the least expensive method of storing energy, which makes them the most cost effective. Additionally, they are dependable. Additionally, since the technology is well-established, they can be readily disposed of and recycled.

  Because flooded lead acid batteries need ventilation and regular maintenance to work properly, the likelihood of the battery leaking rises.

- Lithium ion

  Lithium ion batteries need practically minimal maintenance on a regular basis. Additionally, they have a greater energy density than lead acid batteries, which means they can store more energy in a smaller area. Lithium ion batteries also offer a longer life cycle, or lifetime - most come with a 10-year warranty. This extended lifetime is due to lithium ion batteries' greater depth of discharge, which allows you to consume more of the battery's energy before it has to be recharged.

One of the primary downsides of lithium ion batteries is their cost, which is higher than that of other energy storage technologies. Additionally, owing to its chemistry, lithium ion storage batteries have a greater risk of catching fire due to a phenomenon known as thermal runaway.

- Ni-Cd

  This type of batteries originally appeared in the late 1800's, but saw a significant boost in energy storage capacity in the 1980's. They are a popular choice in the aerospace sector[33].

  The primary advantage of Ni-Cd batteries is their durability. Additionally, they are capable of operating under high temperatures. Additionally, they are maintenance-free and do not need sophisticated battery management systems. The primary disadvantage of Ni-Cd batteries is that cadmium is very poisonous.

4.2.5. Diesel Generator

A diesel generator (DG) (alternatively called a diesel genset) is a device that generates electrical energy by combining a diesel engine with an electric generator (typically an alternator). This is a unique instance of an engine-generator. Although the majority of diesel compression-ignition engines are intended to operate on diesel fuel, some are converted to run on other liquid fuels or natural gas.

Diesel generators are used in areas that are not connected to the power grid, as an emergency power source in the event of grid failure, and for more complicated applications such as peak shaving, grid support, and export to the power grid.

A "generating set" or "genset" is a bundled combination of a diesel engine, a generator, and other auxiliary equipment (such as a base, canopy, sound attenuation, control systems, circuit breakers, jacket water heaters, and starting system).

Rating: Generators must provide the projected power requirements reliably and without harm, which is accomplished by the manufacturer assigning a certain generator set model one or more ratings. While a particular brand of generator used as a backup generator may only need to run for a few hours per year, the same model used as a prime power generator must run continually. When the standby generator is functioning, it may be operated at a set overload - e.g. 10% - that may be tolerated for the projected short running duration. A generator of the same kind will have a greater rating for standby duty than it will for continuous activity. Manufacturers provide a grade to each set based on globally recognized criteria.

Sizing: Typically, however, the set size is determined by the amount of the maximum load that must be connected and the permitted maximum voltage drop, not by the ratings themselves. If the set is to be used to start motors, it must be at least three times the size of the biggest motor that is generally started first. This suggests that it is unlikely to function at a level comparable to the selected set's ratings.

5 | Methodology

The main approaches that can be used to design the system and analyze it environmentally, economically and socially will be addressed in-depth throughout this chapter. Figure 5.1 illustrates the major phases and flow of the work that will be performed.

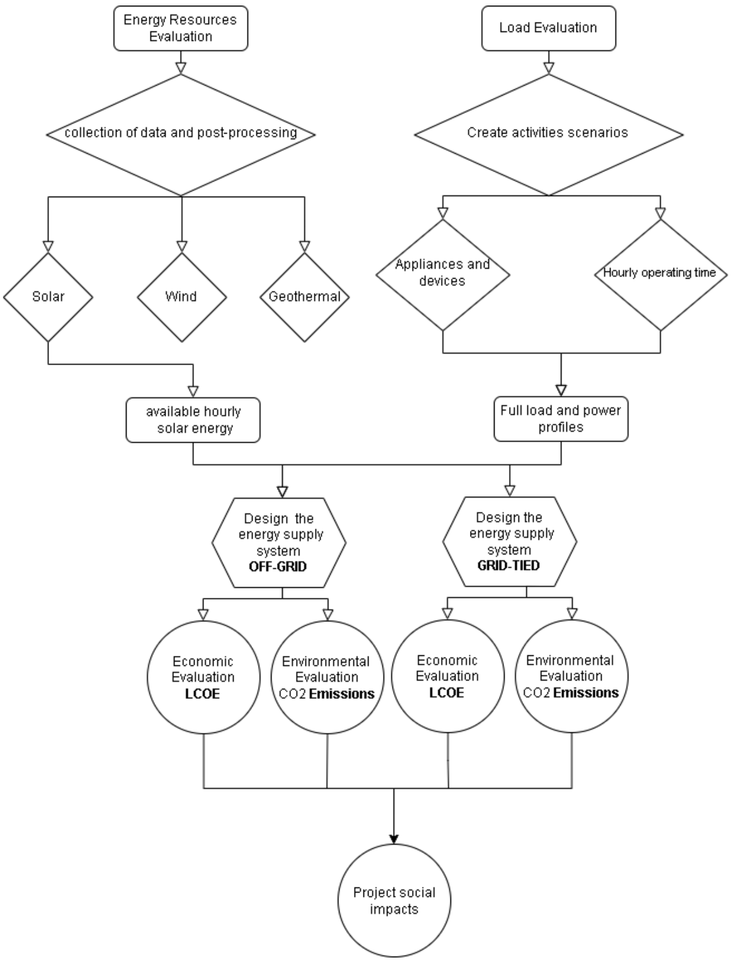

Figure 5.1: Work flow diagram

5.1. Data Analysis

Many data were collected from a variety of sources, with certain economic data being double-checked by Eritrean students and other project participants. Different databases have been analyzed and compared in order to determine consistency, to obtain more precise and correct results, and to solve Eritrea's lack of reliable data.

The solar databases are included in the table below, along with their frequency, granularity, and format:

Data base	Periodicity	Granularity	Format
PVGIS	2005-2020	Monthly-Daily-Hourly	Excel
PVSyst	1990-2020	Monthly-Daily-Hourly	Excel
NASA	2001-Up to date	Monthly-Daily-Hourly	Excel & others
Governments/Local data base	-	-	-

Table 5.1: Solar data base

Other data used during the calculation summarized in the below table:

Data type	Source
Appliances selection	Different websites
Energy demand	Center activities
Diesel price	Local reports
Electricity price	Local reports
System components prices	International price
CO2 emmissions	International data
Country economic data	World Bank

Table 5.2: Main data resources

Before starting the data collection and processing, the location on which the system will serve should be determined not only for the solar energy but also for the other project parameters such as the economical and environmental analysis. this data such as longitude, latitude, time zone, azimuth, optimum solar panel tilt angel, inflation rate, discount rate and CO_2 emission rates.

5.1.1. Energy forecasting

According to many energy organizations and institutions such as the Institute of Electrical and Electronics Engineers (IEEE) Energy Forecasting Working Group [34], the Global Energy Forecasting Competition [35], the term "Energy Forecasting" has general meaning, kilo-watt per hour (kWh) forecasting is a most precise word. On the other hand, there are several types of energy forecasting; gas and electric load forecasts, as well as renewable energy output, price, and demand response. But here we will be focusing more in the way of evaluating the load demands of energy that required by the facility.

The first step is to determine the amount of energy required for both fundamental and productive purposes. Lights, cooking, heating, and cooling are included in this category. There are public services like education, health care, and public infrastructure, as well as climate change mitigation efforts, agriculture, rural industry, and rural industry are all involved in the productive applications of literature.

In rural areas, particularly for off-grid systems, it is necessary to conduct a load demand assessment in order to establish the best size of power plants and batteries. Inconsistencies between trustworthy and faulty estimates result in inefficiencies and wastes, which have significant social, economic, and environmental consequences for the economy and the environment.

Firstly to start the calculation, we started to design the electrical system by studying the load demand. To start the evaluation of the loads two main question should be answered:

- How many people will use the center facilities?
- What are the quantity and the types electrical devices that will be utilized in the center?

To follow these questions, different approaches can be used. Most of these approaches are software and codes that generate an approximate load profile depending on some inputs. This project went through different stages; at the beginning the study, some architectural plans were provided by a thesis made by Politecnico Di Milano under the name of (check the name). The thesis highlighted the type of the appliances and the devices that will serve the center and could be used by the center residents.

It is very important to determine the rated power of each device and appliance. To do so, many websites provides the average energy consumption of electrical devices and these devices can easily be compared taking into account the center location and the common devices that are used in that region.

Architectural Plans

It is very useful in the phase of load calculation, to check the architectral plans if they are present. Architects make their plans based on the same data that is needed to calculate the consumption in the builing, e.g. number of people will occuipy the places and thier activities. Based on this they divide the building and specify the all areas used by the residents, workers, visitors. checking the architectural plans can give a very good approximation of the devices, appliances and equipment that will be used. moreover a provision scenario can be made reflecting the people activities during the days. even if the plans are primary. Following the plans and checking the results of the load and power profiles and compare them with the average data in the internet can help to reach an acceptable final scenarios of energy consumption hourly, daily, weekly and annually.

Active period

By active period it is meant the period of the year that the building will be working in its full capacity. Building activities can determine weather the building will be serving continuously or there are some periods of the year that will be closed partially or totally. It is very crucial to know this information because of its effect in the design phase. the design of electrical system is generally made to cover the highest demand in the specific period. so to avoid the over-design and hence paying more money in something useless, the exact working periods of the building during a year should be known.

Load and power profiles

After knowing the basic information about the active period of the center, collecting the data of the activities and select the appliances, equipment and devices that will serve in the center, the next step is to create the loads and power profiles. The difference between the power and energy profile is: while the latter shows the amount of required energy (Wh), power profile takes into consideration the actual power(w) needs regardless of operation time. Energy profile is used for sizing the system while power profile is utilized to find the peak power to size other components.In this phase Excel software can be used to plot the profile in graphs as final result. The building is divided in different spaces and each space is fitted with devices that will be used, based on the architectural plans the building in general can consits of:

- Living spaces (Rooms and other living areas that are used for accommodation)
- Rest Spaces (Bathrooms both WC and showers)

- Working places (Offices, laboratories and any other space used for working activities)
- Nutrition spaces (Kitchen and dining places which include both the place where the food is prepared and where people eat and drink)
- Building utilities (any space that serve the whole building such as: water pumps, Central air conditioning systems, outside lighting, technical rooms, laundry, parking etc.)
- Any other special place (Gallery, clinic and etc.)

After serve each space with its electrical devices it is time to specify the working hours for each device during the day. to make more precise profiles the days can be divided into weekdays (working days) and (weekend days) holidays and off days. The week can be consist of 5 working days and two weekend days so one profile for each of these days can be used in all other similar days. of course the requirement can vary during the year so four generic week profiles can be useful to estimate the loads consumption. Winter, Spring Summer and Autumn. To make the power profile the approach is to determine the appliances that will work each hour starting during a full day, from 00:00 until 23:00. then to accumulate all the appliances working in each hour. For the energy profile, the power profile was the base and by multiplying each device power by the turning on duration in every hour the amount of energy consumed is calculated, in other words for each device the amount of energy that will be consumed will be the rated power of this device multiplied by its working period during the specific hour. Then by adding the consumption of all devices in the hour the amount of energy required in the hour can be found. lastly using the accumulation of theses energies during the whole day (24 hours), the load/energy profile can be plotted.

$$P_t = \sum_{i=1}^{n} (P_i) \tag{5.1}$$

Where:

$P_t \equiv$ Power at hour t [kW]

$P_i \equiv$ Rated power of device i [kW]

$$E_t = \sum_{i=1}^{n} (P_i T_i) \tag{5.2}$$

Where:

$E_t \equiv$ Total energy consumption at hour t [kWh]

$P_i \equiv$ Rated power of device i [kW]

$T_i \equiv$ Active working period of device i at hour t [h]

5.1.2. Solar Data

Solar data is available in several databases, there is a variety and differences between them in terms of periodicity, granularity and format, but the thing that they have in common is that they measure two parameters: Global Horizontal Irradiance (GHI) is a measurement of the total solar electromagnetic radiation above a horizontal surface at a given location and time measured in units of watts per meter squared (w/m^2) [36]. (GHI) is a sum of the Direct Normal Irradiance (DNI), accounting for the solar zenith angle when the measurement is taken, and the Diffuse Horizontal Irradiance (DHI).

(DNI) is the amount of direct solar irradiance incident on a surface facing directly towards the sun while (DHI) is sunlight consisting of irradiance scattered in the atmosphere, excluding (DNI), incident on a horizontal surface.

$$GHI = DHI.DNI.cos(z) \tag{5.3}$$

where $z \equiv$ Solar Zenith Angle

PVGIS Other databases were analyzed and compared to ensure consistency in order to acquire more precise and correct results and to solve the lack of trustworthy data for Eritrea [37]. The Ministry of Energy and Mines (MEM) provides average data from wind and solar monitoring stations situated throughout Eritrea, as well as studies undertaken by meteorological sites to identify potential solar locations. PVSyst software delivers solar information from the PVGIS database and NASA on a monthly, daily, and hourly basis throughout the year [38]. Data in Excel format may also be retrieved directly from the PVGIS website.

5.1.3. Solar Energy

The effectiveness of photovoltaic cells and therefore the electricity generation is primarily dependent on solar irradiation, but there are other elements that should be considered since they also impact the efficiency of the cells and hence the energy production. The rated energy from the PV cells mentioned by the manufacturers is based on tests held in specific conditions called Standard Test Conditions (STC), so any variation from the standard conditions will result in efficiency reduction, and the ambient temperature has a graet role effecting the energy production from the PV cells, the efficiency of the cells depends on their temperature which directly connected the air temperature. In other words, any differences in the cell temperature than the STC will effect the PV electricity production. Evans-Florschuetz PV efficiency correlation may be used to determine the real efficiency of the PV cell when temperature differences are taken into consideration.

$$\eta_{pv} = \eta_{ref} * [1 - \beta_p * (T_{cell} - T_{STC})] \tag{5.4}$$

With β_p is the temperature coefficient of power expressed in % /°C.
Another correlation can be applied to derive the cell temperature that differs from the ambient temperature:

$$T_C = T_a + \frac{NOCT - 20C}{800(w/m^2)}.G(w/m^2) \tag{5.5}$$

The Normal Operating Cell Temperature (NOCT) is the equilibrium temperature of solar cells (T_c) inside a module, exposed to the sun, in standardized conditions (CEI EN 60904-3) and ambient temperature (T_a).

As mentioned before the design of a cell in the laboratory is done under defined circumstances, as indicated by the JRC and the European Commission, which sets Standard Test Conditions (STC) based on the following criteria, if not mentioned in the datasheet:

1. Irradiance on the whole surface of the module of 1000 w/m^2
2. Cell temerature of 25 C.
3. Mass of air of 1.5.

5.1.4. PV modules production

After define the main parameters that are used in the solar calculation, it is the time now to go through the design phase of the solar system, and the start will be with specifyng the number of modules required to power the loads. the first step in the design is to calculate the number of modules that required to energize the building. Three different approaches has been held, the first two based on hand calculations and the third the results is compared with homer software. but before starting the panels calculations, the type of the modules that will be used should be specified. As mentioned before in the previous chapter, the technologies and hence the types of the PV panel are huge, so to select which type that will be used is not an easy task, any mistake in choosing will lead to unreliable design, since the solar panels are main component of the system. The more data is present the more precise is the panels selection and the better electrical system design. The data can be helpful for the selection:

- The rated power (It is the major factor on which all the energy calculation will be depend on)
- Module size (it becomes very important when the location where the system will be installed is limited by specific area). Generally the modules have typical size "width and length" the higher rated power with the same area will lead to higher power to area efficiency.
- Availability in the market (It is very important to study the site location and the markets near to it to check the availability of the technologies, and possibilities of importing the equipment). It is very crucial to select modules that available and also if the local market is familiar to it specially when the selected site in a rural area, this can be a great motivation to get use of the advantage in the knowledge of installation, maintenance and replacement in case of damage.
- Price: Since the economic of these kind of project plays a great role to determine the feasibility, it is very important to choose wisely among the different technologies. The best module to use is not only determined based on the technical data but also its price and affordability of the communities that will take advantage of it. Not only a deep compromise between price and technicalities is crucial, rather it is fundamental difference between good and poor design.

After knowing the rated power of the Pv module that will be used. It is time to calculate the number of module required for the loads. the three approaches can be detailed as follows:

- The average monthly solar irradiation ($kWh/m^2/month$):This method uses solar irradiation as a main input along with other factors that effect the electricity generation by the PV modules. Not only the average solar data is available in the PVGIS, but also the average monthly temperature can be downloaded from the website. Temperature as discussed before degragrade the generation effeiciency, other important input is the average daylight hours from which the period of generation can be determined. However there are additional factors that affect the efficiency such as optical losses, electrical losses, inverter losses, shading and dirt, and since it is very difficult to find precise numbers to all this losses, some scholars gives an average numbers. All these losses can be accumulated under overall losses.

$$\text{(Day Length)}_i = \frac{2}{15} cos^{-1}(-tan(\phi)tan(\zeta_i)) \tag{5.6}$$

Where:

$\phi \equiv$ Local latitude [degree]

$\zeta \equiv$ Solar declination [degree]

$i \equiv$ day of the year

Beside the thermal losses due to the temperature differences there are other fixed losses which can be summarized as follows:

$$\eta_{fix} = \eta_{opt}\eta_{mismatch}\eta_{DC}\eta_{inv}\eta_{dirt}\eta_{sh} \tag{5.7}$$

Where:

$\eta_{opt} \equiv$ Optical efficiency: related to the protective material above the panel[η_{opt} =98%].

$\eta_{mismatch} \equiv$ Mismatching efficiency: losses occurs when the modules are not operating in the Maximum power point range [$\eta_{mismatch}$ = 95%].

$\eta_{DC} \equiv$ DC efficiency: losses in DC connection cables [η_{DC} =98%].

$\eta_{inv} \equiv$ Inverter efficiency: [η_{inv} = 98%]

$\eta_{dirt} \equiv$ dust and other fouling factors that affect module performance. [η_{dirt} = 95%]

$\eta_{sh} \equiv$ Near shading efficiency: should be calculated and it depends on near buildings and objects that can make shading on the PV modules.

Finally and after defining the load profile and system efficiency the number of modules required can be calculated using the following equation:

$$N_i \geq \frac{E_i}{Ir_i * P_{STC} * \eta_{sys,i}} \tag{5.8}$$

Where:

$N_i \equiv$ Number of panels required at month i.

$E_i \equiv$ Average daily energy demand at month i Wh/day.

$Ir_i \equiv$ Average solar daily irradiation at month i [Wh/day/m^2].

$P_{STC} \equiv$ Solar panel rated power at STC.

$\eta_{sys,i} \equiv$ Overall system efficiency at month i.

- The Peak Sun Hour approach: this method is quite similar to the previous one, however here, only by using the PSH and with the other overall losses it can be assumed that the module will produce in its peak ($1000W/m^2$), where PSH is the Peak Sun Hours accounting for the duration of the day at which solar radiation is equivalent to 1 sun.

$$N_i \geq \frac{E_i}{PSH * P_{STC} * \eta_{sys,i}} \tag{5.9}$$

Where:

$N_i \equiv$ Number of panels required at month i.

$E_i \equiv$ Average daily energy demand at month i Wh/day.

$PSH \equiv$ Peak solar hour [Wh/day/m^2].

$P_{STC} \equiv$ Solar panel rated power at STC.

$\eta_{sys,i} \equiv$ Overall system efficiency at month i.

- The last method uses Homer software, which uses the location and the average day load profile as inputs, then it is automatically calculate the number of modules required by the system along with the other outputs.

5.1.5. Energy storage

Batteries selection general paragraph

One thing to keep in mind when choosing a battery is that there is no such thing as a perfect battery that will work for all applications. When it comes to choosing the best battery for your application, it all comes down to defining the most critical battery metrics and weighing them against the other factors. Despite the fact that your genuine design targets for the battery are idealistic, you may discover that, in order to accomplish others, you will have to make trade-offs on some elements of performance in order to achieve others when it comes to actual battery performance.

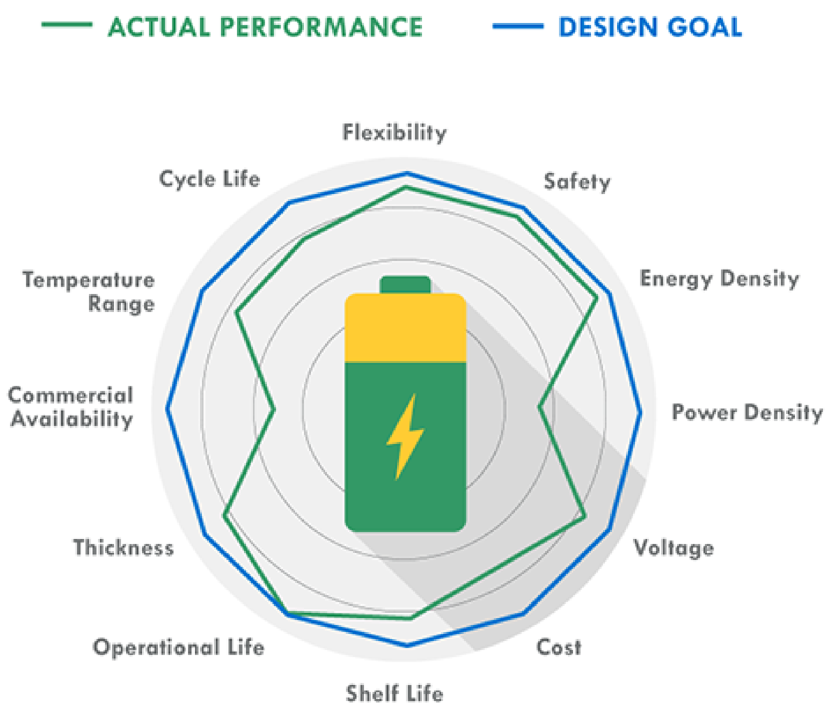

Figure 5.2: Battery design vs performance [39]

Selection criteria

When it comes to choosing a battery, there are several factors to consider. Several of these are chemistry-related, while others are battery design and construction-related. This makes comparing battery metrics more difficult, and often useless, without a more basic knowledge of the components that influence that measure. Some essential aspects in battery selection will be outlined in points in the next section.

- **Single use vs rechargeable:** Whether primary (single-use) or secondary (rechargeable) batteries are needed depends on the application. This is a straightforward choice for the designer. Use of a primary battery is justified for intermittently used applications (such as a smoke alarm, toy, or flashlight) and throwaway applications where charging is inconvenient. Examples include hearing aids, watches (except smartwatches), greeting cards, and pacemakers. Rechargeable batteries are preferable for prolonged use in devices such as a laptop, phone, or wristwatch. Primary batteries have a slower rate of self-discharge, which is advantageous when charging is neither possible or practical. Secondary batteries degrade at a quicker rate. This is less relevant since the majority of gadgets can be recharged.

- **Power vs Energy:** A battery's capacity, which is measured in milliamps or amp hours and is the highest discharge current that the battery can generate over time, determines its runtime. The energy content of different chemical batteries should be taken into account when comparing them. A battery's energy content is determined by multiplying its capacity in Ah by its voltage in Wh. The open-circuit voltage is extensively used in energy estimates (i.e. battery voltage when not connected to a load). The drain rate, on the other hand, has a major influence on both capacity and energy. Theoretical capacity is determined only by active electrode materials (chemistry) and active mass. However, due to the presence of inactive materials and kinetic constraints that prevent the full use of active materials and the production of discharge products on the electrodes, practical batteries achieve only a percentage of the theoretical numbers. Battery manufacturers often mention capacity at a certain discharge rate, temperature, and cut-off voltage; the claimed capacity is affected by all three factors. When comparing capacity statistics from different manufacturers, it is vital to pay great attention to drain rates in particular. If the current drain for the application is higher, a battery with a big capacity on the spec sheet may perform poorly. High-capacity batteries allow for rapid discharge at high drain rates, which is useful in power tool or car starting battery applications. High-capacity batteries often have low energy densities. To increase energy, you would typically increase the size of the battery (for the given chemistry), but to increase power, you would reduce internal resistance. The cell design is critical in generating high power density batteries. In battery textbooks, theoretical and real energy densities for different chemistries are compared. However, since power density is so much dependent on battery structure, these values are rarely provided.

- **Voltage:** Another critical factor to consider is the operating voltage of the battery, which is determined by the electrode materials utilized. Consider aqueous or water-based batteries against lithium-ion batteries as a relevant battery categorization here. Lead acid, zinc carbon, and nickel metal hydride all have nominal voltages between 1.2 and 2 V and employ water-based electrolytes. By contrast, lithium-ion batteries employ organic electrolytes and have a nominal voltage of 3.2 to 4 V. (both primary and secondary). Numerous electrical components work at a voltage of no less than 3 V. Due to the greater working voltage of lithium-based chemistries, a single cell may be utilized to provide the needed voltage rather than two or three aqueous-based cells in series.

  Additionally, certain battery chemistries, such as zinc manganese oxide, have a sloping discharge curve, whilst others have a flat profile. This has an effect on the cutoff voltage.

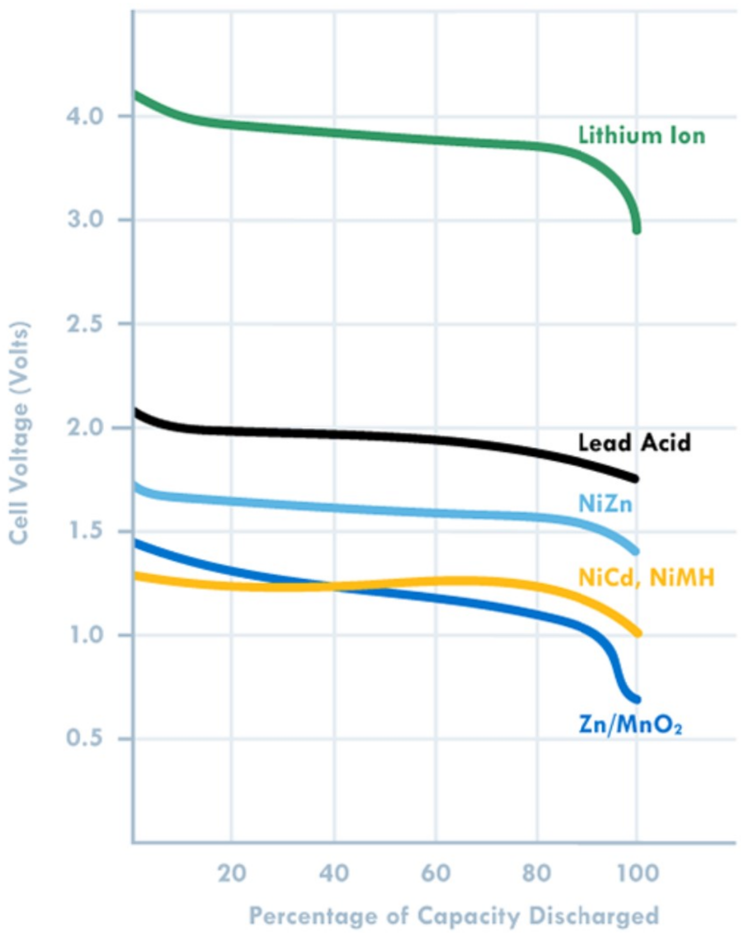

Figure 5.3: Battery Voltage Based on Chemistry [39]

- **Temperature:** The battery's chemistry determines its operational temperature range. For example, zinc-carbon cells with an aqueous electrolyte cannot be used below 0°C. Alkaline batteries' capacity drops somewhat, although not as much as Zinc-carbon batteries' does at these temperatures. Batteries made of lithium and containing organic electrolytes may be utilized at -40°C, although their performance is severely diminished.

  Rechargeable lithium ion batteries can only be charged at full capacity within a narrow temperature range of 20° to 45°C. Lower current and voltage levels are required at higher temperatures, leading in longer charging times. It's possible that a trickle charge, which might lead to thermal runaway, is required to avoid lithium dendritic plating at temperatures below 5°C or 10°C.

- **Depth of Discharge and Life cycle:** The depth of discharge (DoD) of a battery reflects the proportion of the battery that has been depleted in comparison to its total capacity. The term "Depth of Discharge" refers to the capacity discharged from a fully charged battery divided by the nominal capacity of the battery. Normally, the depth of discharge is given as a percentage. The depth of discharge is inversely proportional to the state of charge: as one grows, the other decreases. While the charge status is often stated in percentage points (0 percent equals empty; 100 percent equals full). There is a link between the depth of discharge and the cycle life of the majority of battery technologies, including lead-acid and AGM batteries. A battery's life will be shortened the more often it is charged and drained. It is typically not suggested to completely deplete a battery, since this significantly reduces the battery's usable life. Numerous battery manufacturers propose a maximum DoD for optimum performance. By contrast, cycling The life of a battery is defined as the number of charge/discharge cycles it can withstand throughout its useful life. This number is dependent on how much of the battery's capacity is typically used. If you discharge the batteries at a lower percentage rate on a regular basis, they will last longer than if you often drain the battery to its maximum DoD. A typical lead-acid battery delivers between 200 and 300 discharge/charge cycles, depending on the depth of discharge and operating temperature. The fundamental cause for its low cycle life is grid corrosion of the positive electrode, active material depletion, and plate expansion. These modifications are especially pronounced at higher operating temperatures. Cycling has little effect in halting or reversing the tendency [40].

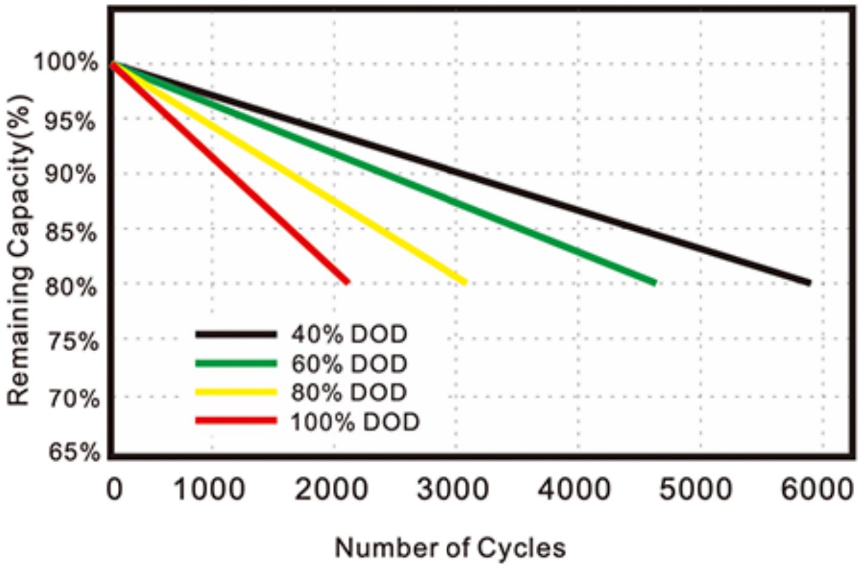

Figure 5.4: Battery Voltage Based on Chemistry [41]

- **Days of autonomy:** The term "days of autonomy" has been used in the industry to characterize the capacity of battery storage in connection to the site's specific requirements; this is defined as the number of days during which the battery can supply the site's loads without the assistance of producing sources. Engineers must be aware of the number of days of autonomy available in the location where the project is located.

The following equations are used to calculate the battery bank capacity:

$$C_{Wh} \geq \frac{E_{load} * DOA}{DOD * \eta_{round-trip}} \tag{5.10}$$

Where:

$C_{Wh} \equiv$ Battery capacity [Wh].

$E_{load} \equiv$ Average daily load demand [Wh/day].

$DOA \equiv$ Days of autonomy [day].

$\eta_{round-trip} \equiv$ Round trip efficiency.

$DOD \equiv$ Depth of discharge.

$$\eta_{round-trip} = \sqrt{\eta_{Batt} * \eta_{inv}} \tag{5.11}$$

Where:

η_{Batt} ≡ Battery efficiency.

η_{inv} ≡ Inverter efficiency. The battery capacity can also be calculated in [Ah] using the following equation:

$$C_{Ah} = \frac{C_{Wh}}{V_{batt}} \tag{5.12}$$

Where:

V_{batt} ≡ Battery bank voltage.

5.1.6. Backup system

It is critical to have a backup diesel generator, even more so if the solar system will be operated as a stand-alone system. Not only will the backup genset deliver energy to the facility during scheduled maintenance or unforeseeable faults, but it may also be utilized to support the system during times of poor solar irradiation, hence avoiding over-designing the solar system, particularly the batteries. Naturally, by keeping an eye on renewable energy penetration. The fundamental process for sizing a generator is as follows: Create a list of all the things that will be powered; the power profile will be used to establish the maximum output of the Genset. Calculate the beginning wattage (energy required to turn on the equipment) and operating wattage (energy required to operate the equipment) for each piece of equipment. These statistics are often etched into the device and documented in the owner's handbook. Add these kW or KVA values together to get the overall power needs. Once the projected wattage required is determined, the generator size may be determined; nevertheless, it is critical to pick a generator with a capacity that is 10-20 percent more than the necessary. This allows us some wiggle room in the event that the equipment is upgraded and requires more power as a consequence. Additionally, it aids in managing "de-rating," or the generator performing below the manufacturer's declared capabilities owing to poor operating circumstances such as harsh temperatures or altitude. Equation 5.13 below can be utilized to estimate the size of the diesel generator needed:

$$P_{Gen} = \frac{P_{load,max} + P_{exp}}{PF * \eta_{cap}} \tag{5.13}$$

Where:

P_{Gen} $\equiv$ Diesel genrator power [kVA].

$P_{load,max}$ $\equiv$ Loads peak power [W].

P_{exp} $\equiv$ Future load expansion [W].

PF $\equiv$ Power factor.

eta_{cap} $\equiv$Diesel generator capacity efficiency.

5.2. Simulation

After having the knowledge for the all system component it is time to connect them all together and check the full system performance. as mentioned before this can be done using some softwares and also through an excel. An excel code generated and the following inputs were kept to be added:

- Hourly solar irradiation
- Hourly ambient temperature
- Shading factor
- Number of panels
- Solar module rated power
- Battery size
- Battery round trip efficiency
- Depth of discharge
- Days of autonomy
- Invertor Efficiency
- Hourly energy demand

A constrain was put later to manage the hybrid scenario which is to run the diesel generator to cover the loads in case of the battery state of charge SOC reaches depth of discharge threshold. The SOC is the main output from this code and it is used to evaluate the performance of the system. The target is to from the system is to fulfil the loads hourly demand while insuring that the battery SOC remain in the designed levels. In addition to that, during the period of poor or non solar irradiation the hourly energy required from the diesel generator is registered also wasted or not accumulated solar energy due to battery reaches its maximum storagable capacity (100 %SOC). The two last outputs will be used later in the next sections to evaluate the project economically and environmentally. The hourly power produced throughout a year is calculated as follows:

$$P_t = N_{PV} * P_{STC} \left(\frac{G_t}{G_{STC}} \right) * (1 * \gamma(T_c - T_{c,STC})) * \eta_{sys} \tag{5.14}$$

Where:

$P_t \equiv$ Power generated at hour t $[W]$.

N_{PV} $\equiv$Number of modules.

P_{STC} $\equiv$Module rated power at STC $[W]$.

$G_t \equiv$ Solar irradiance at hour t $[W/m^2]$.

$G_{STC} \equiv$ Solar irradiance at STC = 1000 W/m^2.

η_{SYS} $\equiv$overall system efficiency. Using the formula 5.15 below, the energy available in the battery can be found and hence to detrmice the state of charge of the battery (SOC).

$$C_{batt,t} = C_{batt,t-1} + (E_{PV,t} * \eta_{char}) - \left(\frac{E_{load,t}}{\eta_{disc}} \right) \tag{5.15}$$

Where:

$C_{batt,t} \equiv$ Battery energy at hour t $[Wh]$.

$C_{batt,t-1}$ $\equiv$Battery energy availabe from hour $t-1$ $[Wh]$.

$E_{PV,t} \equiv$ Energy produced by the PV system at hour t [Wh].

$*\eta_{char} \equiv$ Charging efficiency.

$E_{load,t} \equiv$ Energy demand by the loads at hour t $[Wh]$.

$\eta_{disc} \equiv$ Discharging efficiency.

5.3. Economic feasibility

Before the project begins, an economic feasibility analysis is conducted to determine the price and any other costs associated with the scheme. This research also boosts project reliability. It also aids decision-makers in determining whether a planned scheme should be processed later or now, based on the organization's financial situation. The suggested scheme's pricing benefits are also investigated during this review procedure. To evaluate the project economically, the Levelized Cost of Energy (LCOE) can be used. The following are the LCOE's core ideas, which make it a great tool for economic evaluation:

- Determines the overall costs as a proportion of energy generation
- Calculates the present value of a power plant's total construction and operating costs over a life span.
- Allows for comparison of dissimilar technologies and connection types (e.g., wind, solar, and natural gas, or off-grid and on-grid) with various life spans, project sizes, capital costs, risk, and return on investment, as well as capacity.

The lifetime of the Li-ion batteries normally is 10-15 years, therefore the batteries will be changed during the lifetime of the project. Therefore, it was appropriate to integrate this cost while taking into consideration the discount and inflation rates using the following formula:

$$\text{Present Cost} = (\text{Cost at year N}) * \left(\frac{1 + \text{Inflation rate}}{1 + \text{Discount rate}}\right)^{N} \tag{5.16}$$

For this evaluation, again an excel code was created, the following table shows all parameters that are used as inputs and expected outputs.

5.4. Environmental Impact Assesment

Historically, impacts were mostly evaluated on a socioeconomic basis, taking into account factors such as the cost of the project, the associated market benefits, the impact on quality of life, and the rise in employment prospects, among others. Since the 1960s, there has been rising worry about the impact of human activities on the environment and the implications for the planet's long-term survival. Contamination of land, water, and air, as well as the scarcity of natural resources, began to emerge and became widely disputed. Simultaneously, it became evident that innovations must be considered holistically: they must be allowed if they make economic sense and have acceptable social and environmental consequences. Environmental Impact Assessment (EIA) is a process that evaluates the complete spectrum of a proposed project's environmental impacts. It is one of the instruments used throughout the authorisation process to deliver important information to decision-makers. The overarching objective of EIA is to promote consideration of environmental problems during decision-making in order to "ultimately arrive at more ecologically appropriate activities"[42] . Full description of EIA provided by Wathern says: "EIA can be defined as a process for determining the likely consequences of particular activities on the biogeophysical environment and on human health and welfare and for communicating this information to those responsible for sanctioning the proposal at a stage when it can materially affect their decision." [43] This definition emphasizes that EIA has both analytical and procedural components. The purpose of an EIA is not only to determine the projected environmental consequences of a proposed development (analytical component), but also to ensure that the study's findings may actually influence the decision-making process about the development's approval (procedural part). Analytical components include the procedures and techniques necessary to gather relevant data, identify environmental consequences, evaluate their importance, and suggest impact mitigation solutions, among other things. Academics, specialists, and practitioners have offered such approaches and procedures, which are detailed in the scientific literature and often compiled in guides, handbooks [44].

5.5. Social Assessment

The term "social impact assessment" refers to the methods used to manage the social consequences of planned initiatives [45]. Societal impact assessment (SIA) is currently seen as a strategy for resolving development-related social challenges. There is clarity over what constitutes 'acceptable' SIA procedure:

- It should be an interactive process.
- Provides assistance to impacted individuals, proponents, and regulatory bodies
- Improves one's awareness of and ability to react to change
- Aims to minimize and lessen undesirable consequences while maximizing favorable outcomes throughout the period of a development's life
- Prioritizes the well-being of vulnerable and disadvantaged individuals.

International norms and standards, especially when included into project funding requirements, have acted as an extra impetus, one example is the Equator Principles, a set of performance standards developed by the International Finance Corporation. Environmental and social action plans are required for all projects under the 2006 IFC Performance Standards (a reform of the safeguard rules in effect since 1998) [46]. Impact assessment results are summarized, mitigation and community development strategies are outlined, cost estimates are provided, and monitoring and reporting systems are established in these plans.

6 | Results and discussion

This chapter will go through the stages of creating a solar system and a backup diesel generator, as well as all of the related components in detail. Beginning with a knowledge of the building and the spaces and activities that will be held inside, the project will be evaluated economically, environmentally, and socially, moving through the meteorological data and finishing with an economic, environmental, and social evaluation. This study will take place at Adulis, an archaeological site in the the Northern Red Sea of Eritrea, situated about 30 miles south of Massawa in the Gulf of Zula, as previously reported. The main objective of the building is to serve as a research center with accommodations and other living amenities for researchers, with a portion of the building will be devoted to tourism, including a Gallery hall. The objective is to develop a sustainable energy system for the center that includes the following key features:

1. Total reliance on this system (Self-consumption) due to the lack of a readily available supply of energy/electricity.
2. Reducing energy use by employing the most energy-efficient gadgets feasible.
3. Maximizing the reliance on renewable resources (photovoltaic system), thereby reducing diesel generator penetration.
4. Investigate the possibility of supplying surplus power to neighboring communities.

The procedures used to achieve this goal were the same as those described in the methodology chapter. As a result, nearly the similar headlines will be utilized throughout this chapter, with a concentration on the site of our interest this time.

6.1. Energy forecasting

This part will illustrate the stages that were taken to arrive at the final load and power profiles, as well as some explanations and reasons for the adjustments and results.

6.1.1. Architectural Plans

The initial step was to look for any available architectural plans, and thanks to a thesis written by students at Politecnico di Milano titled "IL PARCO ARCHEOLOGICO DI ADULIS" [6], the initial estimates of the number of people and equipment were based on the designs provided in the thesis. Although the actual number of electrical devices is not specified, plans depict rooms, offices, restrooms, and other places, making them an excellent starting point for selecting devices, determining activities, and so plotting load and power profiles.

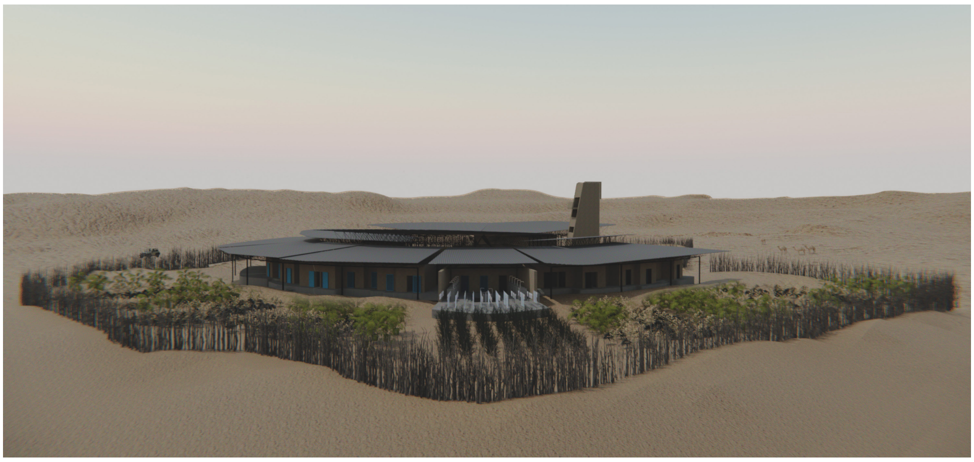

Figure 6.1: Adulis research center [6]

Figure 6.2: Adulis research center layout [6]

Appliances selection

The appliances were selected using the plan of the research center as described in the thesis "IL PARCO ARCHEOLOGICO DI ADULIS" on page 109. The center will accommodate 54 people in total, 42 in rooms and 12 in six tents (2 people in each tent).

The center is divided into different spaces based on this the fundamental appliances necessary for each area were established by the kind of space, the number of occupants, and the activities and purposes of the space. According to the following:

- **Room appliances:** Including lights, ceiling fans, a phone, and laptop chargers.
- **Bathroom appliances:** Such as lights, exhaust fans, and hairdryer or shaving machine sockets.
- **Kitchen appliance:** Including lights, refrigerators, stoves, microwave ovens, exhaust fans, kettles.
- **Dining area:** Lights.
- **Office and laboratory appliances:** Lights, fans, and laptops chargers.
- **Gallery:** Lights, Fans
- **Technical room:** Lights, fan and laptop charger.
- **Generator area:** Lights
- **Outdoor area:** Lights and water pumps.

6.1.2. Working Hours

The next step after defining the appliances for each space and hence for the whole building, is to determine the working hours for each appliances. To do so, the overall working frame for the center was firstly assumed to be from 5:00 until 00:00 (mid-night). Then different scenarios were suggested and modified until reaching the final and most reliable scenario for designing the energy system.

First Scenario

The first scenario is designated as the full load scenario; the following features describe it:

- Working hours are 7:00 to 20:59.

- Six electric stoves are utilized in the kitchen.
- Fans are maintained running 24 hours a day in the rooms to account for the potential of at least one person remaining in the room during the working hours.

Second Scenario

The second scenario is identical to the first, except that electrical stoves are replaced with gas stoves owing to the electrical stoves' very high electricity consumption.

Third Scenario

The following points highlight the key features of the third scenario:

- The working hours have been established as 8:00 in the morning to 17:59 in the evening (10 hours).
- To fit the gallery, the laboratory space is divided.
- From 8:00 until 15:59, all room fans have been switched off (8 hours).
- Sensors were installed in bathrooms to reduce the operating hours of lighting and exhaust fans.
- A split-unit air conditioner with a capacity of 24,000 BTU has been installed to the technical room.
- Lights, fans, and laptops have been removed from the technical room.
- Twenty more lights have been added to the outside area.

Fourth Scenario

The main aspect of this scenario is that the population of the center would be reduced. Residents of the center have been lowered by one-third in comparison to the previous scenario; this proportion assumes that the center will not be completely inhabited for the majority of the year.

- The residents number is only 35.
- Only three tents are inhabited (out of six)
- Six rooms are considered to be vacant.

Fifth scenario

This time, the data was collected not just from architectural blueprints, but also from information given by colleagues [?]. As is usual, the following points outline the changes that occurred in this scenario.

- A total of 50 individuals (42 researchers and eight housekeeping family members) are housed in 16 rooms and seven tents.
- There are just four toilets, each with one light and one exhaust fan.
- There are just two restrooms (showers), each with one light and one exhaust fan.
- The kitchen is equipped with two stoves, one electric oven, and one kettle.
- The number of lights in the gallery, laboratory, rooms, and dining area has been reduced.
- The technical room's air conditioner has been removed.
- Two washing machines have been added.
- another space that serves as a clinic is introduced.
- Each day, a water pump operates for three hours to fill a 10m3 water tank.
- The hours of operation for toilets have been adjusted (working from 05:00 to 23:59, 10 minutes in the peak hours for each toilet and 5 minutes per hour for the resent hours).
- The hours of operation for bathrooms have been adjusted (working from 05:00 to 07:59and from 18:00 to 20:59).

6.1.3. Load and Power profiles

As mentioned in the methodology, now it is time to create the load and power profiles for the center, the profiles were made for the all five scenarios, to allow for a comparison and more understanding to the different scenarios.

Power profile

The model was created for this analysis is able to plot the power profile for all appliances in the center. The center is separated into many zones or spaces. Each location has its own set of devices and equipment. The power profile displays the required power for each hour of the day. The working devices are marked and the rating power is recorded every hour. The total power required is then calculated by adding the total rating powers in a given hour. The same technique is followed again to obtain the whole power profile for one day.

Assuming the repetition of the activities during the weekdays and adding another case for the weekends, two different power profiles will be considered for designing the electrical system components.

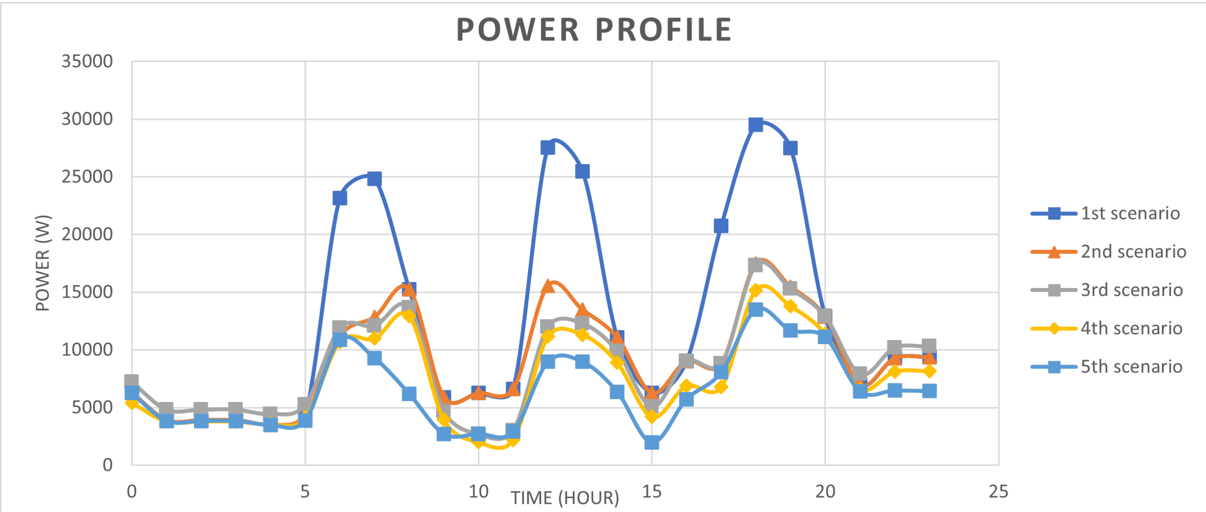

Figure 6.3: Power profile

	1st scenario		2nd scenario		3rd scenario		4th scenario		5th scenario	
	Power [W]	Decrease [%]	Power [W]	Decrease [%]	Power [W]	Decrease [%]	Power [W]	Decrease [%]	Power [W]	Decrease [%]
First Peak	24.8	-	15.3	38.5	13.7	10.5	12.9	5.5	10.9	15.8
Second Peak	27.5	-	15.5	43.5	12.3	21	11.3	8	9	20.7
Third Peak	29.5	-	17.5	40.7	17.3	0.97	15.2	12.5	13.5	10.9

Figure 6.4: Power profile comparison

6.1.4. Load profile

The load profile indicates the energy required, and 24 values are collected every day using a time interval of one hour. The operating period of the equipment for a certain hour is multiplied by its rating power to determine consumption for each device. Repeating this technique hour after hour while accumulating the energy from the previous hour, the total consumption for the day is plotted to indicate the load profile. The yearly load profile is calculated using the same approach as for the power profile. Later phases include a simulation of the system's performance based on the annual load profile.

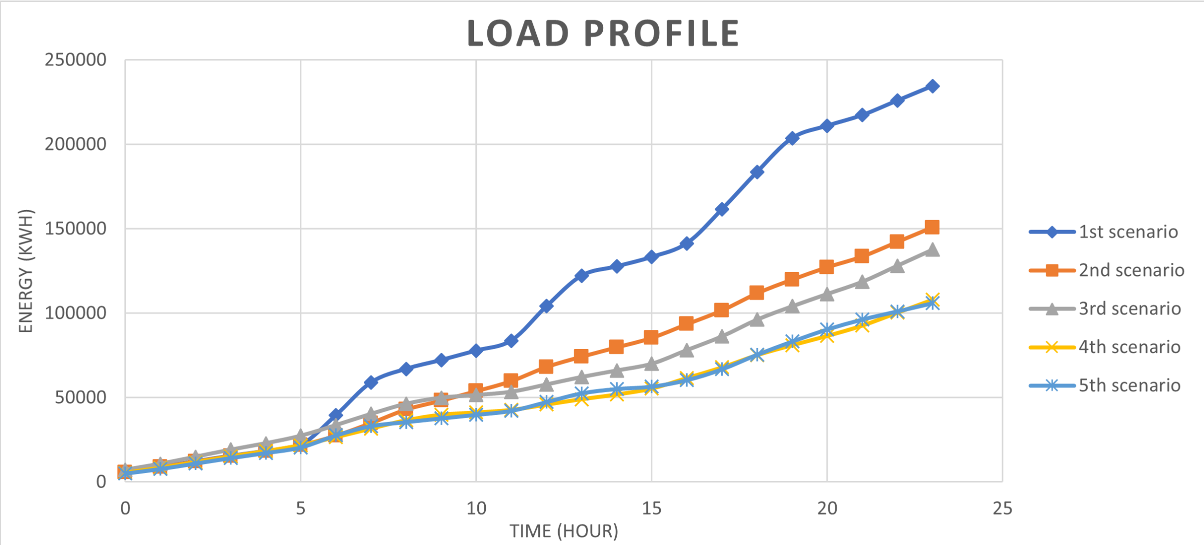

Figure 6.5: Load profile

	Energy [kWh]	Decrease [%]
1st Scenario	235	-
2nd Scenario	151	35.7
3rd Scenario	138	8.7
4th Scenario	108	21.5
5th Scenario	106	2.0

Figure 6.6: Load profile comparison

6.2. Simulation

6.2.1. Overview

To be able to design the solar system, the same flow chart illustrated in the previous chapter is followed. Two parallel paths should be followed, the load side which from the previous section the preliminary results is obtained, and going through this section additional modification will be done pursuing for results closer to the reality. Basically, the activities in the center assumed to be different during the weekends. (I HAVE THE MAIN ASPECTS OF THIS SCENARIO, TO BE WRITTEN OR NOT?). The simulation will depend on one week load demand (five similar working days followed by two days as weekends) repeated for the whole year. The other path is to design the system components, mainly the PV panels and the batteries size. Then during the last stages of the simulation a diesel generator is introduced to the system as trading off between the size the batteries and the penetration of the PV energy.

6.2.2. Solar PV analysis

To start modeling the system it is essential to collect the data related to the energy source that will be used. Solar data for Adulis site is presented in the following table. The main reason behind depending on the solar as the main source of energy to supply the center with the electricity, is that the solar energy is the most reliable and abundant in Adulis, moreover, the PV technology is already implemented in Eritrea.

City	Adulis
Latitude (decimal degrees)	15.26
Longitude (decimal degrees)	39.66E
Elevation (m)	21
Azimuth (degree)	0
Tilt Angle (degree)	16

Table 6.1: Location details

Since the Solar panels will be fixed (without a tracker), the azimuth angle is selected to be zero due to fact that the location is in the northern hemisphere, and 16 degree tilt angle is the optimum angle for the selected site.

Number of modules

Based on the data above the hourly solar irradiance and hourly temperature are collected. The available data for the location is limited and not updated, PVGIS gives data for the avarage monthly solar irradiation and temperature in 2005, which used to calculate the required number of PV panels. The selection of the PV module was based on specific cost, tolerance, and degradation profile. The PS-M60-305 panel manufactured by Philadelphia Solar in Jordan was chosen since it complies with the requirements and to minimize shipping costs. As illustrated in the methodolgy chapter, three different procedures were held to obtain the required number of PV modules, and the main features and results are sammerized as follows:

1. **Average monthly solar irradiation:** The number of modules for each month is obtained but for the design the selected is the highest number of panels which correspond to the worst month average solar irradiation. the calculation leads to 134 modules.
2. **Peak sun hours:** By taking PSH for the adylis is 4.5hours, the resulted nember of mudules is 114 module.
3. **Homer Software:**

The result from the first approach is the most (logical) compared to the others. The PSH depends on average data, so it can can give a first good estimation but it can not predict the odd periods when the solar irradiation is low and hence the system can poorly operate during those periods. Homer results also take yearly average data which lead to same problems as described above. In conclusion, the system will be designed based on 134 PV module each has 305W as rated power, leading to 41kW total system capacity.

6.2.3. Batteries analysis

The selected battery is lithium iron unit with battery management system (BMS). The reasons behind this selection are high specific power, long lifetime, no maintenance or followup required, and high DOD allowance. to calculate the battery size and hence to selct it, some inputs should be determined:

- The loads requirements are 120kWh/day.
- Depth of discharge is assumed to be 80% (recommended for Li-ion batteries)
- efficiency of the battery is 92%
- Days of autonomy: different cases were calculated starting from 3 days of autonomy until reaching 1 day of autonomy and introducing a diesel generator to fulfill the shortage for the demand.

energy storage options

To decide the final size of the storage some options have been discussed as follow:

1. To cover all the loads using only the PV system (100% renewable) For this option we can increase the size by changing the day of autonomy DOD, so the 100% of renewable can be reached by 1.5 DOD which lead to 250kWh battery size.

2. Introduce a diesel generator to cover part of the loads mainly on the days with shortage in solar irradiance Knowing that there are limited days with law solar radiation so increasing the size of the batteries for only those days is not the optimum solution from economical point of view. By keeping 1DOD which lead to 166kWh the diesel generator usage will be 200kWh/year (specifically 7 days in January)

3. Increase the dependence of the diesel generator and decrease the storage size more As mentioned before the law solar radiation is only for limited days, so by decreasing the size with relatively high amount the dependence on the diesel will rise slightly. In numbers with size of 100kWh the generator will cover 600kWh/year (25 days/year mainly in January and February)

Renewable Penetration [%]	**100**	**99.5**	**98**
DOD [days]	1.5	1	-
Batteries size [kWh]	250	166	100
Usage of Generator [days]	0	7	25
Usage of Generator [kWh]	0	200	600
Reduction on batteries size [%]	-	34	60 Compared to 1st case 40 compared to 2nd case

Figure 6.7: Battery Options

6.2.4. Diesel generator

From the power profile which previously calculated the maximum power needed is 14kW, so roughly the size of the diesel generator can be calculated as follows:

Loads power 14kW

Future expansion 10% of the recent power Power factor 80%

Capacity Efficiency 80%

These inputs lead to 24.3kVA, so a generator set around 25-30kVA. Is needed. With this size the generator can fulfil all load demands during the day.

6.2.5. Simulation results

Previously the main system components design was discussed, but to reach the final results many modifications and changes have been done. Before going to the last model on which the other evaluations were done, a quick overview for this modification will summarized as follows:

1. **Load and power profiles:** The fifth scenario is chosen to be the most related scenario to the real activities in the center and also can give reasonable results in terms of system size. so in addition to the weekdays load and power profile another profile has been suggested to work as weekends center activities. The main features of the weekends are:

   - Working areas are kept closed (Offices, Gallery and laboratory)
   - All the loads depend on the people use are shifted by 1 hour late and 2 hours (for bathrooms and breakfast in the kitchen).
   - Room fans are kept working during the day time.
   - Three hours are added to the laundry instead of only one hour in the weekdays.
   - During the last stages and seeking for reduction in battery size, some loads were shifted from the peak period.

   The final load and power profiles on which the last siulation and other calculation were carried out are plotted below:

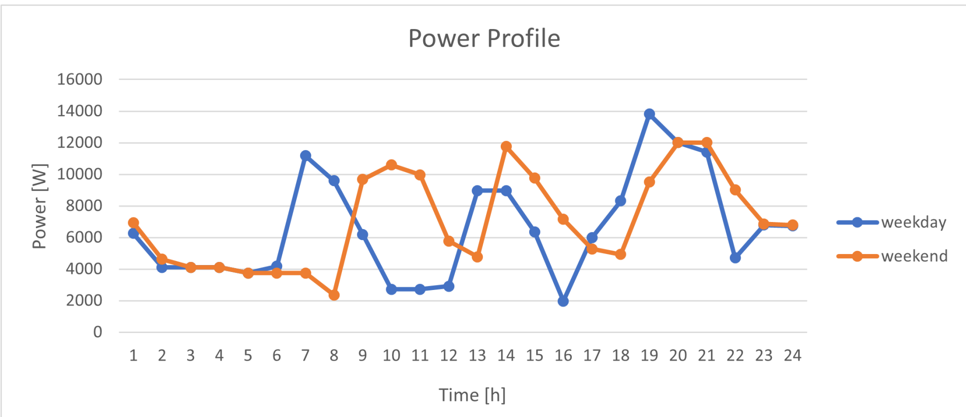

Figure 6.8: Weekday and weekend power profile

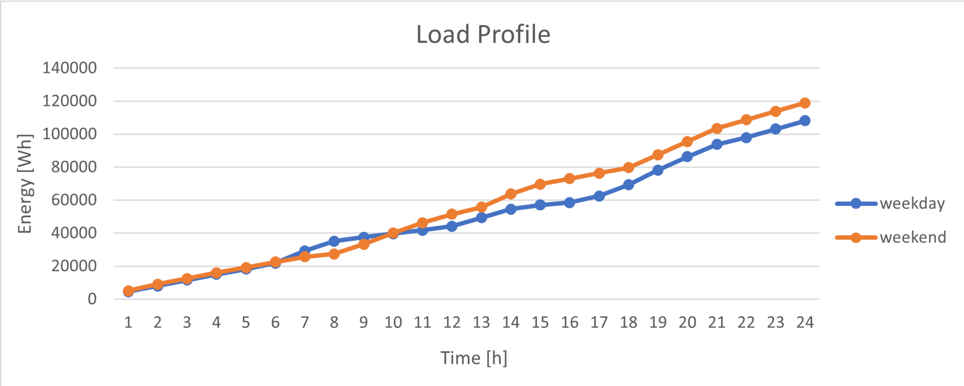

Figure 6.9: Weekday and weekend load profile

2. **Battery size:** As it will be shown in the coming section of the economy evaluation the price of the battery is most domenet compared to other components, due to that the size of the batteriy should be taken carefully. The following points summarize the options that faced until reaching the final size of the battery:

   - The recommended Day of Autonomy (DOA) is 2-3 days but since the center is located in one of the best solar irradiation potentials, a first assumption of 1.5 DOA. This value leaded to a size of 250kWh. Althought this battery can provide the center with all its needs without depending on any other resource (diesel generator) but it decrease the project feasibility from economical side of view.

   - The DOA was then reduced to 1 day which give a size of 167kWh battery with depeding on diesel generator to supply a total of 256kWh during the low solar irradiation periods.

   - After doing the simulation for the both above options, it is found that the battery state of charge is affected and reaching values below 20% only during a limited number of days during the whole year, which gives the opportunity to decrease the battery size more and increase the dependence on the diesel generator during to cover the shortages. This time option suggested that to design the battery for the night loads only but at the same time to keep an eye on the renewable penetration. This option leads to a battery size of 100kWh, with renewable penetration of 98.3%.

3. **Diesel Generator** As illustrated before the diesel generator was introduced firstly as backup system, but later to reduce the battery size it is used also to cover some loads when the battery sate of charge (SOC) drops below 20%.

6.2.6. System Performance

All the modifications and changes done before leaded to the final graphs that shows the performance of the system during a full year with one hour time interval. The State of Charge of the battery is setted to be the guide to check the performance. By making a constrain on the SOC to do not drop below 20% (which reflects the assumed DOD of 80%), and hence the diesel generator will automatically start to work to fulfil the loads demand, and turned off giving the solar system the priority to provide the electricity once the SOC again reaches values above 20%. Firstly the simulation was held throughout the year and then it was repeated to check only the period when the center will exactly work. The charts below show system performance based on the SOC and the diesel generator operation for both the full year scenario and from October to April.

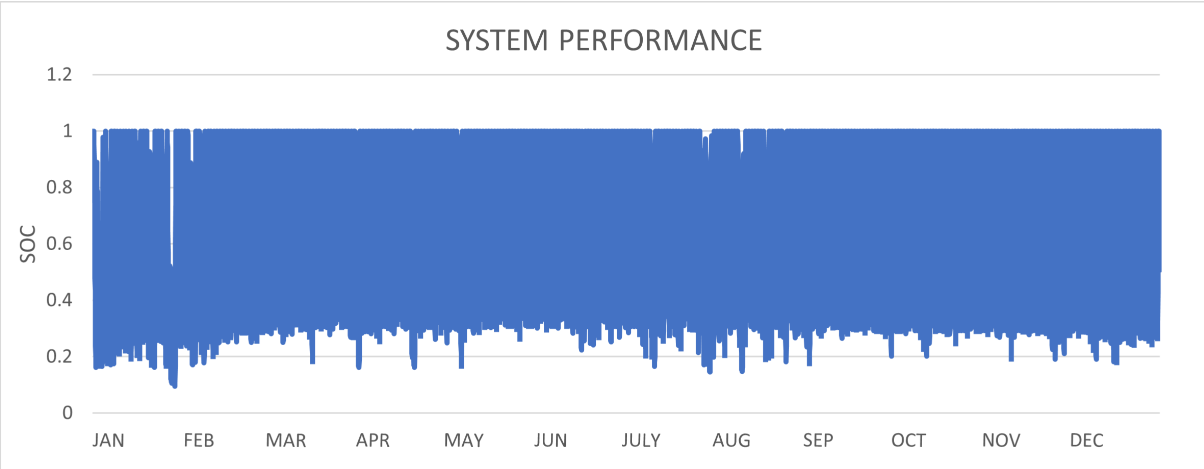

Figure 6.10: System performance

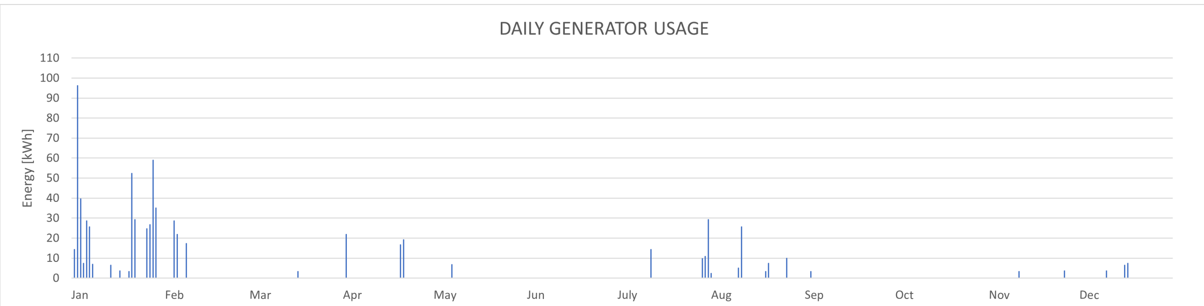

Figure 6.11: Diesel generator performance

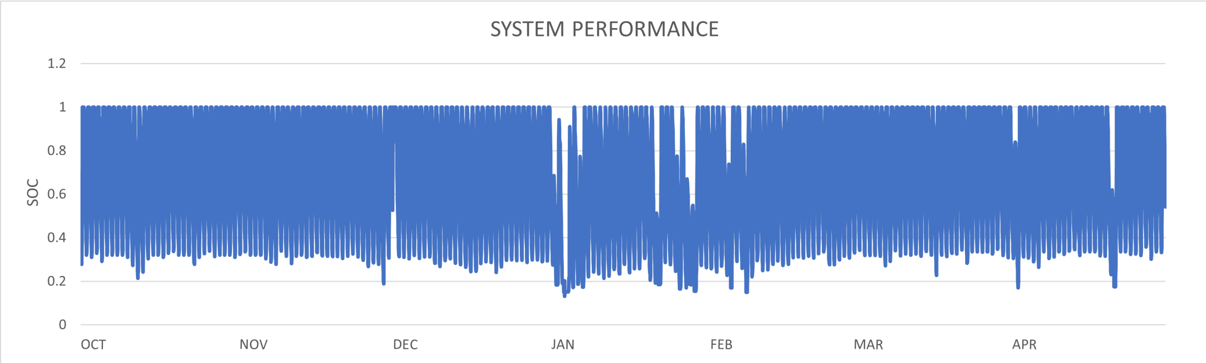

Figure 6.12: System performance during the center operating period

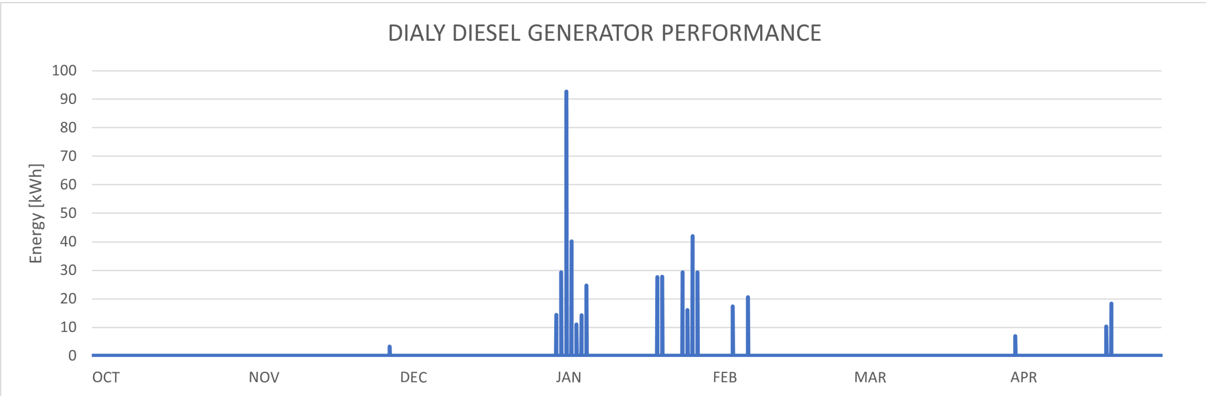

Figure 6.13: Diesel generator performance during the center operating period

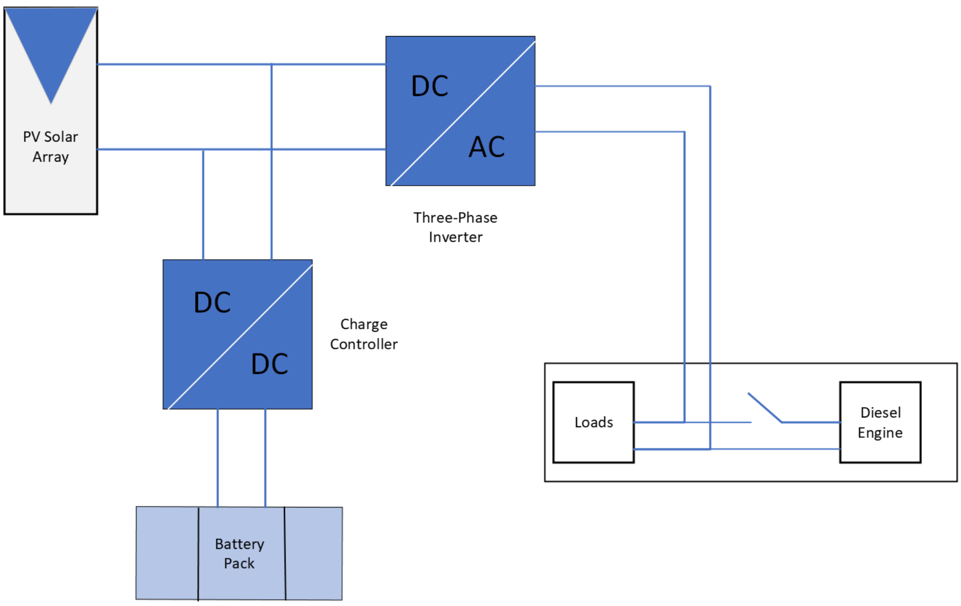

Figure 6.14: System layout (Off-grid)

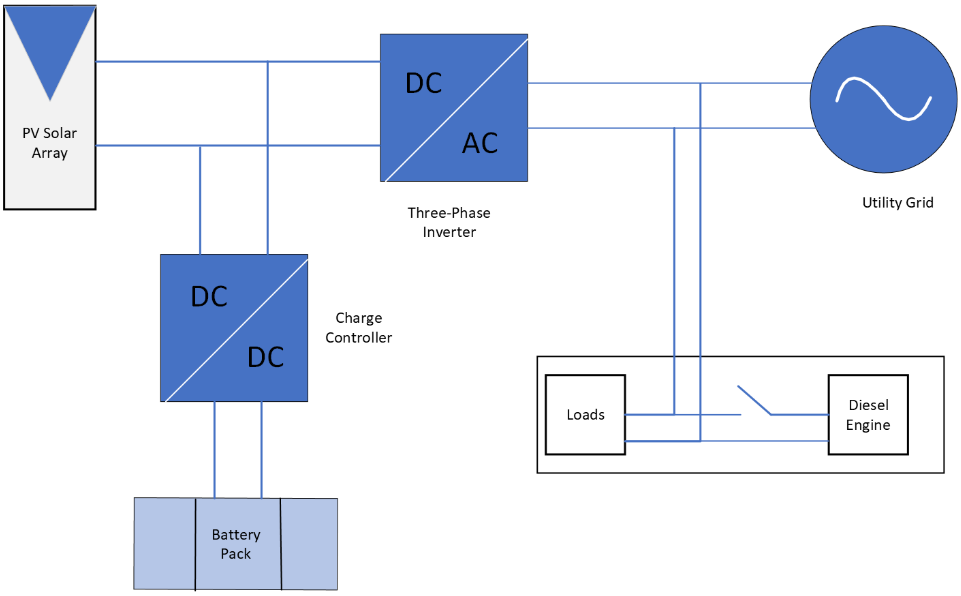

Figure 6.15: System layout (On-grid)

6.3. Economical Analysis

This part of the analysis deals with the economic analysis in terms of Levelized Cost of Energy (LCOE) for three different case scenarios, depending on the following assumption:

Description	Value	Unit
Power Installed	40,870	W
Yearly Electricity Consumed	40,567.14	kWh
Yearly Energy Produced	68,086.52	kWh
PV Panel Cost	701.7	€/kW
Inverter Cost	2630	€/kW
Battery Cost	434	€/kWh
Diesel Generator (35KVA)	12,500	€
Fuel Cost	1.127	€/L
Construction and installation	5	%
Engineering	10	%
O&M	1	%
Inflation	3.4	%
Discount Rate	3	%
Lifetime	25	Years

Figure 6.16: LCOE input data

- **First Scenario:** Off-grid (LCOE)
- **Second Scenario:** Grid-tied system (LCOE)- 60% of the price
- **Third Scenario:** Grid-tied System (LCOE)- same price

	Off-Grid	Grid-tied (Selling Price 60% Real Electricity Price)	Grid-tied (Selling Price 100% Real Electricity Price)
Energy Produced [MWh/year]	68	68	68
Energy Used [MWh/year]	43	43	43
Energy Sold [MWh/year]	0	25	25
Real Electricity Price [€/kWh]	-	0.18	0.18
Selling Price to Grid [€/kWh]	-	0.11	0.18
LCOE [€/kWh]	0.19	0.13	0.09
Compare to real price	+5.5%	-28%	-50%

Figure 6.17: LCOE Results

6.4. Environmental Analysis

The life cycle analysis data for CO_2 emissions used in this section were taken from two different sources. The first source is International Journal of Renewable Energy Research (IJRER) [47] and the second source is MDPI journal [48].

Two different scenarios are developed using the sources mentioned above

- **First scenario:** Off-grid CO_2 emissions avoided

Fossil Fuel	0.62	kgCO2/kWh	1014175
generator	0.62	kgCO2/kWh	25521.49
INTERNATIONAL JOURNAL			
pv	1713	kgCO2/kWp	41
installaion	3.19	kgCO2/kg	2479
inverters	317	kgCO2/units	2
batteries	150	kgCO2/kWh	200
	CO2 emissions from the PV	108775	
	CO2 emissions from the FF	628788.5	
	CO2 emissions savings	504190.2	
		504.2 ton of CO_2 Avoided	
MDPI			
		Min	Max
	PV emissions (kgCO2/kWh)	0.032	0.052
	CO2 emissions from the PV	32453.6	52737.1
	CO2 emissions from the FF	628788.5	628788.5
	CO2 emissions savings	580.5 ton of CO_2 Avoided	560.2 ton of CO_2 Avoided

Figure 6.18: Off-grid CO_2 emissions avoided

- **Second scenario:** Grid-tied system CO_2 emissions avoided

Fossil Fuel	0.62	kgCO2/kWh	1583247
generator	0.62	kgCO2/kWh	25521.49
INTERNATIONAL JOURNAL			
pv	1713	kgCO2/kWp	41
installaion	3.19	kgCO2/kg	2479
inverters	317	kgCO2/units	2
batteries	150	kgCO2/kWh	200
	CO2 emissions from the PV	108775	
	CO2 emissions from the FF	981613.1	
	CO2 emissions savings	857014.8	
		857.0148 ton of CO_2 Avoided	
MDPI			
		Min	**Max**
	PV emissions (kgCO2/kWh)	0.032	0.052
	CO2 emissions from the PV	50663.9	82328.84
	CO2 emissions from the FF	981613.1	981613.1
	CO2 emissions savings	915125.9	883460.9
		915.1 ton of CO2 Avoided	883.5 ton of CO2 Avoided

Figure 6.19: Grid-tied system CO_2 emissions avoided

The pie chart below shows the CO_2 emissions contribution of the different components based on the LCA:

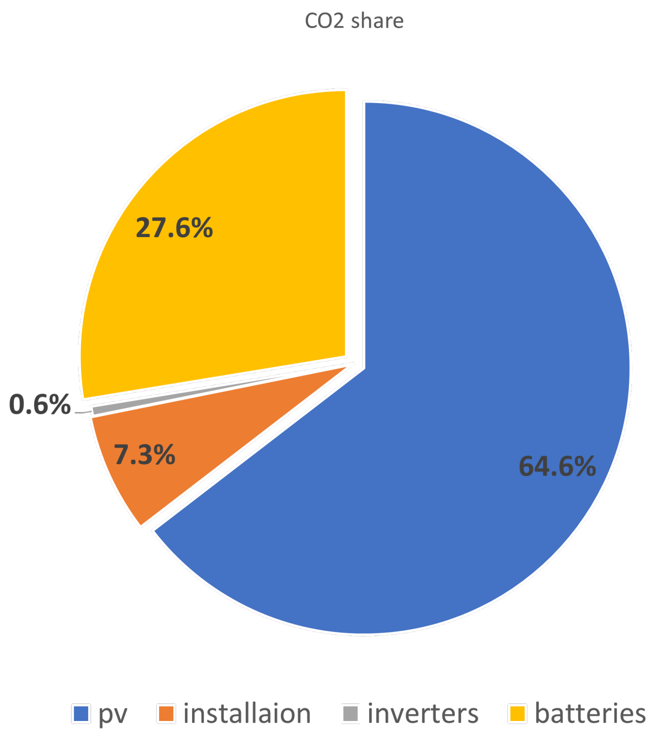

Figure 6.20: CO_2 emissions contribution of the different components

6.5. Social Impact

There are many possibilities to make the project useful for the people live near by the Adulis Research Center. Making a quick social assessment on the area located closed to the center we can summarize the following issues the people around are suffering from:

1. Lack of jobs opportunities in the rural areas is forcing people to migrate to cities.
2. In this location, there is a serious lack of water.
3. The construction of schools are below satisfactory. The condition of many schools is in a pathetic state with broken walls, poor lighting and poor air ventilation.

For these reasons, the Adulis Research Center project will affect the social environment of the area as follows:

- Near the site there are agricultural lands, where they use diesel generators for the water pumps to irrigate the plants. The project can be a good solution for those farmers to use the excess electricity produced to fill a water tank and use this water for irrigation purposes and for human use as well [49].
- Around 2-4 km away from the archaeological site, on the way to zula, there is a primary school which lacks any source of electricity. The project can be a great addition to the students knowing that weather in the most year months is very hot. So if the surplus of the electricity is used to run fans in the classrooms, a comfortable environment will be created and hence better results will be achieved. Moreover a water pump can be run making a great addition by make clean drinkable water available for the students.
- 80.7% of Eritreans do not have access to basic water services. Human and animal waste is often found in open water sources due to a lack of basic domestic cleanliness [50]. Water contamination is exacerbated by deforestation and bad agricultural practices. The access of clean water is important specially for girls in schools. When girls hit puberty, they begin menstruating. If girls cannot practice proper hygiene or have access to clean water at school, they often miss out on education. Some have to skip class until their menstruation ends, which is around a week. During that week, they do not learn whatever their schools teach[51].
- The center and specially the gallery will encourage tourism. This will create a new indirect job opportunities for the locals and will enable them to sell locally produced items for the tourists and promote sustainability and self sufficiency for these people livings.

- Lastly, the implementation of such project and sustainable technology in the area can motivate others to start a similar projects which can change the people lives in the area, by introducing not only clean but reliable and sustainable source of energy.

7 | Conclusions and Recommendations

7.1. Conclusion

The aim of the project was to design an optimal off-grid PV solar system for Adulis Research Center in Eritrea. The second part of the project was to make an economic, environmental and social impact viability analysis of the project. The analysis was done to estimate and compare different scenarios to predict the load profile of the center and design the system accordingly. The difficulty of accurately predicting the load profile and the lack of data was the main reason to implement many case scenarios and that conveyed which scenario is most likely to occur. For that reason, a simple but intelligent model was created to easily obtain the required result.

Five different cases of load profiles for Adulis Research Center were obtained to demonstrate the possible demand resulting from the different electrical equipment and the people's life style. The first scenario represented the full load with an exaggeration of the kitchen equipment. The second scenario highlighted the replacement of electrical stoves with gas ones. The third scenario included air conditioning and some modifications on the working periods of some devices. The fourth scenario assumed that the center will be partially inhibited.The fifth scenario replaced some devices and limits the number of people to 50.

The analysis showed that the fifth scenario is the most relevant to reality, thus the case study for the design of the PV solar system was done according to it. The main constraints for the analysis is to minimize the capital cost of the investment while ensuring the total energy demand of the Center is met. For this reason, a hybrid system of PV solar energy and diesel engine is proposed. The analysis showed that 134 PV solar panels with a total rating of 41 kW would be optimum. This figure took into account the solar irradiance, ambient air temperature and all Balance Of the System (BOS) efficiencies- DC-AC inverter, battery and MPPT. This configuration generates an average of 42.2MWh/year.

This accounts for about 98.3 % of total energy needed for the center. The deficit is compromised using a 35KVA diesel generator.

Further analysis was carried out to calculate the state of charge (SOC) thus the optimal battery size was selected. The main constraint for the state of charge (SOC) was to remain above 20%. The calculations demonstrated that a lithium ion battery of 100 kWh capacity would be sufficient.

The economic analysis showed good results for the LCOE. The proposed design, has a high cost of investment due to the battery packs' cost. The LCOE was found to be 0.19€/kWh, 0.13€/kWh, and 0.09€/kWh for the off-grid scenario, on-grid (selling electricity at reduced rate) and on-grid (selling at full price) respectively.

Environmental impact on the other hand showed a considerable amount of CO_2 emission savings. The CO_2 emission savings were calculated using two methods. The first methods gave an exact quantity of CO_2 savings while the second approach gave a range for the minimum and maximum CO_2 emission savings. However, due to the fact that Eritrea's electricity production was mainly dependant on fossil fuels, thus the avoided CO_2 emissions are significant in comparison to the emissions resulting from the equivalent amount of energy supplied by the grid. An average 537 ton of CO_2 emission will be saved for the project's lifetime in off-grid scenario, and 878 ton of CO_2 related to on-grid scenario in which the surplus will be sold back to the grid.

Finally, the social impact assessment of the project was carried out and it showed vital benefits for the people living in the surroundings. Access to clean and portable water was the main use for the excess of energy produced from the system, particularly given that the Center will not be operating the entire year but only for six months per year. Another proposal is to use the excess energy for a nearby school, this can ensure student's physical safety and promote education in rural areas.

7.2. Recommendations

Firstly, investigate or acquire more accurate data for the activities in the center to calculate a more precise load profile. Secondly, updated economic data such as inflation and discount rate should be applied in Eritrea since they play a significant role in the LCOE calculation. This yields a better estimate of the system's economic viability. The On-grid analysis carried out in this study was based on a hypothetical scenario of where acces to a transmission line is possible, whereas in reality there is no transmission line crossing by the region where the center is located. Further analysis based ona connection to the nearest transmission line will reflect a better estimation for the CO_2 emission savings and the LCOE calculations. Moreover, the social impact was based on information from archaeologists work in Adulis site, so further study need to be done to specify the actual needs and more detailed systems requirements to fulfil these needs.

Bibliography

[1] World Energy Council. World energy trilemma index 2020. Technical report, World Energy Council, London, united Kingdom, 2020.

[2] United Nations. Transforming our world the 2030 Agenda for Sustainable Development, 2015. *https://www.un.org/ga/search/viewdoc.asp?symbol=A/RES/70/1 Lang=E.*

[3] International Energy Agency. Africa energy outlook 2019. Technical report, 2019 .

[4] CIA World Factbook, Eritrea, 2021. *https://www.cia.gov/the-world-factbook/countries/eritrea/.*

[5] Ministry of Information, Eritrea. Eritrea at a glance, 2009. *https://shabait.com/2009/10/01/eritrea-at-a-glance/.*

[6] M. Cinzia, C. Sara, and C. Valentina. Il parco archeologico di adulis proposta per un polo sostenibile di formazione e ricerca in area subsahariana. Master's thesis, Scuola di Architettura Urbanistica Ingegneria delle costruzioni, Politecnico di Milano .

[7] H. E. Beck and et al. Present and future köppen-geiger climate classification maps at 1-km resolution. Sci Data, 2018 .

[8] International Monetary Fund. World economic outlook. Technical report, IMF, Washinton,DC, USA, 2019 .

[9] Ministry of information, Eritrea. Adulis: The ancient port-city of er- itrea part i, 2017. *https://shabait.com/2017/05/24/adulis-the-ancient-port-city-of-eritrea-part-i/.*

[10] C. Zazzaro. The Ancient Red Sea Port of Adulis and the Eritrean Coastal Region: Previous investigations and museum collections. Archaeopress, 2013.

[11] Global Change Data Lab, *https://ourworldindata.org/grapher/share-of-the-population-with-access-to-electricity?country=BRA RWA IND CHN HTI AFG USA*

[12] Sunday Standard, *https://www.sundaystandard.info/more-have-access-to-electricity/: :text=It%20also%20requires%20households%20to%20meet%20 a%20specified,urban%20household%20it%20is%20500%20kWh%20per%20year.*

[13] Our World in Data, *https://ourworldindata.org/grapher/number-of-people-with-and-without-electricity-access?country=TTO TCA Central+Europe+and+the+Baltics VCT Africa+Western+and+Central Africa+ Eastern+and+Southern ATG BIH KNA STP Fragile+and+conflict+affected+situations.*

[14] Enerdata, 2020, *https://www.enerdata.net/publications/executive-briefing/world-electrification-decarbonisation.html*

[15] International Energy Agency (IEA) Africa's energy future matters for the world, 2029, *https://www.iea.org/news/africas-energy-future-matters-for-the-world*

[16] Millennuim Solutions Afria Corp (MSA Corp), *https://ms-africa.com/#: :text=Energy%20in%20Africa%20is%20a%20scarcer%20commodity% 20than,More%20than%20500%20million%20people%20live%20without%20electricity.*

[17] Across the Sahara, *https://flairng.com/africa/what-percentage-of-africas-total-population-has-access-to-electricity.html* .

[18] World Economic Forum, 2015, *https://www.weforum.org/agenda/2015/06/how-can-africa-develop-its-electricity-infrastructure/.*

[19] Global Wind Atlas, *https://globalwindatlas.info/.*

[20] Global Solar Atlas, *https://globalsolaratlas.info/map.*

[21] The World Bank, Access to electricity (% of population) - Eritrea, *https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ER*

[22] International Renewable Energy Agency (IRENA), Energy profile: Eritrea, 2021, *https://www.irena.org/IRENADocuments/Statistical_Profiles/Africa /Eritrea_Africa_RE_SP.pdf.*

[23] Yohannes, Ermias. "Geothermal Exploration in Eritrea - Status report." Short Course IV on Exploration for Geothermal Resources, organized by UNU-GTP, KenGen and GDC, at Lake Naivasha, Kenya, 2009.

[24] Ministry of Information, Eritrea, Promoting Solar Energy in Eritrea, 2020, *https://shabait.com/2020/10/14/promoting-solar-energy-in-eritrea/.*

[25] Lebassi, Bereket, and Robert Van Buskirk. "Numerical Simulation of Wind Distributions for Resource Assessment in Southeastern Eritrea, East Africa.", 2005.

[26] Government of Eritrea, United Nations Development Program (UNDP), and Global Environment Facility (GEF), "Wind Energy Applications in Eritrea, Termination review" 2009, *https://erc.undp.org/evaluation/documents/download/3600.*

[27] Green, Martin A., et al. "Progress and outlook for high-efficiency crystalline silicon solar cells." Solar Energy Materials and Solar Cells 65.1-4, 2001.

[28] Lafond, F., Bailey, A. G., Bakker, J. D., Rebois, D., Zadourian, R., McSharry, P., Farmer, J. D. (2017). How well do experience curves predict technological progress? A method for making distributional forecasts.

[29] Qazi, Salahuddin. Standalone photovoltaic (PV) systems for disaster relief and remote areas. Elsevier, 2016.

[30] Goswami, D. Yogi, Frank Kreith, and Jan F. Kreider. Principles of solar engineering. CRC Press, 2000.

[31] Iclodean, Calin, et al. "Comparison of different battery types for electric vehicles." IOP conference series: materials science and engineering. Vol. 252. No. 1. IOP Publishing, 2017.

[32] Jung, Joey, Lei Zhang, and Jiujun Zhang, eds. Lead-acid battery technologies: fundamentals, materials, and applications. Vol. 8. Crc Press, 2015.

[33] M. Anderman, "Ni-Cd battery for aircraft: battery design and charging options," Proceedings of 9th Annual Battery Conference on Applications and Advances, 1994.

[34] IEEE Working Group on Energy Forecasting and Analytics , *https://site.ieee.org/pes-psope/subcommittees/power-system-economics-subcommittee/working-group-on-energy-forecasting-and-analytics/* .

[35] Global Energy Forecasting Competition,*http://www.drhongtao.com/gefcom.*

[36] Global Solar Atlas, *https://globalsolaratlas.info/support/faq.*

[37] Photovoltaic Geographical Information System, *https://re.jrc.ec.europa.eu/pvg_ tools/en/.*

[38] PVSyst, *https://www.pvsyst.com/help/pvmodule_ database.htm.*

[39] DRF Solutions, *https://www.dfrsolutions.com/blog/how-to-select-the-right-battery-for-your-application-part-1-battery-metric-considerations.*

[40] Depth of discharge *https://federalbatteries.com.au/news/what-depth-discharge-and-why-it-so-important.*

[41] CBC International, *https://www.cbcinter.co.th/wp-content/uploads/2019/04/CBC48V150Ah − LithiumbatteryforTelecomBTS.pdf.*

[42] Burris, R. K., and Larry W. Canter. "Cumulative impacts are not properly addressed in environmental assessments." Environmental impact assessment review 17.1, 1997.

[43] Wathern, Peter. "An introductory guide to EIA." Environmental impact assessment: theory and practice, 1988.

[44] Geneletti, Davide. Ecological evaluation for environmental impact assessment. Koninklijk Nederlands Aardrijkskundig Genootschap, 2002.

[45] Vanclay, Frank. "International principles for social impact assessment." Impact assessment and project appraisal 21.1, 2003.

[46] Esteves, Ana Maria, Daniel Franks, and Frank Vanclay. "Social impact assessment: the state of the art." Impact Assessment and Project Appraisal 30.1, 2012.

[47] Dhakal, Rabin, et al. "Towards a Net Zero Building Using Photovoltaic Panels: A Case Study in an Educational Building." International Journal of Renewable Energy Research (IJRER), 2021.

[48] Temporelli, Andrea, Maria Leonor Carvalho, and Pierpaolo Girardi. "Life cycle assessment of electric vehicle batteries: an overview of recent literature." Energies, 2020.

[49] Kidane, Tesfai T., Si Wei, and Kibrom T. Sibhatu. "Smallholder farmers' willingness to pay for irrigation water: Insights from Eritrea." Agricultural Water Management, 2019.

[50] World Vision Organisation https://www.worldvision.org/clean-water-news-stories/10-worst-countries-access-clean-water.

[51] The Borgen Project Organization *https://borgenproject.org/eritreas-lack-of-clean-water/: :text=Despite%20the%20fact%20that%20Eritrea,Eritreans%20lack%20basic %20water%20services.*

A | Appendix A: Devices lists

Device	Power (W)	Morning	Afternoon	Evening	Comments
Room bulb	10	5:00 - 7:59		18:00 - 23:59	
Kitchen bulb	15	6:00 - 8:59	12:00 - 14:59	15:00 - 21:59	
Toilet bulb	7	5:00 - 23:59			10 mins/h (5:00 - 7:59 and 12:00 - 14:59 and 19:00 - 21:59) 5 mins/h (8:00 - 11:59 and 15:00 - 18:59 and 22:00 23:59)
Generator bulb	13	00:00 - 6:59		18:00 - 23:59	
Food court bulb	13			18:00 - 23:59	
Outdoor bulb	30	00:00 - 6:59		18:00 - 23:59	
Tower bulb	15	00:00 - 6:59		18:00 - 23:59	
Office bulb	10	08:00 - 17:59			
Gallery	10	08:00 - 17:59			
Living area bulb	10	6:00 - 7:59		18:00 - 23:59	
Laptop charger (office and lab)	60	08:00 - 17:59			
Laptop charger (rooms)	60	00:00-00:59	15:00 - 18:59	22:00 - 23:59	30 mins/h
Laptop charger (foodcourt/dining area)	60	8:00 - 23:59			
Phone charger	7	00:00 - 3:59	16:00 - 16:59	19:00 - 20:59	30 mins/h
Ceiling fan (office, lab, gallery)	65	08:00 - 17:59			
Ceiling fan (rooms)	65	00:00 - 7:59	16:00 - 23:59		
Ceiling fan (living area)	65	8:00 - 23:59			
Ceiling fan (technical room)	65	24 hours			To cool the electric devices
Ceiling fan (food court/dining area)	65		11:00 - 23:59		
Ceiling fan(kitchen)	65	6:00 - 8:59	12:00 - 14:59	17:00 - 21:59	

Device	Power (W)	Morning	Afternoon	Evening	Comments
Exhaust fan toilet	12	5:00 - 23:59			5-10 mins/h
Exhaust fan showers	12	5:00 - 7:59		18:00 - 20:59	
Exhaust fan kitchen	12	6:00 - 8:59	12:00 - 14:59	17:00 - 20:59	
TV	60		12:00 - 22:59		
TV standby	5	00:00 - 11:59		23:00 - 23:59	
Oven	2000	6:00 - 8:59	12:00 - 14:59	18:00 - 20:59	15 mins/h
Fridge	300	24 hours			17 min/h
Stove	1200	6:00 - 7:59	12:00 - 13:59	17:00 - 19:59	
Kettle	2000	6:00 - 8:59	12:00 - 14:59	18:00 - 20:59	15 mins/h
Gen. batt. Charger	1000	-			
Water pump	750	9:00 - 11:59			used to fill a 10m^3 water tank 60m head
Split A\C unit	318	-			
Washing machine	1000			20:00 - 21:59	

B | Appendix B: Power and load profiles calculations, Sample

				room bulb 10	kitchen bulb 15	WC bulb 7	Generator bulb 13	food courtbulb 13	outdoor bulb 30	tower bulb 15	office bulb 10	living area 10	laptop charger 60	phone charger 7	ceiling fan 65	exhaust fan 12	TV 60	oven 2000	fridge 300	microwa ve 1200	kettle 2000	gen. batt. 1000	water pump 1000	split ac unit 318	washing maine 1000					
location		appliance		quantity	power W	total power	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
tower		light		4	15	60	60	60	60	60	60	60	60	0	0	0	0	0	0	0	0	0	0	0	60	60	60	60	60	60
		socket		4		0																								
office 1		light		2	10	20	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	0	0	0	0	0	0
		laptop		1	60	60	0	0	0	0	0	0	0	0	60	60	60	60	60	60	60	60	60	60	0	0	0	0	0	0
		socket		2		0																								
		fan		1	65	65	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
4x WC		light		4	7	28	0	0	0	0	0	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28
		exhaust fan		4	12	48	0	0	0	0	0	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
		socket		2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
lab		light		3	10	30	0	0	0	0	0	0	0	0	30	30	30	30	30	30	30	30	30	30	0	0	0	0	0	0
		laptop		6	60	360	0	0	0	0	0	0	0	0	360	360	360	360	360	360	360	360	360	360	0	0	0	0	0	0
		socket		4		0																								
		fan		1	65	65	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
gallery		light		4	10	40	0	0	0	0	0	0	0	0	40	40	40	40	40	40	40	40	40	40	0	0	0	0	0	0
		fan		1	65	65	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
houskeeper room		light		0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		laptop		0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		charger		0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		fan		0	65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8x corridors		light		8	10	80	0	0	0	0	0	80	80	80	80	0	0	0	0	0	0	0	0	0	80	80	80	80	80	80
living area		light		1	10	10	0	0	0	0	0	0	10	10	0	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10
		socket		2		0																								
		fan		1	65	65	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
		TV (standby 5W)		1	60	60	5	5	5	5	5	5	5	5	5	5	5	5	60	60	60	60	60	60	60	60	60	60	60	5
2x bathroom		light		2	7	14	0	0	0	0	0	14	14	14	0	0	0	0	0	0	0	0	0	0	14	14	14	0	0	0
		exhaust fan		2	12	24	0	0	0	0	0	24	24	24	0	0	0	0	0	0	0	0	0	0	24	24	24	0	0	0
		socket		0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12x double room	12	light	1	12	10	120	0	0	0	0	0	120	120	120	0	0	0	0	0	0	0	0	0	0	120	120	120	120	120	120
		laptop	2	24	60	1440	1440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1440	1440	1440	0	0	0	1440	1440
		charger	2	24	7	168	168	168	168	168	0	0	0	0	0	0	0	0	0	0	0	0	168	0	0	168	168	0	0	0
		fan	1	12	65	780	780	780	780	780	780	780	780	780	0	0	0	0	0	0	0	0	780	780	780	780	780	780	780	780
4x triple room	4	light	1	4	10	40	0	0	0	0	0	40	40	40	0	0	0	0	0	0	0	0	0	0	40	40	40	40	40	40
		laptop	3	12	60	720	720	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	720	720	720	0	0	0	720	720
		charger	3	12	7	84	84	84	84	84	0	0	0	0	0	0	0	0	0	0	0	0	84	0	0	84	84	0	0	0
		fan	1	4	65	260	260	260	260	260	260	260	260	260	0	0	0	0	0	0	0	0	260	260	260	260	260	260	260	260
kitchen		fridge		2	300	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
		oven		1	2300	2300	0	0	0	0	0	0	2300	2300	2300	0	0	0	2300	2300	2300	0	0	0	2300	2300	2300	0	0	0
		stove		2	1300	2600	0	0	0	0	0	0	2600	2600	0	0	0	0	2600	2600	0	0	0	2600	2600	2600	0	0	0	0
		katle		1	2000	2000	0	0	0	0	0	0	2000	2000	2000	0	0	0	2000	2000	2000	0	0	0	2000	2000	2000	0	0	0
		socket		4		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		light		1	15	15	0	0	0	0	0	0	15	15	15	0	0	0	15	15	15	0	0	15	15	15	15	15	0	0
		exhaust fan		1	12	12	0	0	0	0	0	0	12	12	12	0	0	0	12	12	12	0	0	12	12	12	12	0	0	0
		fan		1	65	65	0	0	0	0	0	0	65	65	65	0	0	0	65	65	65	0	0	65	65	65	65	65	0	0
technical room		light		1	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		AC		0	318	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		sochet		2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		fan		1	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
foodcourt		light		3	13	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	39	39	39	39	39
		fan		3	65	195	0	0	0	0	0	0	0	0	0	0	0	195	195	195	195	195	195	195	195	195	195	195	195	195
		microwave oven		0	1200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		laptop		2	60	120	0	0	0	0	0	0	0	0	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
tents		tents		7		0	0																							
		light		7	10	70	0	0	0	0	0	70	70	70	0	0	0	0	0	0	0	0	0	0	70	70	70	70	70	70
		charger		14	7	98	98	98	98	98	0	0	0	0	0	0	0	0	0	0	0	0	98	0	0	98	98	0	0	0
		socket		14		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		fan		7	65	455	455	455	455	455	455	455	455	455	0	0	0	0	0	0	0	0	455	455	455	455	455	455	455	455
laundry		light		1	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0	0
		washing machine		2	1000	2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2000	2000	0	0
clinic		light		2	10	20	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	0	0	0	0	0	0
		fan		1	65	65	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
generator		light		2	13	26	26	26	26	26	26	26	26	0	0	0	0	0	0	0	0	0	0	0	26	26	26	26	26	26
		battery charger		0	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		socket		1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parkings		light		10	30	300	300	300	300	300	300	300	300	0	0	0	0	0	0	0	0	0	0	0	300	300	300	300	300	300
outdoor		light		40	30	1200	1200	1200	1200	1200	1200	1200	1200	0	0	0	0	0	0	0	0	0	0	0	1200	1200	1200	1200	1200	1200
		water pump		0	1000	0	0	0	0	0	0	0	0	0	0	0	1000	1000	1000	0	0	0	0	0	0	0	0	0	0	0
						16971	6261	4101	4101	4101	3751	4175	11177	9591	6193	2721	2721	2916	8963	8963	6363	1971	5976	8318	13811	12001	11411	6711	6781	6726

Figure B.1: Power profile calculations

location	appliance	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
tower	light	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	socket																								
office 1	light	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	socket																								
	fan	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
4x WC	light	0	0	0	0	0	0.1667	0.1667	0.1667	0.0833	0.0833	0.0833	0.0833	0.1667	0.1667	0.1667	0.0833	0.0833	0.0833	0.0833	0.1667	0.1667	0.1667	0.0833	0.0833
	exhaust fan	0	0	0	0	0	0.1667	0.1667	0.1667	0.0833	0.0833	0.0833	0.0833	0.1667	0.1667	0.1667	0.0833	0.0833	0.0833	0.0833	0.1667	0.1667	0.1667	0.0833	0.0833
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
lab	light	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	socket																								
	fan	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
gallery	light			0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	fan			0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
houskeeper room	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	charger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8x corridors	light	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
living area	light	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	socket																								
	fan	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	TV (standby 5W)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2x bathroom	light	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
	exhaust fan	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12x double room	light	0.5	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	laptop	0.5	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.5
	charger	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.5
	fan	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
4x triple room	light	0.5	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	laptop	0.5	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.5
	charger	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0
	fan	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
kitchen	fridge	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833	0.2833
	microwave oven	0	0	0	0	0	0	0.25	0.25	0.25	0	0	0	0.25	0.25	0.25	0	0	0	0.25	0.25	0.25	0	0	0
	stove	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0
	katle	0	0	0	0	0	0	0.25	0.25	0.25	0	0	0	0.25	0.25	0.25	0	0	0	0.25	0.25	0.25	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	light	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	1	1	1	1	0	0
	exhaust fan	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	1	1	1	1	0	0
	fan	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	1	1	1	1	0	0
technical room	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	AC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	sochet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	fan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
foodcourt	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	fan	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	microwave oven	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
tents	tents	tents																							
	light	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	charger	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	fan	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
laundry	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
	washing machine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
clinic	light	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
generator	light	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	battery charger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parkings	light	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
outdoor	light	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
	water pump	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Figure B.2: Devices activity schedule

location	appliance	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
tower	light	60	60	60	60	60	60	60	0	0	0	0	0	0	0	C	0	0	0	60	60	60	60	60	60
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
office 1	light	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	60	60	60	60	60	60	60	60	60	60	0	0	0	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
bathroom lab	light	0	0	0	0	0	4.6667	4.6667	4.6667	2.3333	2.3333	2.3333	2.3333	4.6667	4.6667	4.6667	2.3333	2.3333	2.3333	2.3333	4.6667	4.6667	4.6667	2.3333	2.3333
	exhaust fan	0	0	0	0	0	8	8	8	4	4	4	4	8	8	Ɛ	4	4	4	4	8	8	8	4	4
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
lab	light	0	0	0	0	0	0	0	0	30	30	30	30	30	30	30	30	30	30	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	360	360	360	360	360	360	360	360	360	360	0	0	0	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
gallery		0	0	0	0	0	0	0	0	40	40	40	40	40	40	40	40	40	40	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
room 1	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	charger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
corridor 1	light	0	0	0	0	0	80	80	80	80	0	0	0	0	0	C	0	0	0	80	80	80	80	80	80
living area	light	0	0	0	0	0	0	10	10	0	0	0	0	0	0	C	0	0	0	10	10	10	10	10	10
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
	TV (standby 5W)	5	5	5	5	5	5	5	5	5	5	5	5	60	60	60	60	60	60	60	60	60	60	60	5
bathroom 2*3	light	0	0	0	0	0	14	14	14	0	0	0	0	0	0	C	0	0	0	14	14	14	0	0	0
	exhaust fan	0	0	0	0	0	24	24	24	0	0	0	0	0	0	C	0	0	0	24	24	24	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
room 4	light	0	0	0	0	0	120	120	120	0	0	0	0	0	0	C	0	0	0	120	120	120	120	120	120
	laptop	720	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	720	720	720	0	0	0	720	720
	charger	84	84	84	84	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	84	84	0	0	0
	fan	780	780	780	780	780	780	780	780	0	0	0	0	0	0	C	0	780	780	780	780	780	780	780	780
room 5	light	0	0	0	0	0	40	40	40	0	0	0	0	0	0	C	0	0	0	40	40	40	40	40	40
	laptop	360	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	360	360	360	0	0	0	360	360
	charger	42	42	42	42	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	42	42	0	0	0
	fan	260	260	260	260	260	260	260	260	0	0	0	0	0	0	C	0	260	260	260	260	260	260	260	260
kitchen	fridge	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98	169.98
	microwave oven	0	0	0	0	0	0	575	575	575	0	0	0	575	575	575	0	0	0	575	575	575	0	0	0
	stove	0	0	0	0	0	0	2600	2600	0	0	0	0	2600	2600	C	0	0	2600	2600	2600	0	0	0	0
	katle	0	0	0	0	0	0	500	500	500	0	0	0	500	500	500	0	0	0	500	500	500	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	light	0	0	0	0	0	0	15	15	15	0	0	0	15	15	15	0	0	15	15	15	15	15	0	0
	exhaust fan	0	0	0	0	0	0	12	12	12	0	0	0	12	12	12	0	0	12	12	12	12	0	0	0
	fan	0	0	0	0	0	0	65	65	65	0	0	0	65	65	65	0	0	65	65	65	65	65	0	0
technical room	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	fan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	sochet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
foodcourt	light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	39	39	39	39	39	39
	fan	0	0	0	0	0	0	0	0	0	0	0	195	195	195	195	195	195	195	195	195	195	195	195	195
	microwave oven	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	laptop	0	0	0	0	0	0	0	0	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
tents	tents																								
	light	0	0	0	0	0	70	70	70	0	0	0	0	0	0	C	0	0	0	70	70	70	70	70	70
	charger	98	98	98	98	0	0	0	0	0	0	0	0	0	0	C	0	98	0	0	98	98	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	fan	455	455	455	455	455	455	455	455	0	0	0	0	0	0	C	0	455	455	455	455	455	455	455	455
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	10	10	0	0
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	2000	2000	0	0
		0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	65	65	65	65	65	65	65	65	65	65	0	0	0	0	0	0
generator	light	26	26	26	26	26	26	26	0	0	0	0	0	0	0	C	0	0	0	26	26	26	26	26	26
	battery charger	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
	socket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	C	0	0	0	0	0	0	0	0	0
parkings	light	300	300	300	300	300	300	300	0	0	0	0	0	0	0	C	0	0	0	300	300	300	300	300	300
outdoor	light	1200	1200	1200	1200	1200	1200	1200	0	0	0	0	0	0	0	C	0	0	0	1200	1200	1200	1200	1200	1200
	water pump	0	0	0	0	0	0	0	0	0	1000	1000	1000	0	0	C	0	0	0	0	0	0	0	0	0
		4560	**3480**	**3480**	**3480**	**3256**	**3617**	**7394**	**5808**	**2403**	**2156**	**2156**	**2351**	**5180**	**5180**	**2580**	**1406**	**4079**	**6673**	**8941**	**8092**	**7502**	**6153**	**5136**	**5081**
		5062	8040	11520	15000	18256	21873	29266	35074	37477	39633	41790	44141	49321	54500	57080	58486	62566	69239	78180	86272	93774	99926	105063	110144

Figure B.3: Load profile calculations

C | Appendix C: Number of Panels and simulation sample calculations

month		daylength	irradiation(kWh/mth/m2)	irradiation(kWh/day/m2)	irradiance w/m2	temp	cell temprature	losses(w)	losses %	thermal efficiency	last efficiency	number of PV
jan		11.35	114.57	3.695806452	325.6217138	27.8	37.97567856	16.22608603	0.053200282	0.946799718	0.799312194	133.185133
feb		11.68	152.92	5.461428571	467.5880626	28.1	42.71212696	22.14901476	0.072619721	0.927380279	0.782917815	92.01507265
mar		12.08	209.01	6.742258065	558.1339457	32	49.4416858	30.5643281	0.100210912	0.899789088	0.759624636	76.82047608
apr		12.52	188.9	6.296666667	502.9286475	31.1	46.81652023	27.28155855	0.089447733	0.910552267	0.768711182	81.28445621
may		12.88	212.51	6.85516129	532.2330194	30.8	47.43228186	28.05156846	0.091972356	0.908027644	0.766579832	74.86974256
june		13.06	200.98	6.699333333	512.9657989	33.1	49.13018121	30.17479161	0.098933743	0.901066257	0.760702854	77.20310619
jul		12.98	179.32	5.784516129	445.6483921	33	46.92651225	27.41910357	0.0898987	0.9101013	0.768330465	88.52507776
aug		12.68	184.85	5.962903226	470.2605068	33.6	48.29564084	29.13119887	0.095512127	0.904487873	0.763591468	86.40971617
sep		12.15	198.55	6.618333333	544.7187929	33.8	50.82246228	32.29098908	0.105872095	0.894127905	0.754845322	78.75439549
oct		11.83	199.8	6.44516129	544.8149865	32.3	49.32546833	30.41899814	0.09973442	0.90026558	0.760026902	80.31906642
nov		11.45	169.85	5.661666667	494.4687045	30.1	45.55214702	25.70045984	0.084263803	0.915736197	0.773087587	89.88938519
dec		11.27	159.5	5.14516129	456.5360506	27.3	41.56675158	20.71672285	0.067923681	0.932076319	0.786882329	97.17904356

nearshading	1		
alpha-power	0.41	alpha power	-0.0041
panel power	305		
optical efficiency	0.98		
mismatch efficiency	0.95		
DC efficiency	0.98		
inverter efficiency	0.974		
dirt efficiency	0.95		
OVERALL-EFFICIENCY	0.844225214		
bi-directional efficiency	0.972		
round-trip efficiency	0.953		
Number of Panels	133.185133	134	134
average efficiency	0.770384382		
PSH	4.5		
Number of Panels	113.4910001	114	

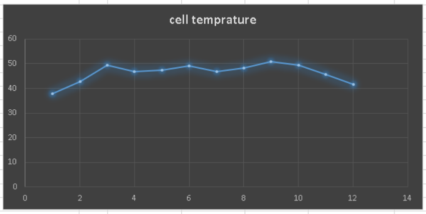

Figure C.1: Number of panels

		date	irradiance (w/m2)	amb. Temp ®	cell temp ®	shading efficiency	prod.power (w)	consum.energy (wh)	power from/to batt	batt. SOC		Wasted energy	from diesel generator	
1	0	20160101:0007	0	28.18	28.18	1	0	4559.98	-4749.979167	1	0.951143071	0	0	0
	1	20160101:0107	0	27.8	27.8	1	0	3479.98	-3624.979167	0.951143071	0.913857571	0	0	0
	2	20160101:0207	0	27.42	27.42	1	0	3479.98	-3624.979167	0.913857571	0.876572071	0	0	0
	3	20160101:0307	0	27.04	27.04	1	0	3479.98	-3624.979167	0.876572071	0.839286571	0	0	0
	4	20160101:0407	81.63	28.22	30.26075	1	2755.76972	3255.98	-521.0523746	0.839286571	0.833927176	0	0	0
	5	20160101:0507	368.31	29.41	38.61775	1	11998.45668	3616.646667	8046.53761	0.833927176	0.916691562	0	0	0
	6	20160101:0607	622.59	30.59	46.15475	1	19618.33567	7393.646667	11735.70144	0.916691562	1.037401634	3636.270013	0	0
	7	20160101:0707	810.78	31.54	51.8095	1	24899.78164	5807.646667	18328.44958	1	1.188521196	18328.44958	0	0
	8	20160101:0807	945.83	32.49	56.13575	1	28468.43109	2403.313333	25022.51304	1	1.25737442	25022.51304	0	0
	9	20160101:0907	1004.33	33.45	58.55825	1	29885.03491	2156.313333	26619.57271	1	1.273801319	26619.57271	0	0
	10	20160101:1007	972.91	33.88	58.20275	1	28999.02359	2156.313333	25769.00184	1	1.26505259	25769.00184	0	0
	11	20160101:1107	863.4	34.32	55.905	1	26015.56363	2351.313333	22717.68028	1	1.233667569	22717.68028	0	0
	12	20160101:1207	690.74	34.75	52.0185	1	21192.82304	5179.646667	15372.64932	1	1.158118679	15372.64932	0	0
	13	20160101:1307	459.04	33.88	45.356	1	14516.60636	5179.646667	8963.481303	1	1.092195808	8963.481303	0	0
	14	20160101:1407	172.95	33	37.32375	1	5665.861716	2579.646667	2962.766447	1	1.030474169	2962.766447	0	0
	15	20160101:1507	0	32.13	32.13	1	0	1406.313333	-1464.909722	1	0.984932357	0	0	0
	16	20160101:1607	0	31.69	31.69	1	0	4079.313333	-4249.284722	0.984932357	0.941225429	0	0	0
	17	20160101:1707	0	31.24	31.24	1	0	6673.313333	-6951.368056	0.941225429	0.869725643	0	0	0
	18	20160101:1807	0	30.8	30.8	1	0	8941.313333	-9313.868056	0.869725643	0.773925857	0	0	0
	19	20160101:1907	0	30.46	30.46	1	0	8091.646667	-8428.798611	0.773925857	0.687229643	0	0	0
	20	20160101:2007	0	30.12	30.12	1	0	7501.646667	-7814.215278	0.687229643	0.606854857	0	0	0
	21	20160101:2107	0	29.78	29.78	1	0	4142.646667	-4315.256944	0.606854857	0.562469357	0	0	0
	22	20160101:2207	0	29.56	29.56	1	0	5136.313333	-5350.326389	0.562469357	0.507437429	0	0	0
	23	20160101:2307	0	29.33	29.33	1	0	5081.313333	-5293.034722	0.507437429	0.452994786	0	0	0
2	24	20160102:0007	0	29.1	29.1	1	0	4559.98	-4749.979167	0.452994786	0.404137857	0	0	0
	25	20160102:0107	0	28.66	28.66	1	0	3479.98	-3624.979167	0.404137857	0.366852357	0	0	0
	26	20160102:0207	0	28.23	28.23	1	0	3479.98	-3624.979167	0.366852357	0.329566857	0	0	0
	27	20160102:0307	0	27.79	27.79	1	0	3479.98	-3624.979167	0.329566857	0.292281357	0	0	0
	28	20160102:0407	77.99	29	30.94975	1	2625.284356	3255.98	-656.9746293	0.292281357	0.285523904	0	0	0
	29	20160102:0507	363.43	30.22	39.30575	1	11804.10892	3616.646667	7859.963764	0.285523904	0.366369245	0	0	0
	30	20160102:0607	612.12	31.43	46.733	1	19238.34467	7393.646667	11370.91009	0.366369245	0.483327178	0	0	0
	31	20160102:0707	803.78	31.89	51.9845	1	24664.90678	5807.646667	18102.96971	0.483327178	0.669529152	0	0	0
	32	20160102:0807	907.63	32.34	55.03075	1	27460.53251	2403.313333	24054.93041	0.669529152	0.916951293	0	0	0
	33	20160102:0907	984.23	32.8	57.40575	1	29447.40197	2156.313333	26199.44509	0.916951293	1.1864313	18125.26526	0	0
	34	20160102:1007	960.45	33.08	57.09125	1	28778.65364	2156.313333	25557.44669	1	1.262876595	25557.44669	0	0
	35	20160102:1107	879.42	33.35	55.3355	1	26569.12026	2351.313333	23249.09465	1	1.239133545	23249.09465	0	0
	36	20160102:1207	691.45	33.63	50.91625	1	21322.4239	5179.646667	15497.06614	1	1.159398395	15497.06614	0	0
	37	20160102:1307	408.11	32.87	43.07275	1	13037.82316	5179.646667	7543.849437	1	1.07759388	7543.849437	0	0
	38	20160102:1407	190.56	32.1	36.864	1	6255.161004	2579.646667	3528.493763	1	1.036293079	3528.493763	0	0
	39	20160102:1507	0	31.34	31.34	1	0	1406.313333	-1464.909722	1	0.984932357	0	0	0
	40	20160102:1607	0	31.15	31.15	1	0	4079.313333	-4249.284722	0.984932357	0.941225429	0	0	0
	41	20160102:1707	0	30.97	30.97	1	0	6673.313333	-6951.368056	0.941225429	0.869725643	0	0	0
	42	20160102:1807	0	30.78	30.78	1	0	8941.313333	-9313.868056	0.869725643	0.773925857	0	0	0
	43	20160102:1907	0	30.41	30.41	1	0	8091.646667	-8428.798611	0.773925857	0.687229643	0	0	0
	44	20160102:2007	0	30.04	30.04	1	0	7501.646667	-7814.215278	0.687229643	0.606854857	0	0	0
	45	20160102:2107	0	29.66	29.66	1	0	4142.646667	-4315.256944	0.606854857	0.562469357	0	0	0
	46	20160102:2207	0	29.62	29.62	1	0	5136.313333	-5350.326389	0.562469357	0.507437429	0	0	0
	47	20160102:2307	0	29.57	29.57	1	0	5081.313333	-5293.034722	0.507437429	0.452994786	0	0	0
3	48	20160103:0007	0	29.52	29.52	1	0	4559.98	-4749.979167	0.452994786	0.404137857	0	0	0
	49	20160103:0107	0	28.91	28.91	1	0	3479.98	-3624.979167	0.404137857	0.366852357	0	0	0
	50	20160103:0207	0	28.3	28.3	1	0	3479.98	-3624.979167	0.366852357	0.329566857	0	0	0
	51	20160103:0307	0	27.69	27.69	1	0	3479.98	-3624.979167	0.329566857	0.292281357	0	0	0
	52	20160103:0407	64.99	28.36	29.98475	1	2196.552842	3255.98	-1103.569956	0.292281357	0.280930352	0	0	0
	53	20160103:0507	363.58	29.03	38.1195	1	11869.99397	3616.646667	7923.213412	0.280930352	0.362426261	0	0	0
	54	20160103:0607	597.13	29.7	44.62825	1	18945.01699	7393.646667	11089.31551	0.362426261	0.476487792	0	0	0
	55	20160103:0707	801.05	30.49	50.51625	1	24747.51566	5807.646667	18182.27423	0.476487792	0.66350547	0	0	0
	56	20160103:0807	930.72	31.28	54.548	1	28222.68584	2403.313333	24786.5976	0.66350547	0.918453331	0	0	0
	57	20160103:0907	994.82	32.07	56.9405	1	29829.72193	2156.313333	26566.47225	0.918453331	1.191708474	18638.32388	0	0
	58	20160103:1007	960.06	32.34	56.3415	1	28868.79449	2156.313333	25643.98191	1	1.263766671	25643.98191	0	0

number of panels	134		DOD	0.8
WEEKEND LOAD	70		efficiency	0.9
battery capacity	97222.22222		DoA	1
			round trip eff.	0.96
total energy produced	68.1		energy required	40.59
energy not comulated	25.1			
energy used	42.9		energy from pv	42.2
energy from diesel	0.7			
pecentage of renewable	98.33			
pecentage of wasted energy	37			

0	1
0	2

Figure C.2: Simulation sample

D | Appendix D: LCOE calculations

year	CAPEX	efficincy	O&M	Fuel cost	energy used per year	PV energy	savings	CF	ACF	CCF
0	144729.1				40567.14286	68086.52	7754.022	-136975	-136975.1128	-136975
1	0	0.97	1447.291	1125.992	40567.14286	66043.93	7754.022	5180.739	5181.205273	-131794
2	0	0.96515	1447.291	1072.464	40567.14286	65713.71	7754.022	5234.267	5235.208776	-126559
3	0	0.96032425	1447.291	1046.662	40567.14286	65385.14	7754.022	5260.069	5261.488703	-121297
4	0	0.955522629	1447.291	1021.481	40567.14286	65058.21	7754.022	5285.25	5287.152337	-116010
5	0	0.950745016	1447.291	996.9054	40567.14286	64732.92	7754.022	5309.825	5312.214453	-110698
6	0	0.945991291	1447.291	972.9214	40567.14286	64409.26	7754.022	5333.809	5336.68947	-105361
7	0	0.941261334	1447.291	949.5143	40567.14286	64087.21	7754.022	5357.216	5360.591463	-100001
8	0	0.936555027	1447.291	926.6704	40567.14286	63766.78	7754.022	5380.06	5383.934169	-94616.6
9	0	0.931872252	1447.291	904.376	40567.14286	63447.94	7754.022	5402.355	5406.730996	-89209.9
10	0	0.927212891	1447.291	882.6181	40567.14286	63130.7	7754.022	5424.113	5428.995029	-83780.9
11	0	0.922576827	1447.291	861.3836	40567.14286	62815.05	7754.022	5445.347	5450.739042	-78330.2
12	0	0.917963942	1447.291	840.6599	40567.14286	62500.97	7754.022	5466.071	5471.975501	-72858.2
13	0	0.913374123	1447.291	820.4349	40567.14286	62188.47	7754.022	5486.296	5492.716574	-67365.5
14	0	0.908807252	1447.291	800.6964	40567.14286	61877.53	7754.022	5506.034	5512.974137	-61852.5
15	0	0.904263216	1447.291	781.4329	40567.14286	61568.14	7754.022	5525.298	5532.759781	-56319.7
16	0	0.8997419	1447.291	762.6327	40567.14286	61260.3	7754.022	5544.098	5552.08482	-50767.7
17	0	0.89524319	1447.291	744.2849	40567.14286	60954	7754.022	5562.446	5570.960295	-45196.7
18	0	0.890766974	1447.291	726.3785	40567.14286	60649.23	7754.022	5580.352	5589.396985	-39607.3
19	0	0.886313139	1447.291	708.9029	40567.14286	60345.98	7754.022	5597.828	5607.405408	-33999.9
20	0	0.881881574	1447.291	691.8477	40567.14286	60044.25	7754.022	5614.883	5624.995833	-28374.9
21	0	0.877472166	1447.291	675.2029	40567.14286	59744.03	7754.022	5631.528	5642.178279	-22732.7
22	0	0.873084805	1447.291	658.9585	40567.14286	59445.31	7754.022	5647.772	5658.962527	-17073.8
23	0	0.868719381	1447.291	643.1049	40567.14286	59148.08	7754.022	5663.626	5675.358124	-11398.4
24	0	0.864375784	1447.291	627.6327	40567.14286	58852.34	7754.022	5679.098	5691.374388	-5707.02
25	0	0.860053905	1447.291	612.5328	40567.14286	58558.08	7754.022	5694.198	5707.020412	-3.3E-10

Figure D.1: LCOE, Off-Grid

year	CAPEX	efficincy	O&M	Fuel cost	energy used per year	PV energy	energy sold	savings	CF	ACF	CCF
0	144729.1				40567.14286	68086.52	27519.38	8375.649	-136353	-136353.4859	-136353
1	0	0.97	1447.291	1125.992	40567.14286	66043.93	25476.79	8150.271	5576.988	5577.48989	-130776
2	0	0.96515	1447.291	1072.464	40567.14286	65713.71	25146.57	8113.835	5594.08	5595.086393	-125181
3	0	0.96032425	1447.291	1046.662	40567.14286	65385.14	24818	8077.581	5583.628	5585.134995	-119596
4	0	0.955522629	1447.291	1021.481	40567.14286	65058.21	24491.07	8041.508	5572.736	5574.742116	-114021
5	0	0.950745016	1447.291	996.9054	40567.14286	64732.92	24165.78	8005.616	5561.419	5563.921672	-108457
6	0	0.945991291	1447.291	972.9214	40567.14286	64409.26	23842.12	7969.903	5549.69	5552.687228	-102904
7	0	0.941261334	1447.291	949.5143	40567.14286	64087.21	23520.07	7934.369	5537.563	5541.052009	-97363.4
8	0	0.936555027	1447.291	926.6704	40567.14286	63766.78	23199.63	7899.012	5525.051	5529.028904	-91834.3
9	0	0.931872252	1447.291	904.376	40567.14286	63447.94	22880.8	7863.833	5512.165	5516.630481	-86317.7
10	0	0.927212891	1447.291	882.6181	40567.14286	63130.7	22563.56	7828.829	5498.919	5503.868987	-80813.8
11	0	0.922576827	1447.291	861.3836	40567.14286	62815.05	22247.91	7794	5485.325	5490.756362	-75323.1
12	0	0.917963942	1447.291	840.6599	40567.14286	62500.97	21933.83	7759.345	5471.394	5477.304243	-69845.8
13	0	0.913374123	1447.291	820.4349	40567.14286	62188.47	21621.33	7724.864	5457.137	5463.52397	-64382.3
14	0	0.908807252	1447.291	800.6964	40567.14286	61877.53	21310.38	7690.554	5442.567	5449.426601	-58932.8
15	0	0.904263216	1447.291	781.4329	40567.14286	61568.14	21001	7656.417	5427.693	5435.022907	-53497.8
16	0	0.8997419	1447.291	762.6327	40567.14286	61260.3	20693.16	7622.45	5412.526	5420.323389	-48077.5
17	0	0.89524319	1447.291	744.2849	40567.14286	60954	20386.85	7588.653	5397.077	5405.33828	-42672.1
18	0	0.890766974	1447.291	726.3785	40567.14286	60649.23	20082.08	7555.025	5381.355	5390.077552	-37282.1
19	0	0.886313139	1447.291	708.9029	40567.14286	60345.98	19778.84	7521.565	5365.371	5374.550922	-31907.5
20	0	0.881881574	1447.291	691.8477	40567.14286	60044.25	19477.11	7488.273	5349.134	5358.767861	-26548.8
21	0	0.877472166	1447.291	675.2029	40567.14286	59744.03	19176.89	7455.147	5332.652	5342.737596	-21206
22	0	0.873084805	1447.291	658.9585	40567.14286	59445.31	18878.17	7422.186	5315.936	5326.469117	-15879.5
23	0	0.868719381	1447.291	643.1049	40567.14286	59148.08	18580.94	7389.39	5298.994	5309.971185	-10569.6
24	0	0.864375784	1447.291	627.6327	40567.14286	58852.34	18285.2	7356.759	5281.835	5293.252336	-5276.32
25	0	0.860053905	1447.291	612.5328	40567.14286	58558.08	17990.94	7324.29	5264.466	5276.320885	2.82E-11

Figure D.2: LCOE, Grid-tied

List of Figures

Acknowledgements

I'd like to express my gratitude to prof. Riccardo Mereu, my supervisor, for his persistent advice and support.
Additionally, I want to thank Amani Medani, my mother, my reason for being and my primary drive for accomplishing anything.
Without you, my friend Abdallah Yousif, this would not be possible.
Finally, I'd want to show my thankfulness to Mishkat Sobhi and Dr. Methani Eltayeb for their support and help with thesis.