Department of Mechanical and Aerospace Engineering

Investigating Integrated Renewable Energy Solutions to Electrical Supply Issues in a Small Town in Sudan

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Signed: Almogdad Abdeen Date: 24/08/2019

ABSTRACT

Currently, many developing countries are suffering overwhelming energy supply issues due to unprecedented rapid urbanisation and unreliable power infrastructure. Their national grids invariably generate energy with high carbon emissions, contributing to pollution and climate change, yet they are still ineffective and often don't meet demand. Solving energy problems on a localised renewable scale could bypass the obstacles of unwilling or financially limited governments, and an unstable, unpredictable central supply.

Many towns in Sudan have suffered from scheduled power blackouts, with unreliable power supply due to a lack of power generation capacity. These long daily hours of load-shedding have caused immense frustration among inhabitants. Hence, to tackle these power problems, this project aimed to investigate the possibility of supplying a small Sudanese town with an integrated renewable energy system, which could be implemented as an alternative to the current incapable existing energy system.

The town's total annual demand was estimated, including the residential, public services and commercial sectors. Many developing countries have abundant untapped natural renewable energy resources; this town is no exception as it was assessed to have high levels of solar irradiance and biomass.

Four main systems Scenarios were modelled on a basis of Solar Photovoltaic and Anaerobic Digestion, using HOMER and AD Excel spreadsheet tools. These Scenarios were compared with established technical, financial and environmental evaluation criteria. The study suggested two feasible integrated renewable energy systems, both of which are superior to the current energy system; each has particular characteristics which function better than the other in certain contemporary and projected circumstances.

ACKNOWLEDGEMENTS

There are many people besides myself without whom this thesis would not have been possible. I am extremely grateful to my supervisor, Dr. Paul Tuohy, whose continual support, guidance and motivation propelled me throughout this project. In addition, I would like to thank all my lecturers, colleagues and University staff who have made me feel at home at Strathclyde and gave me the basis to flourish as a person and an engineer.

The generous scholarship I have received from the SFC (Scottish Funding Council), and the Department of Mechanical and Aerospace Engineering, has made it possible for me, not only to study, but to envisage myself at the cutting edge of sustainable engineering in the future.

My family and friends have been behind me throughout this research journey, and I would particularly like to thank my siblings and my Mum. I hope this project could contribute to improving the energy sector in my beloved homeland Sudan, in the near future.

I would especially like to dedicate this thesis to the spirit of my Dad, who always believed in me.

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ABBREVIATIONS

PV: Photovoltaic

AD: Anaerobic Digestion

CHP: Combined Heat & Power

DM: Dry Matter

AC: Alternative Current

DC: Direct Current

CO2: Carbon Dioxide

COE: Cost of Electricity

NPC: Net Present Cost

FITS: Feed-In Tariffs

KW: Kilowatt

KWh: Kilowatt-Hours

KWh/M2: Kilowatt-Hours Per Meter Square

MW: Megawatt

MWh: Megawatt-Hours

GW: Gigawatt

GWh: Gigawatt-Hours

KV: Kilovolt

M3: Cubic Metre

CH4: Methane

H2S: Hydrogen Sulphide

Li-Ion: Lithium Ion

M/S: Meter Per Second

O&M: Operation & Maintenance

GHG: Greenhouse Gas

LPG: Liquefied Petroleum Gas

MTCO2e: Metric Tons of Carbon Dioxide Equivalent

CAIT: World Resources Institute Climate Analysis Indicators Tool

KTOE: Kilotons of Oil Equivalent

GHI: The Global Horizontal Irradiance

DHI: Direct Normal Irradiance

DNI: Diffuse Horizontal Irradiance

HOMER: The Hybrid Optimization Model for Electric Renewables

NREL: North American National Renewable Energy Laboratory

HVAC: Heating, Ventilation, and Air Conditioning

NNFCC: National Non-Food Crops Centre

AEP African Energy Portal
CGD: Centre for Global Development Organisation

NEC: National Electricity Corporation of Sudan

WRE: Ministry of Water Resources, Irrigation and Electricity

STPGC: Sudanese Thermal Power Generating Company

SGHC: The Sudanese Hydro Generation Company

MDEC: Merowe Dam Electricity Company

SETCO: Sudanese Electricity Transmission Company

1 INTRODUCTION

It is an undeniable fact that electricity has revolutionised people's lives. People have become so reliant on electricity for their everyday tasks, it is like water and food. Achieving universal access to a reliable energy supply is fundamental for solving many global development challenges, empowering socio-economic benefits, enabling shops and businesses to stay open longer, giving communities access to better healthcare, and providing children with domestic lighting for after-school study time (ROCKEFELLER, 2017). That is why ensuring access to reliable, affordable, sustainable and modern electrical supply for all is one of the crucial goals of the United Nations for sustainable development by 2030 (UN, 2015).However, currently more than 1 billion people around the world are living in comprehensive un-electrified communities. 95% of those live without electricity supply reside in developing countries in Asia and sub-Saharan Africa, according to the International Energy Agency (IEA, 2017).

As the world today continues to urbanise, about 55% of the world's population is thought to be living in an urban area or town, with that figure set to rise to 70% over the coming decades. India, China and Nigeria will account for 35% of the projected growth of the world's urban population between 2018 and 2050 according to the Population Division of the UN Department of Economic and Social Affairs (DESA, 2018). Although population growth is a good sign for the developing world, unplanned urbanisation can have a devastating impact on local energy systems in these developing countries. In fact, it can widen the gap between the energy demand and supply capacity. Urbanisation can also put more stress onto existing poorly managed energy infrastructures, especially an unreliable grid or transmission lines, which can lead to power blackouts and financial losses.

Typically, most projects and energy police in developing countries have focused on large capital investments in the areas of power plants, extending transmission lines and supplying petroleum and natural gas products. These investments have generally been considered as an adequate method of dealing with urbanisation and industrialisation issues in those countries. However, with the shifting political landscape of the developing world, combating energy issues on larger, nationwide scales has proven to be unfeasible; this suggests that the focus should shift to more decentralised energy systems.

Renewable energy systems can play a big role in solving power supply shortages in these rural towns in developing countries, considering these are likely have abundant solar, wind, biomass and hydro resources. According to International Renewable Energy Agency (IRENA) Director-General Adnan Z. Amin: "*Renewable energy is now the solution for countries looking to support economic growth and job creation, just as it is for those seeking to limit carbon emissions, expand energy access, reduce air pollution and improve energy security*." (IRENA, 2018).

In light of climate change, renewable energy has the capability to reduce the greenhouse gas emissions in developing nations. A report released by Centre for Global Development Organisation (CGD, 2015), reveals that 63% of the world's annual emissions are produced by developing countries such as China, India and many sub-Saharan African nations. Figure 1 below outlines the breakdown of the worldwide GHG missions.

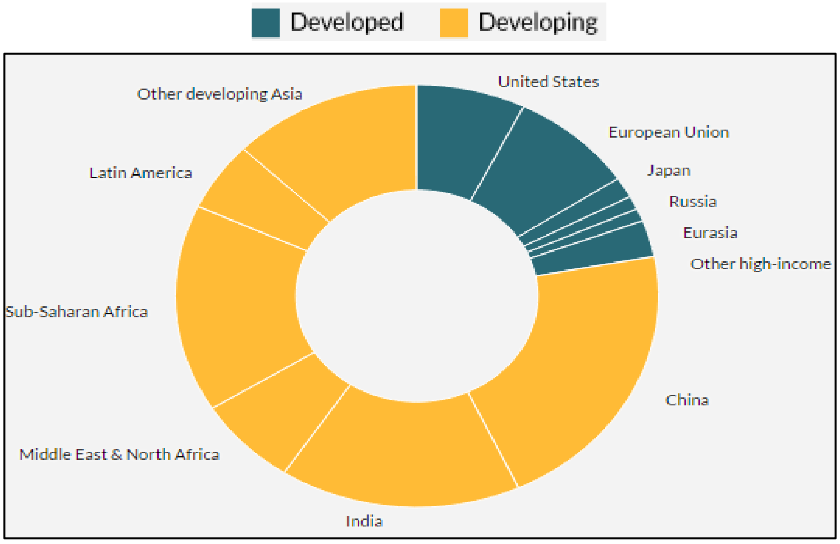


Figure 1:The Worldwide GHG Emissions Percentage (CGD, 2015)

Renewable energy (RE) technologies can be seen as complementary options for remote or rural towns where either conventional energy is absent, or the grid cannot be financially and technically extended. These technologies are also a feasible option if the town has a good grid connection, but long blackouts of power continue due to the deficiency of reliable generation capacities, as well as transmission losses (S Szabó, A Jäger-Waldau, L Szabó , 2010).

The strong dependence on centralised energy systems, which mainly operate on fossil fuels and require huge capital subsidies, is actually one of the reasons behind the high cost of delivered electricity in many developing countries. (R.B.Hirematha, S. Shikhab, N.H. Ravindranathb, 2007). Nevertheless, in order to address these problems - particularly the unreliable, costly electrical power supply in rural or urban areas - there is an urgent need for alternative power generation and distributive energy systems, based on small scale, decentralised, renewable energy approaches which can function in the attendance and absence of the grid line.

1.1 Overview of Sudan Power Sector

This part describes an overview and explanatory background of the current power sector in Sudan - in terms of the present energy supply, consumption figures as well and the main obstacles that the Sudanese power sector faces.

1.1.1 Current Sudan Power Sector Records

The primary sources of energy in Sudan are biomass, oil, hydroelectricity, and renewable energy. The total primary energy generation is equal to approximately 18400 kilotons of oil equivalent (IEA, 2016). 56% of Sudan's total energy generation comes from biomass, due to the fact that 70% of the population reside in rural areas. The biomass energy enables people to meet their demand for heating, cooking, and lighting. The second primary source is oil at 39%, which accounts for 6167 kilotons of the total energy consumption. 767 kilotons of oil equivalent are generated through hydroelectricity, which comprises 5% of the total energy generation. Furthermore, Sudan imports about 8% of its fuel oils (gasoil, aviation and LPG) from neighbouring countries (Rabah et al., 2016). On the demand side, the total energy consumption of Sudan is 11797 kilotons, distributed across the residential (38%), transportation (33%), services (16%), industry (12%) and agriculture (1%) sectors.

For a better understanding of the energy sector in Sudan, a recent study conducted by Rabah et al (2016) designed an energy Sankey diagram – the first of its kind for Sudan - in 2014. See Figure 2 below.

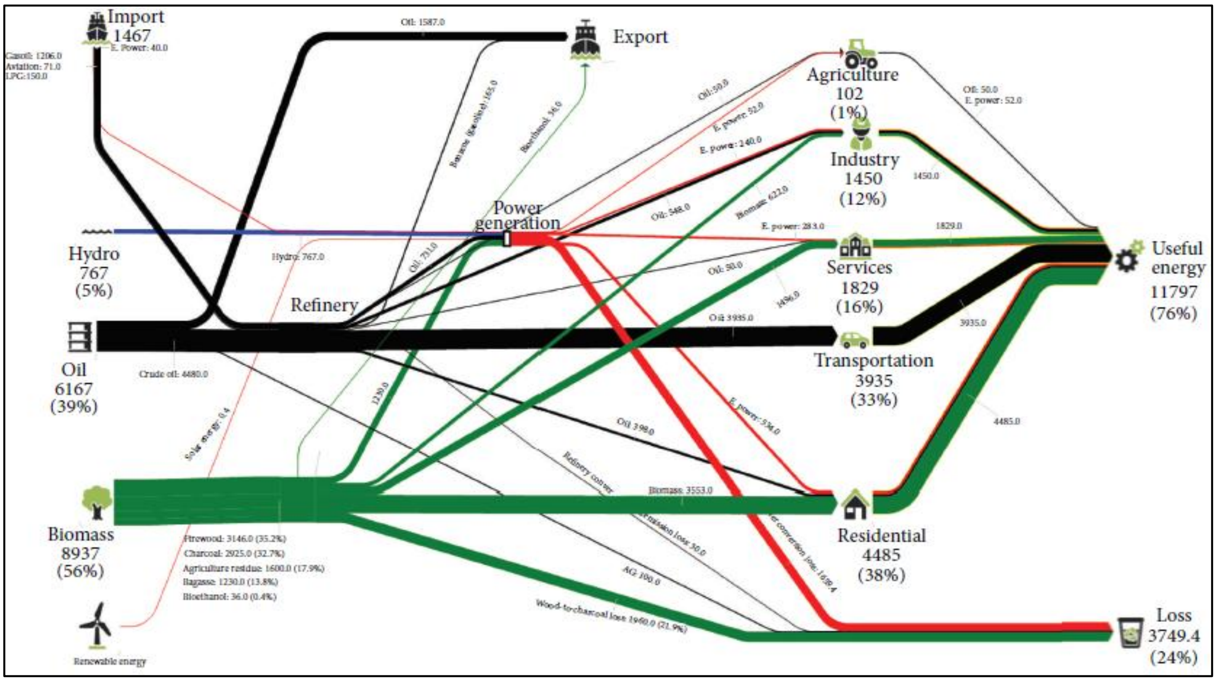


Figure 2: Sankey Diagram for Sudan Presents the Energy Balance in 2014 (Rabah Et Al., 2016)

Referencing the same study, and with regards to electrical power generation in Sudan, currently the total installed power capacity is around 4GW. Thermal power generation capacity represents 46% of this total generation with approximately 2.4GW. Hydropower can be seen to play a vital role in the power sector, as it accounts for 38% of Sudan's total power generation capacity, with approximately 1.5 GW. The rest of Sudan's electricity capacity is imported from Ethiopia (Rabah et al., 2016).

The Ministry of Water Resources, Irrigation and Electricity is the Sudanese governmental body responsible for managing the electric power sector; it was established in 2010 to replace the previous National Electricity Corporation of Sudan (NEC). Under the Ministry of Electricity, there are 5 state-run companies responsible for electricity generation, transmission and distribution in the country (Ghandour, 2016). Figure 3 below demonstrates the structure of electricity in Sudan.

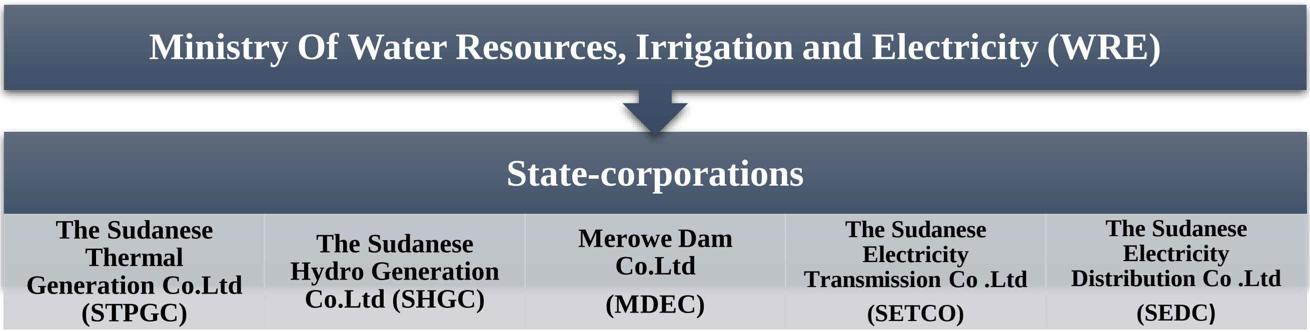


Figure 3: Structure of Electricity in Sudan (Ghandour, 2016)

Electricity in Sudan is transmitted through two interconnected electrical grids, the Blue Nile Grid and the Western grid, covering only a small portion of the country. The 500 KV Line is mainly utilised to transmit high-voltage power for long distances, from big power stations to major sub-station units in the country. Then, the power is distributed via 220 KV and 110 KV between the key cities. The distribution of this power within the cities is mainly via 66 KV, 33 KV, and 11 KV lines (GENI, 2013), as presented below in Figure 4.

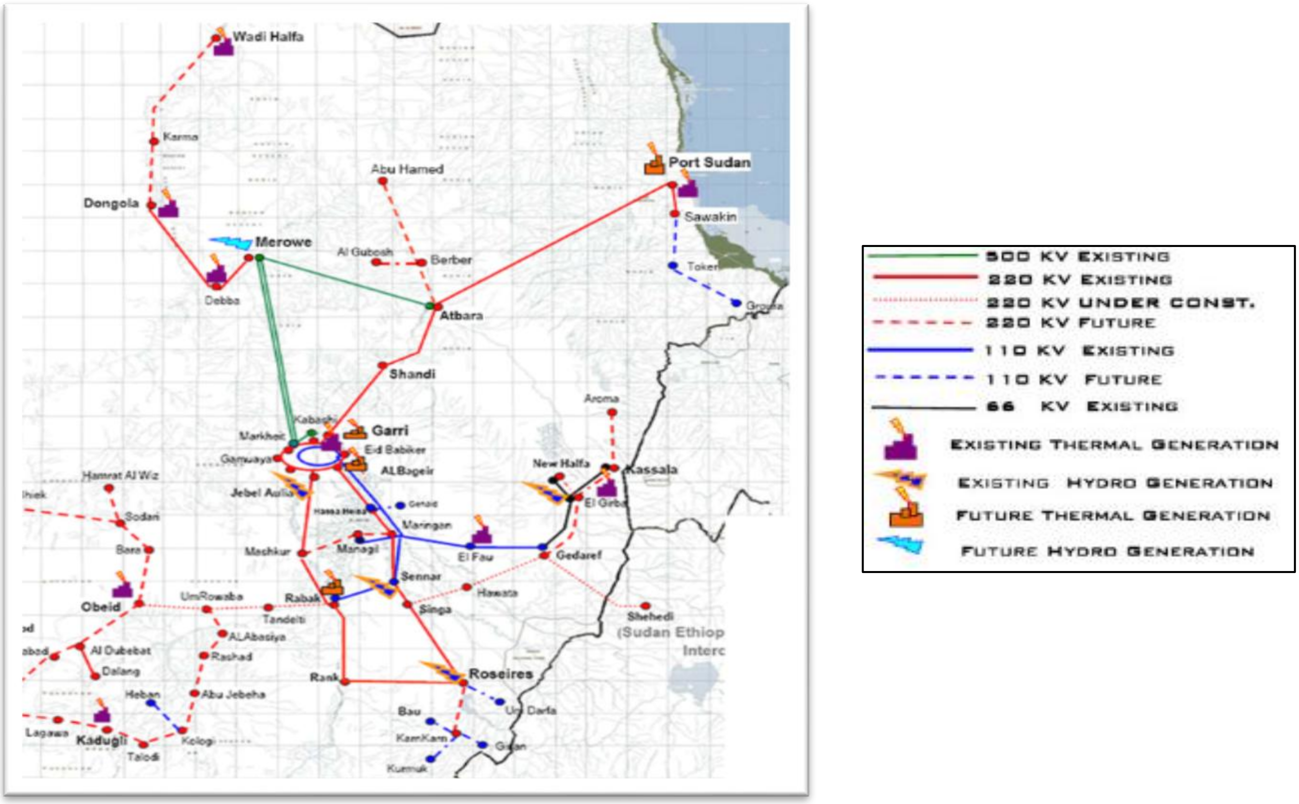


Figure 4: Sudanese Electricity Grid Transmission & Distribution Lines (GENI, 2013)

1.1.2 Electrical Power Sector Problems in Sudan

Despite continuous economic growth, Sudan is still considered one of the least developing countries in terms of its electrical power sector. According to the African Energy Portal (AEP), 24 million people living in Sudan - roughly two-thirds of the total population - have no access to electricity and are ‘left behind in the dark’ (AEP, 2016). The off-grid diesel generator has recently become the only remaining option for generating power, particularly in rural Sudanese towns, yet it is still very expensive and inefficient.

Many regions of Sudan have suffered from poor infrastructure and frequent power outages in the past 10 years, which has created a sense of anger and injustice among the citizens (Ghandour, 2016). The power demand continues to exceed the supply and has resulted in a load-shedding of around 8 to 10 hours per day on average: according to newspaper announcements from the Sudanese Electricity Distribution Company (Jamal, 2019). The gap between demand and supply has been continuously widening due to two core factors. Firstly, there is a relatively low power generation capacity due to a shortage of fuels in thermal plants, and a deficiency of the power plants’ turbines. Secondly, is because of transmission and distribution losses, taking both technical and non-technical forms. These losses are estimated to be between 20-25%, which are significantly above the international standard of 10-15% (Rabah et al., 2016).

Another significant point is that the total GHG emissions in Sudan in 2011 was 400 $MtCO_2e$. The GHG profile was dominated by burning biomass, which contributed to 82% of the total emissions, followed by the GHG emissions from the energy sector which accounted for 39.5 $MtCO_2e$ - about 9% of the total emissions – according to the World Resources Institute Climate Analysis Indicators Tool (CAIT, 2017). In addition, the current environmental footprint of Sudan is 0.40 Tonnes CO2 per Capita (Countryeconomy, 2019)

1.2 The Case Study: East Soba Town

East Soba, where this research study was conducted, is a small town located in the Eastern Nile province of Khartoum State, in central Sudan. The town is 22km from the city of Khartoum. East Soba is geographically positioned at a point of longitudes 32° 38' 51” East, and latitudes 15° 30' 18" North. The town is bordered by the Blue Nile from the west and surrounded by an abundance of small villages. The total population of the town is estimated to be around 20,000 inhabitants, spread across an area of 11km square, and living generally in terraced and semi-detached houses. The town’s primary sources of income are agriculture, animal trading and catering businesses. Figure 5 below displays the location of East Soba town.

Figure 5: The Location of East Soba Town, Sudan (Google Map)

1.3 East Soba Town - Specific Power Supply Problems

Although the town is connected to the national grid, it still suffers from scheduled and continued power outages. It is worth highlighting that the average load-shedding in the town is estimated at around 8 hours a day, impacting heavily on peoples’ and businesses’ everyday tasks. In fact, most of the town’s residents with low, limited incomes, can’t afford to pay for diesel generators to meet their electrical needs during the load-shedding. These generators are not only costly but also very loud, emphasising the need to develop cheaper, less intrusive alternatives. Additionally, the lack of generation capacity, and consistent transmission and distribution loss, are believed to be the key reasons behind regular load-shedding in the town. Moreover, the Sudanese government's overdependence on using costly fossil fuels in the process of harnessing, generating and transmitting the power, has increased the carbon emissions in many towns, including East Soba, to a high level.

1.4 Aim of the Project

The main goal of this project is to investigate and design a strategy to provide a reliable power supply on a local scale for a small town in Sudan through an integrated renewable energy system. Providing reliable, sustainable and affordable power is crucial for the continued sustainable development of any town or city. In fact, there are consistent power blackouts in many cities and towns in Sudan besides East Soba, triggering frustration among citizens who struggle with a daily wait for the electricity's return in order to perform even basic everyday tasks. It is also worth mentioning the significant role that renewable energy can play in providing a clean and reliable power supply, considering the availability of renewable energy resources such as high solar radiation, wind and organic waste in East Soba.

In order to develop a strategy that can provide a reliable, affordable and sustainable power supply, there are some critical objectives which will be undertaken within this study, summarised as below:

- Estimating the current energy demand for the town of East Soba
- Evaluating the availability of renewable energy sources in East Soba
- Examining the possibility of supplying the town of East Soba by renewable energy and finding the optimum options for meeting the demand.
- Modelling the demand and supply comparatively, in various scenarios, to the current existing grid system.
- Recommending an integrated energy system with a technical, environmental and financial summary, as well as future uncertainty consideration.

1.5 Research Scope & Methodology

1.5.1 Scope

This study analyses the possibility of supplying the town of East Soba with an alternative integrated renewable energy system, which could generate a reliable electricity supply to overcome the regular power blackouts and reduce reliance on the unstable grid. The annual energy demand of East Soba has been evaluated, and cooling buildings using air conditioning appears to be the largest part of the town's current load. This study's focus is directed towards the highest consumers of power in the town: the residential, commercial and public service sectors. The transportation sector is disregarded in this instance as it is currently fuelled by diesel and petrol only, with no prospect of electrical cars becoming available in Sudan in the near future.

The study simulates the current grid-connected system in the town to enable a full comparison to alternative renewable energy supply systems, considering the demand and supply both during and off the load-shedding.

However, this research is limited only to the electricity supply sector. East Soba has no heating supply requirement so that sector will not be considered. Additionally, while this study's proposed renewable power supply strategy is on a local scale only, nevertheless some recommendations have been suggested if it were to be scaled up for future potential implementation, in towns in other developing countries.

1.5.2 Methodology

The research approach starts with a critical literature review. The literature review, which aims to accomplish an overall understanding of this research, starts by evaluating different ways of collecting the energy demand data of the town from similar case studies. Current demand figures from the town of East Soba are also reviewed, including monthly energy consumption for the domestic, commercial, public services sectors. In addition, sources of renewable energy supply in the town from solar, wind, biomass are critically reviewed as part of the literature chapter, to help identify the best possible supply options for study. The literature review looks at comparable studies revealing the pros and cons for various energy modelling software systems. It also evaluates different hybrid energy systems with their components, which would allow later supply-demand modelling and creating relationship in various scenarios.

The city's current energy demand is estimated after collecting the data through qualitative, quantitative surveys as well as expert consultation via phone calls. The collected demand data included a wide range of different premises in East Soba: 11 houses, a school, a medical centre, a mosque, a police station, a restaurant, a supermarket, and a pharmacy. The total final demand profile for the town is then established following an optimisation process of the data and is monitored on an hourly basis in summer and winter, considering various aspects such as appliances, usage hours, and opening times of the premises.

On the energy supply side, an assessment of the town's renewable resources is performed and concluded by recommending the solar and organic waste as the most appropriate method of generating a reliable, renewable power supply. Furthermore, the study examined the demand-supply matching analysis. This matching analysis is carried out through HOMER and Anaerobic digestion economic assessment tool, after they were chosen as modelling software. HOMER is used to model the current non-renewable supply system in the town, which is connected via the main grid, including periods of load-shedding. Following that, an examination of various renewable supply scenarios to match the city's demand during and off the load-shedding are considered.

A further technical, environmental and economic investigation for the best possible scenario of the recommended energy system is carried out based on assessment criteria consist of load-shedding coverage, carbon emissions reduction, COE, NPC, Capital cost, and payback period of the system. Moreover, uncertainty analysis is considered as part of the system investigation to allow better design in the future. Following that, a summary of the study result with some future work recommendations are revealed at the end of the study. The full research methodology steps can be summarised below in Figure 6.

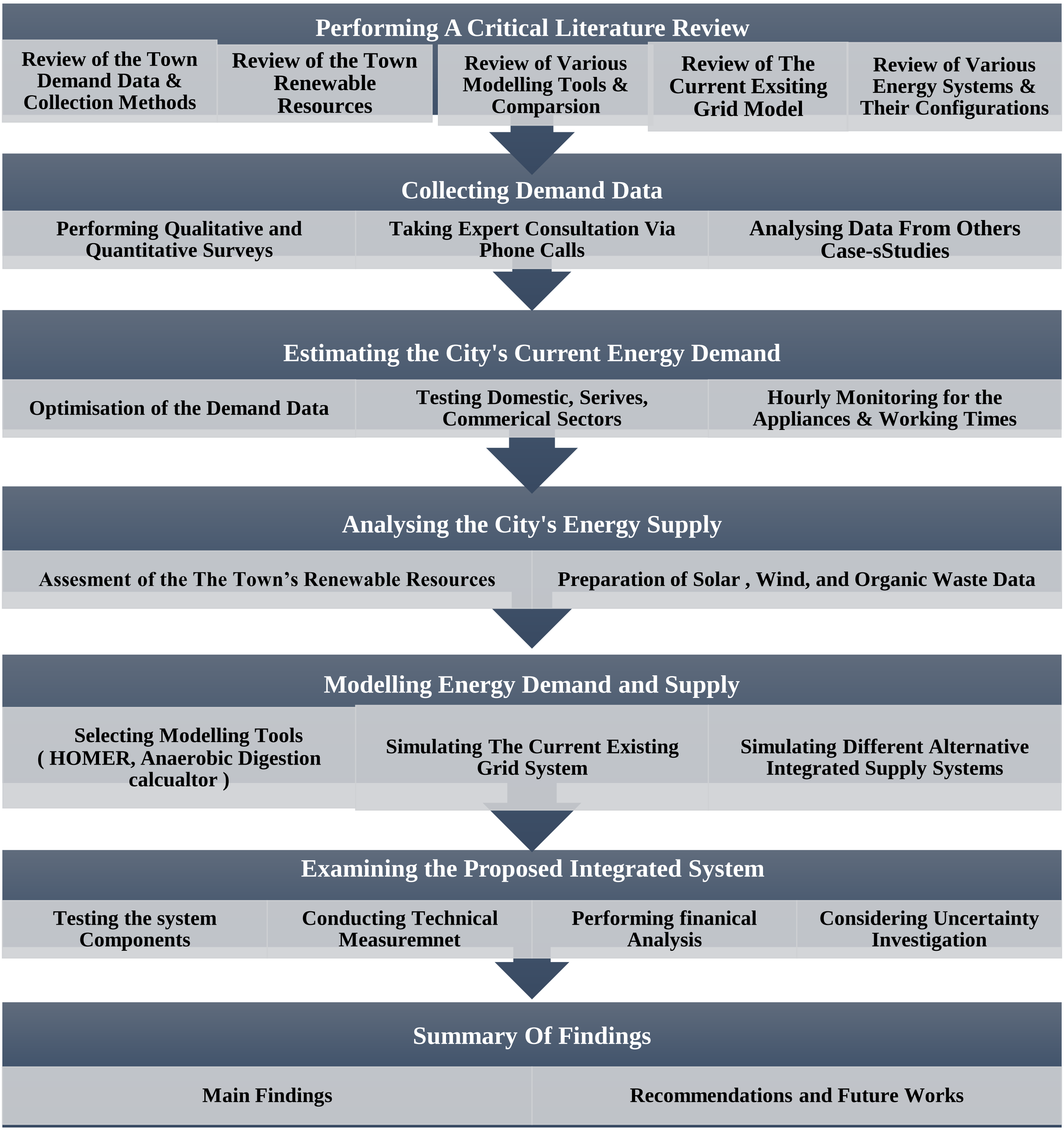


Figure 6: Research Methodology Steps

2 CRITICAL LITERATURE REVIEW

The aim for this literature review is to provide evidence of the knowledge gap that validates the need for this research study. Also, this review is a form of support for the methodology used in the study, as well as a source of information for comparison, triangulation and referencing. Given the above purposes, the literature review is divided into four main categories: Understanding of the Current Demand in the town of East Soba, Assessment of Renewable Energy Potential, Review of Modelling Tools and Review of Various Integrated Renewable Energy Systems with their Configurations.

2.1 Understanding of the Current Demand in the Town of East Soba

In Sudan, the biggest proportion of electrical consumption comes from the residential sector, 4663 GWh, which is nearly half of the country's total consumption. This is followed by the services and industry sectors, which account for approximately 2105 GWh - 25% - and 1395 GWh - 16% - respectively. In addition, the agriculture sector consumes a small amount - 5% - of the total Sudanese demand at around 418 GWh. Moreover, the transportation sector is usually powered by diesel and petrol engines, and therefore there is no electrical demand for this sector in Sudan (Rabah et al, 2016). Figure 7 below illustrates the percentage of the electricity demand in Sudan per sector.

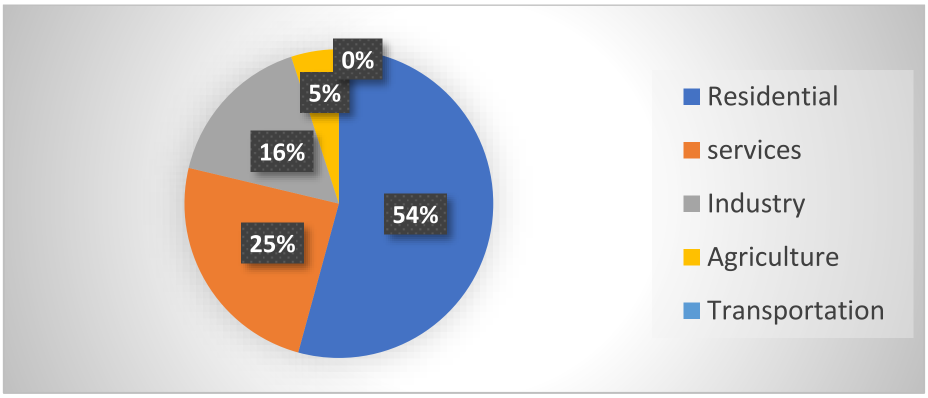


Figure 7: Breakdown of Electricity Consumption in Sudan By Different Sectors (Rabah Et Al, 2016)

To better understand the current electrical demand in the town of East Soba, several case studies for similar towns and villages in developing countries were selected. Three benchmarks were chosen to evaluate the studies being presented: the mechanism of the demand data collection, sectors which were covered in the demand, and the total estimated electricity demand of the town.

Sen and Bhattacharyya (2014) published a study discussing off-grid electricity generation with renewable energy technologies in an Indian village with a population of 1624. The demand data was collected through the Indian state government records with expert opinions and personal judgements for further validation. The demand profile covered four sectors: residential (304 houses), commercial (10 shops, 5 small manufacturing units), services (1 community centre, 1 medical centre, 1 school, 1 post office) and agricultural (12 water pumps). They measured the village's total demand by examining the performance of appliances, their power consumption and the demand peak throughout the day in summer and winter cases, and eventually reached an estimated total demand of 179 MWh/annual. Although the study is a great example of understanding energy demand, it only represented a very small village with limited requirements, so its methods may not be applicable to larger towns with a bigger demand.

Another study presented by ONIYERE (2016) investigated a hybrid renewable energy system for a rural Nigerian village, with no grid connection and a population of 2-3000 inhabitants. The demand of the village was estimated based on general information from literature; analyzing residential (1000 houses), commercial (1 factory) and services (1 clinic, 2 schools, 1 central water pump) sectors. The study found that the residential and commercial sectors are the highest consumers, with 3.2 MW as the peak. Even though the study accomplished an analysis of the village's total demand, inaccurate and limited demand data was used. Also, no consideration of appliances or their power usage and operation times was included in the demand analysis.

A particularly relevant study conducted by Hamouda (2018) investigated the possibility of supplying a small Sudanese town in Khartoum state with renewable energy. The study estimated the demand by using quantitative and qualitative surveys along with expert opinions. These surveys covered the town's highest energy-consuming sectors: residential (610 houses), commercial (3 restaurants, 3 bakeries, 3 supermarkets) and public services (3 schools, 1 mosque). The demand data was optimised by considering various appliances, their power rate, and operating times. The study established an hourly demand profile based on random values between the low and the high average of the demand in the summer and winter, resulting eventually in an estimated total demand of 4 GWh/year. Despite the fact that the study demonstrated a comprehensive and relative demand analysis example for a small town, neither the appliances in the commercial, or public services, premises were monitored over 24-hour periods to establish more accurate average statistics.

Similar case studies are presented in other literature as well. For example, Castellanos et al. (2015) performed a study for a village in West Bengal of around 1000 inhabitants, Bashir and Modu (2018) investigated a village in North-eastern Nigeria with 850 inhabitants, while Enonche (2016) provided a case study for a small urban community in Nigeria with a population of almost 900. The demand data from these three studies was estimated based on other comparable literature. The demand profile in the Castellanos et al. (2015) study, covered the residential and services (1 school, 1 medical centre, 1 water pump) sectors, as did the Bashir and Modu (2018) research, covering the same two categories, residential (148 houses) and services (1 school, 1 mosque) sectors. However, Enonche (2016) focused only on the residential sector of 48 estate houses.

The demand for the Nigerian villages were estimated after examining each appliance, their power rate, and operating times, and the concluded total demand figures were 231 MWh/year and 648 MWh/year respectively (Bashir and Modu,2018) (Enonche,2016). Nevertheless, the overall electrical load for the village in West Bengal was estimated to be 22 MWh/year, without any mention of appliance investigation in this study (Castellanos et al. 2015). Although the three studies managed to explore the total demand through the appliances' performances, they showed gaps of knowledge in the collection methods of the demand data, while also lacking consideration for separate summer and winter analysis. Table 1 summarises the above selected studies in terms of their demand data, sectors analysed, and the estimation of the total final demand.

Case Study	Country Of The Study	Data Collection Mechanism	Type of Sectors Analysed	Total Demand Estimation (MWh/Y)	Demand Evaluation
Sen and Bhattacharyya (2014)	India	Government Records Expert Opinions	Residential: 304 houses. Commercial: 10 shops, and 5 Small manufacturing units. Services: 1 community Centre, 1 medical Centre, 1 school, and 1 post office. Agriculture: 12 water pumps.	179	Simulated the performance of the appliances, their power rating and the demand peak throughout the day in summer and winter cases. However, Limited demand requirements.
ONIYERE (2016)	Nigeria	Estimation from Literature	Residential: 1000 houses. Commercial: 1 factory. Services: 1 clinic, 2 schools, and 1 central water pump.	3.2	Inaccurate and limited demand data. No consideration for appliances, their power usage, and operation times.
Hamouda (2018)	Sudan	Quantitative & Qualitative Surveys Expert Opinion	Residential: 610 houses Commercial:3 restaurants, 3 bakeries, and 3 supermarkets. Services: 3 schools, and 1 mosque.	4	Wider demand analysis, simulating the performance of the appliances with their power rating. Incomplete Appliances analysis on 24 hours for the commercial, and public services premises.
Castellanos et al. (2015)	India	Estimation from Literature	Residential: 150 houses Services: 1 school, 1 medical Centre, and 1 water pump.	22	No consideration for appliances. Inaccurate mechanism of demand data collection.
Bashir and Modu (2018)	Nigeria	Estimation from Literature	Residential:148 houses. Services: 1 school, and 1 mosque.	231	Incomplete demand measurement in summer and winter times. Limited data for the village premises.
Enonche (2016)	Nigeria	Estimation from Literature	Residential: 48 estate houses.	648	Simulated the performance of the appliances, power rates, and hours of usage. Inaccurate mechanism of collecting the demand data.

Table 1: List of Previous Studies That Show How to Estimate and Analyse Current Energy Demands

To sum up, it is revealed that demand analysis often has considered only a very small-scale and limited set of data without enough details on how the data was collected and optimised. Moreover, most studies don't have a comprehensive analysis of the appliances' performance based on a typical 24-hour period in summer and winter, in particular for commercial and public services sectors, which would have given a more reliable demand investigation. The load profiles didn't consider shifting energy demand due to altered circumstances such as businesses' working hours, schools-holiday months, and mosques' prayer times. Therefore, all these issues are considered in the present study, thereby bridging this knowledge gap

2.2 Assessment of Renewable Energy Resources Potential

Various renewable energy resources in Sudan including Solar, Wind, and Biomass have been appraised to see their potential for supplying the town of East Soba.

2.2.1 Solar Energy

Solar radiation, which arrives on the earth, is the most crucial renewable energy resource stemming from nature. In fact, it powers the ocean, the Earth's bio-system, the atmospheric current system and has big effects on the global climate (Duffie and Beckman, 2006). Therefore, a reliable radiation data is highly required in order to model a solar energy system. The total radiation from the sun based on a horizontal surface on earth is called Global Horizontal Irradiance, which is a very fundamental factor to aid the understanding of solar energy.

The Global Horizontal Irradiance can be defined, according to the National Renewable Energy Laboratory (NREL), as the total of the direct normal irradiance that comes from the sun at its current position in the sky, plus the diffuse horizontal Irradiance which has been scattered by molecular fragments in the atmosphere, as well as the ground-reflected radiation, which can usually be ignored because is often insufficient (NREL, 2019) . The total global radiation can be summarised in the equation below:

$$\boxed{\mathbf{GHI = DHI + DNI * \cos (Z)}}$$

Where:

GHI = The Global Horizontal Irradiance kWh/m2

DHI = direct normal irradiance kWh/m2

DNI = diffuse horizontal Irradiance kWh/m2

Z = solar zenith angle of the sun

Sudan has been considered as one of the countries best placed to utilise solar energy. The average sunshine hours range between 8.5 to 11 per day. The average solar radiation in Sudan ranges from 5.5 to 6.9 kWh/m2 day, taking into consideration that the global average solar radiation ranging from 3.05 to 7.62 kWh/m2 day (Omer,A.M., 2015).

The map in Figure 8 explains the Global Horizontal Irradiation in Sudan. It can be seen that Khartoum state, which contains both Sudan’s capital city Khartoum and nearby East Soba, is located in area with an average solar irradiance of between 6.2 to 6.4 kWh/m2 day. The full monthly average Solar Global Horizontal Irradiance (GHI) for East Soba Town is summarised in Figure 9.

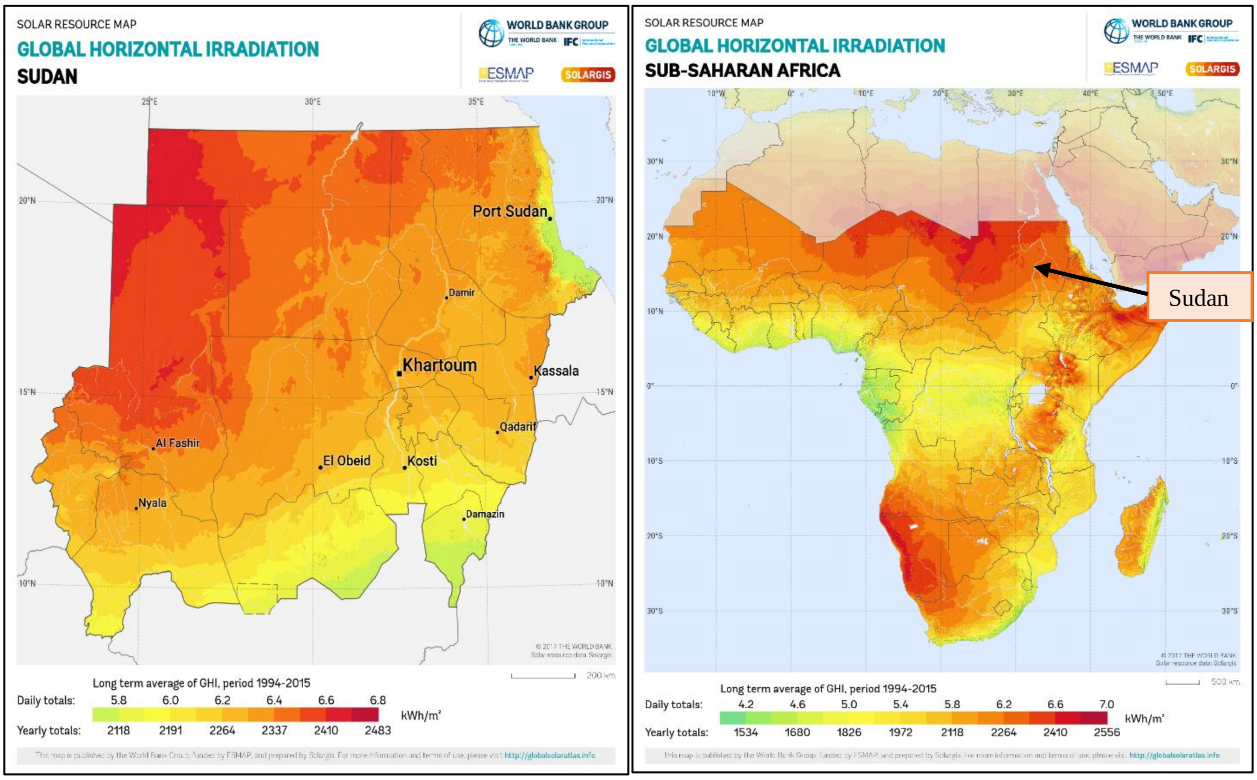


Figure 8:Sudan’s Global Horizontal Radiance Map (Solargis, 2019)

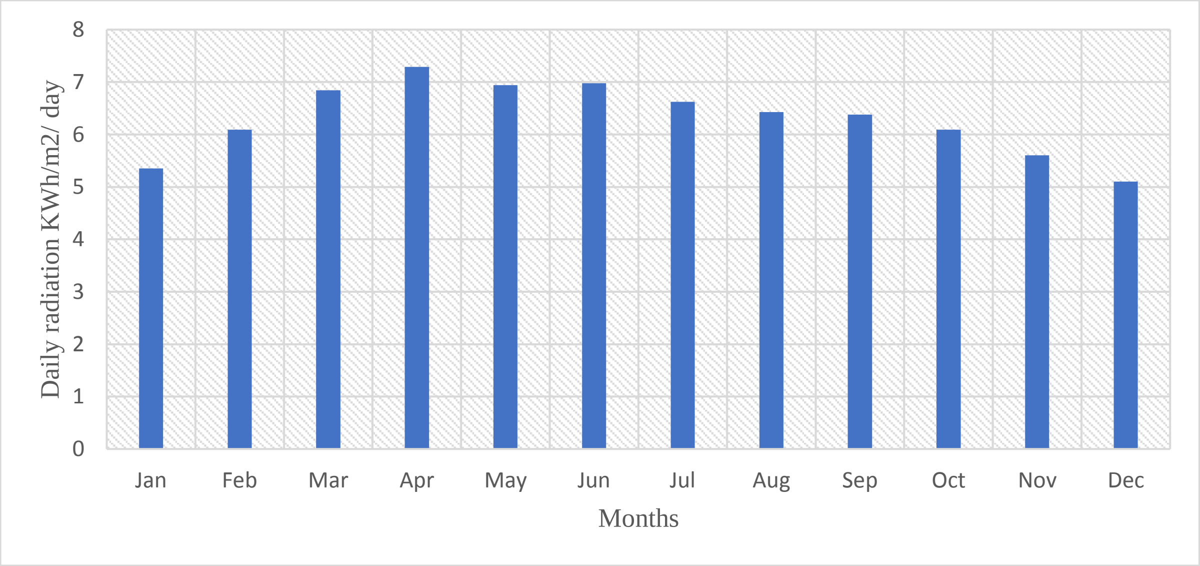


Figure 9: Monthly Average Solar Global Horizontal Irradiance (GHI) For East Soba Town, Sudan (Nasa, 2019)

3.2.2 Wind Energy

Forms of wind power in Sudan have, to date, mainly been used for water pumping and irrigation. The wind power depends on the wind’s velocity, density and swept area, as is described in the equation below (REUK, 2019).

$$P = 1/2 * \rho * A * V3$$

Where:

P ≡ Power output of the wind turbine (W)

ρ ≡ Air density (kg / m2)

A ≡ Swept area (m2)

V ≡ Wind velocity (m/s)

In the light of the above-mentioned equation, a report from Windpower Engineering & Development Institution USA (2010), observed the importance of higher wind speed to generate a greater power output from wind turbines. The wind speed is mostly affected by the height of the turbine; thus, a taller tower will increase the productivity of any wind turbine by giving it access to higher wind speed. The report also explained that the rotor swept area is a substantial part of the wind turbine, thus the larger the rotor, the more energy it can capture. Moreover, the air density fluctuates slightly with air temperature and elevation. The ratings for wind turbines rely on a standard temperature of 59° F (15° C) at sea level. Figure 10 displays how the density of the air decreases with height.

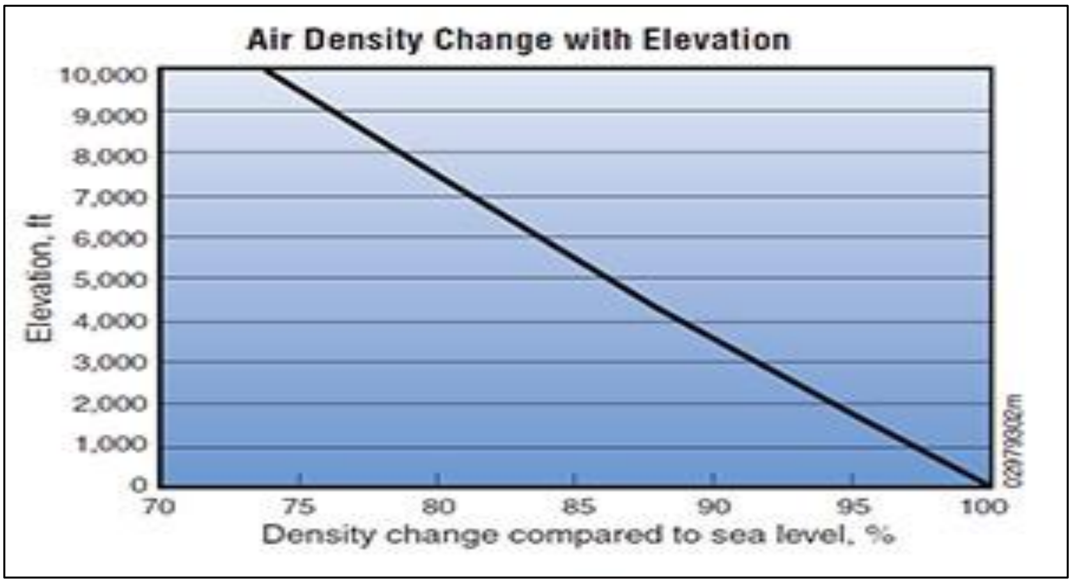


Figure 10: The Relationship Between Air Density and Elevation (WPED, 2010)

According to a study conducted by Omer A.M (2000) aimed to assess the potential of renewable energy resources, Sudan has considerable wind resources; annual average wind speeds exceed 5 m/s across 50 % of the country, particularly in the northern region and the coastal area along the red sea. The study also revealed that the average wind speeds in 75% of the country are between 3-5 m/s, which is currently mainly exploited for water pumping and irrigation.

According to data on Khartoum state on the Global Wind Atlas website (2019), sponsored by the World Bank Group, the wind speeds in East Soba are approximately 5.3m/s. These wind speeds were calculated based on a height of 50m, using a section of the top 10% windiest area. Presented in Figure 11 below.

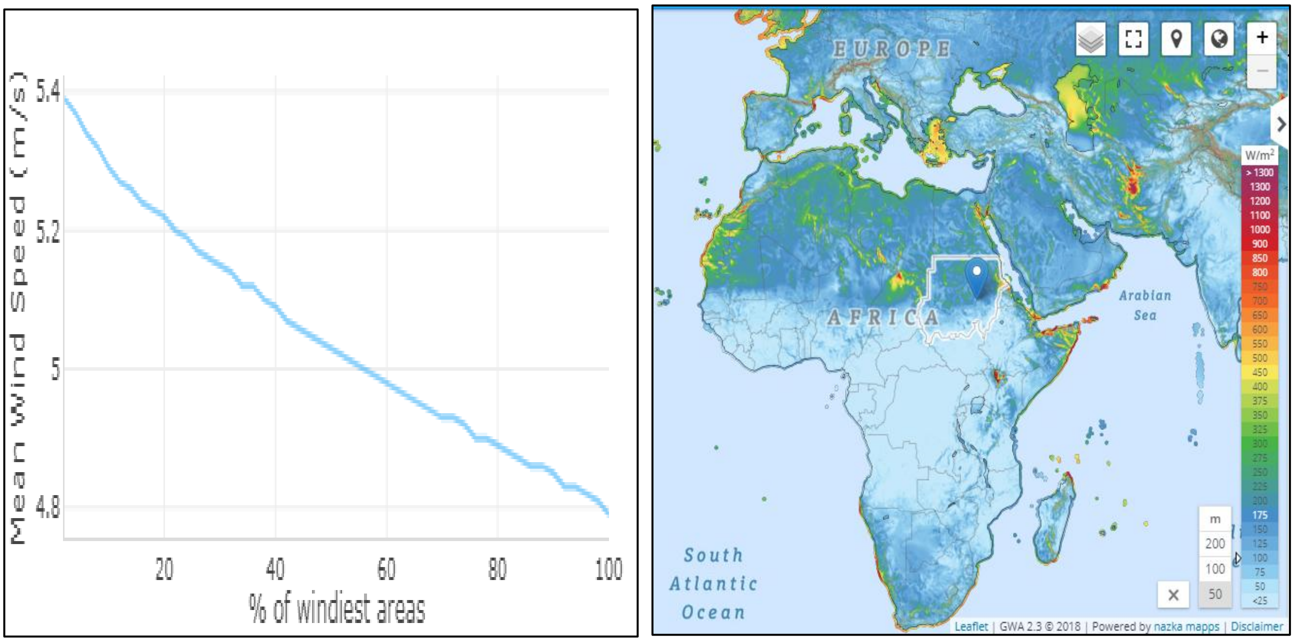


Figure 11: Wind Speeds in East Soba, Khartoum, Sudan (Globalwindatlas, 2019)

2.2.2 Biomass Energy

Biomass is widely exploited in Sudan due to the country's agriculture-based economy. The main usage of Sudan's biomass comes directly from burning fuel-wood and crop residues (Omer,A.M., 2015). The biomass used for generating energy can be divided into five types: firewood, charcoal, agriculture residue, bagasse, bioethanol, and animal waste (Rabah et al, 2016). Sudan has a high potential to utilise waste that is produced by household, vegetable market, cotton stalk and paper industries, to generate a useful energy through a system of either incineration, gasification, digestion (biogas production), fermentation, or cogeneration (Omer,A.M., 2015). Currently the biomass residues have been used in various applications as presented below in Table 2.

Type of Residue	Current Use / Availability
Wood industry waste	No residues available
Vegetable crop residues	Animal feed
Food processing residue	Energy needs
Sorghum, millet, and wheat residues	Fodder, and building materials
Groundnut shells	Fodder, brick making, and direct fining oil mills
Cotton stalks	Domestic fuel considerable amounts available for short period
Sugar, bagasse, and molasses	Fodder, energy need, and ethanol production (surplus available)
Animal manure	Fertiliser, brick making, and plastering

Table 2: Sudan's Biomass Residues, Current Use and General Availability (Omer, A.M., 2015)

To examine Sudan’s potential biomass resources, in particular organic waste, two comparable case-studies in developing countries were selected for review. These studies evaluated organic waste levels on both country- and city-wide scales.

A study published by Rabah et al (2016) aimed to model the energy demand and supply in Sudan. The study estimated the total animal dung produced in Sudan in 2014, based on average dung production per head of cows, sheep, goats, and camels, at 49M tonnes of dung. The study also found that the total agricultural waste, coming largely from sorghum, millet, wheat, groundnut, sesame, sunflower, and cotton, was around 2M tonnes per year.

Another study was conducted by The World Bank (2010) to appraise the solid waste management system for a city of 150,000 residents in Pakistan. The study found that the total annual organic waste was around 15,184 tonnes. This yearly total was comprised of roughly 8030 tonnes from municipal households, 2847 tonnes from animal manure, and 4307 tonnes from agricultural waste. The study also estimated that a typical farm animal can produce between 15 to 20kg of waste per day. In addition, the average overall solid waste generation rate for the city was calculated at 0.3 kg per person per day.

There are geographical, agricultural and climatic similarities between the city in the above-mentioned case study conducted by The World Bank (2010), and the town of East Soba in Sudan; therefore, it can be assumed there is a comparable considerable amount of organic waste in East Soba. These organic waste resources can be exploited to produce electricity through an anaerobic digestion system. The total organic waste of East Soba was assumed to be around 5258 annual tonnes, estimated based on the assumptions below:

- 200 animals in total (cows, sheep, and poultry) with an average of 17 Kg manure per animal per day
- 20,000 inhabitants, with an average of 0.3 Kg of municipal household waste per person per day
- 20 agricultural lands with an average of 250Kg of waste per land per day. the agriculture waste mainly comes from vegetable crops residues, wheat straw, and maize silage

2.2.3 Hydro Energy

Sudan is a rich county when it comes to water resources. The country has the longest river in the world, the Nile, at 6,650km. The Nile is one of the African continent's most important water sources, and is formed by two major tributaries, the White Nile and the Blue Nile (Melina, 2010). The total installed capacity of hydropower in Sudan is 1585MW, generated by five major operational hydro plants in the country as expressed in Table 3.

Name	Installed capacity (MW)
Merowe Dam	1250
Roseires Dam	280
Sennar Dam	15
Jebel Aulia Dam	30
Khasm El Girba Dam	10

Table 3: Hydroelectric Power Plants in Sudan (Rabah Et Al, 2016)

East Soba is located just one Kilometer away from the East bank of the Blue Nile. However, the possibility of harnessing and installing hydro turbines from this river would face several social, environmental, financial and technical limitations which are summarised as follows:

- **Social & Environmental Constraints**

Dam construction along the Blue Nile river puts several significant environmental and social assets at risk. A report conducted in 2012 by the Nile Basin Initiative (NBI), an intergovernmental partnership of 10 Nile Basin countries, stated that constructing a dam on the Blue Nile river would have a detrimental impact on local communities; people would lose their houses and agricultural lands because these surrounding areas would become the newly formed reservoir. Moreover, the report also revealed that any poor design within the dam could cause negative environmental impacts such as soil erosion, water quality deterioration, and eutrophication, as has happened in some previous hydropower case studies in Africa.

- **Financial Constraints**

Building a hydropower turbine will require a huge capital investment, generally beyond the financial resources of the Sudanese government. Investments would be required from international agencies such as The World Bank. However, these agencies follow standard rules regarding environmental and social impacts, and must embark on a mitigation process, which could take a long time and might delay the implementation of any hydro project (NBI, 2012).

- **Technical Constraints**

The Blue Nile river has a high-water flow rate and contributes to 80-90% of the volume of the Nile river (Satti et al., 2015). The river basin is very complex, with multiple curves surrounding Khartoum city, where the Blue Nile river joins the White Nile river. Furthermore, the area across the Nile riverbank near East Soba is actually a vibrant zone which is often crowded with tourists, small sailing vessels and boats, with two main bridges linking Khartoum city to the East Nile Province.

These natural factors cause numerous potential issues preventing construction of a dam, such as flooding, lack of available land, and lack of straight stretches of the river’s basin. Consequently, it will be difficult to consider the hydropower option in this town.

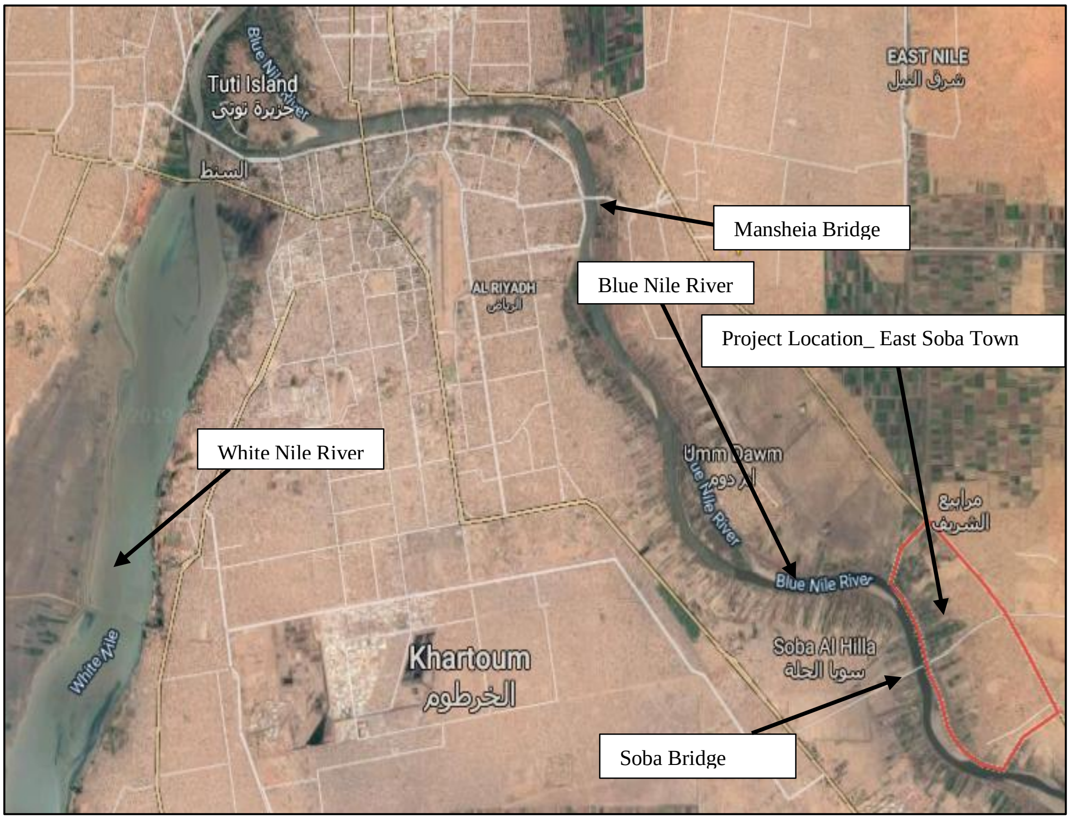


Figure 12: The Map Shows the Blue Nile And the Difficulties Around the Project Area Such As Bridges, Tourists And A Large Residential Zone

2.2.4 *Summary of Renewable Energy Potential in East Soba*

Throughout this literature review, four different renewable energy resources options have been assessed for supply analysis as demonstrated in Table 4. Energy generation from wind and hydro are not selected for further exploration since they present weak potential due to poor wind speed, and construction difficulties for hydropower turbines in the town’s vicinity. Eventually, solar energy and anaerobic digestion are nominated since they offer strong potential due to the excellent solar irradiance and high availability of organic waste in the town.

Type of Resource	Availability	World Benchmark	Evaluation
Solar Energy	Between 6.2 To 6.4 KWh/m2 Day Average Annual Global Horizontal Irradiance	From 3 to 7.62 KWh/m2 Day	Excellent
Wind Energy	5.3m/s Average Wind Speed At 50m Height	Greater Than 6 m/s	Poor
Organic Wastes	5258 Average Annual Tonnes of Wastes	-	Good
Hydro Energy	Available River but There Are Construction Difficulties	-	Poor

Table 4: Summary of Renewable Energy Resources Potential in East Soba, Sudan

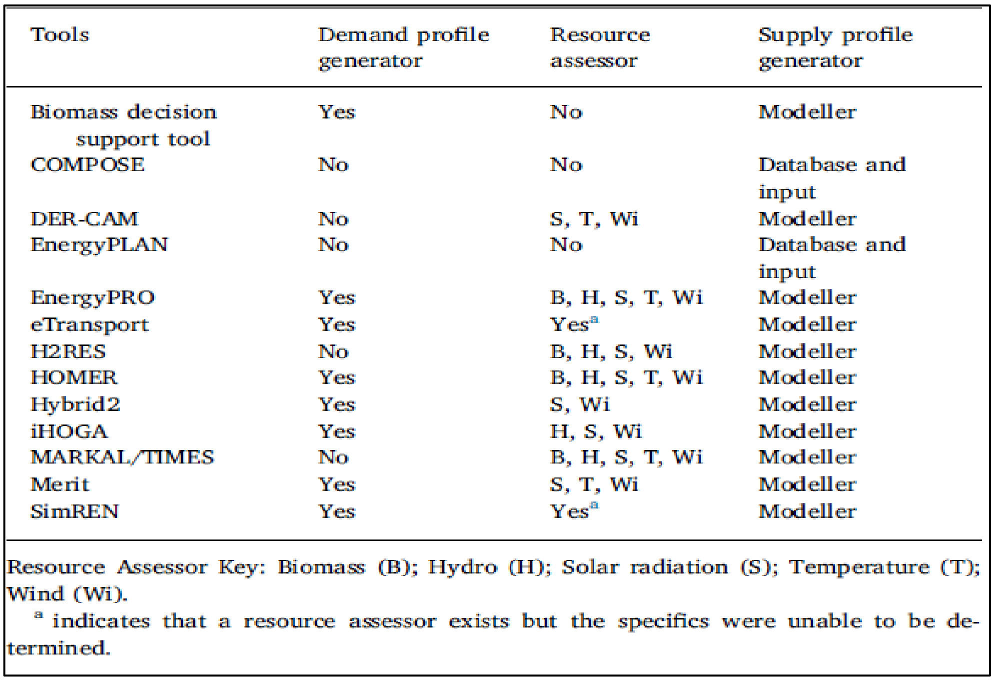
2.3 Review of Energy Modelling Tools

Energy modelling software is a significant requirement in any system design for a community or town. This section of the literature aims to review and evaluate different modelling tools in order to enable the selection of the most appropriate one for this study.

A study conducted at the University of Strathclyde by A. Lyden et al. (2018), provided a framework on how to identify the most appropriate modelling tool to design a community energy system. The study recognised four steps in choosing the optimal energy modelling tool:

- Initial screening process to identify potentially suitable tools
- Classification and clarification of modelling software capabilities
- Development of software selection using tables
- Demonstration of software selection through a case study

According to the same study, a set of criteria were applied to test more than 51 modelling tools to identify their potential software suitability. The study resulted in 15 modellers which can be used to envisage a community scale energy system. Two of these 15 modelling tools were eliminated due to obstacles in accessing to information required for more intensive analysis. Table 5 reveals the modelling tools which passed the study conditions.



Tools	Demand profile generator	Resource assessor	Supply profile generator
Biomass decision support tool	Yes	No	Modeller
COMPOSE	No	No	Database and input
DER-CAM	No	S, T, Wi	Modeller
EnergyPLAN	No	No	Database and input
EnergyPRO	Yes	B, H, S, T, Wi	Modeller
eTransport	Yes	Yes[a]	Modeller
H2RES	No	B, H, S, Wi	Modeller
HOMER	Yes	B, H, S, T, Wi	Modeller
Hybrid2	Yes	S, Wi	Modeller
iHOGA	Yes	H, S, Wi	Modeller
MARKAL/TIMES	No	B, H, S, T, Wi	Modeller
Merit	Yes	S, T, Wi	Modeller
SimREN	Yes	Yes[a]	Modeller

Resource Assessor Key: Biomass (B); Hydro (H); Solar radiation (S); Temperature (T); Wind (Wi).

[a] indicates that a resource assessor exists but the specifics were unable to be determined.

Table 5: Selected Energy Modelling Tools After Passing the Study Criteria (A. Lyden Et Al., 2018)

G. Mendes et al. (2011) reviewed various energy modelling tools for planning Integrated Community Energy Systems. The study analysed 6 modelling tools based on criteria of simulation and optimisation of distributed generation and Microgrid. The study found that The Hybrid Optimization Model for Electric Renewables (HOMER) software which was developed in 1993 by the North American National Renewable Energy Laboratory (NREL) is the optimal modelling tool for a Microgrid energy system. The software has the capability to perform energy analysis in either grid-connected or off-grid situations.

Other case studies, presented by D.Enonche (2016), Montero (2018) and Shaahid and El-Amin (2009), assessed HOMER software as part of their main aims; to investigate off-grid hybrid systems in Nigeria, Spain, and Saudi Arabia. All studies justified choosing HOMER software as the main tool for their system analysis after an illustration that the software is competent in:

- Establishing a detailed demand profile
- Providing supply options for renewable and non-renewable technology
- Carrying out and optimising demand and supply matching
- Sensitivity and financial analysis.

HOMER software has also been selected and recommended as a modelling tool in a similar case-study published by Salih et al. (2014). This research aimed to examine a renewable micro-hybrid system for telecommunication equipment in remote areas of Sudan. The study stated that HOMER software was able to simulate a set of energy system configurations and classify them from the most cost-effective to the least cost-effective, based on comparisons of the net present cost (NPC), cost of electricity production (COE) and carbon emissions

There are other types of modelling tools capable of analysing only one energy system such as anaerobic digestion. These tools have also been examined in this section. In a study conducted by Clegg (2018), a community anaerobic digestion system was analysed. 4 crucial criteria were set to choose the most suitable anaerobic digestion modelling tool as following:

- Ability to model a community or small-town anaerobic digestion system
- Ability to input feedstock data
- Ability to inspect product end uses such electricity, gas, heat and digestate
- Ability to perform financial analysis.

Based on these criteria, many AD modelling tools from both universities and commercial organisations have been reviewed. Some of these modelling tools like World online calculator (Biogas World, 2019) and PlanET biogas global calculator (PlanET, 2019) are too shallow and are unable to perform any sort of detailed technical and cost analysis. Moreover, some modelling tools are considered limited in their input feedstock data with no adjustment allowance like Biteco Biogas calculator (Biteco-energy, 2019).

Another AD modelling tool was developed by Geraghty et al. (2004) at the University of Strathclyde, as part of their masters group project to investigate the viability of Anaerobic Digestion in rural and community-based situations. The tool is an Excel based spreadsheet designed to carry out full detailed energy and economic balances for the plant. The tool allowed various input data as follows:

- The demographics of the area neighbouring the plant
- Type and number of feedstocks available in the area
- Commercial wastes in the local area

- Economic parameters such as annual revenue, capital cost, and O&M costs
- Plant design specifications, like digestion temperature, feed density, component efficiencies, and energy conditions
- Digestion characteristics, such as dry solids, biogas yield, and methane percentage.

According to Clegg (2018) this Excel AD modelling tool analyses the input data and gives outcomes for: digester size, biogas engine size, biogas yield output, electrical output, heat output, transport costs, process heat, electrical loads and overall energy balance. Despite that fact that this AD tool gives a detailed technical and economic outcome, its abilities are limited – it can only focus on one demographical site at a time. This is a disadvantage, as you need to delete and input new site details for each case, as described by the AD modelling designer Geraghty (2006).

Another AD Excel-based spreadsheet is a tool called The Anaerobic Digestion Economic Assessment Tool. This was developed through a partnership between bioeconomy consultants NNFCC and The Andersons Centre (2010) to assist AD developers in examining the viability and optimisation of their plants. This tool specialises in Comparing the economics of different AD technology and feedstock options. The input data for this tool can be summarised as below:

- Type and number of Feedstocks available
- Efficiency of the energy conversion and methane percentage
- Economic parameters include: Capital cost, annual running costs, and general overheating costs
- Digestate specifications.

The tool analyses the input data, along with other parameters, in order to give a detailed result including total biogas production output, total electricity and heat output, biogas yield output, digestate values, electricity production price and a summary of the annual finance performance, comprised of AD profit and loss, total income and return on capital (ROC). Although the tool gives a comprehensive AD analysis, its drawback is that it is designed only to suit the AD market in the United Kingdom.

Therefore, following a review and evaluation of different modelling tools from the above-mentioned case studies, it is concluded that the most appropriate software for the research study will be: HOMER, the AD calculator developed by Geraghty et al. (2004), and The Anaerobic Digestion Economic Assessment Tool. see Table 6.

Energy Modelling Software	Reason for Selection
The Hybrid Optimization Model for Electric Renewables (HOMER)	Analyse Grid-connected energy systems Provide various renewable supply options Demand supply matching Economic & sensitivity analysis
AD Calculator Developed by Geraghty Et Al. (2004).	Input various data Design AD plant Technical & economic measurement
The Anaerobic Digestion Economic Assessment Tool	Input various data Biogas & electricity output summary Financial measurement

Table 6: Summary of the Final Selected Modelling Software

2.4 Review of Integrated Renewable Energy Systems

An Integrated or Hybrid energy system is a combination of two or more forms of energy generation, providing increased system efficiency as well as better balance in energy supply (Ginn, 2016). The combination can be formed of renewable or non-renewable energy sources. However, this study will base its review on an integration of two or more renewable energy systems such as PV, wind, or anaerobic digestion, to provide a reliable power supply to East Soba.

2.4.1 Review of the System Components

2.4.1.1 Solar Photovoltaic (PV)

The PV system converts the solar radiation to energy. The conversion occurs when the sunlight falls on solar cells, based on the principal of semiconductor technology. The current produced by these solar panels is direct current (DC) which is then converted to alternating current (AC), used to deliver power to houses and office buildings or even stored in batteries (D. Enonche, 2016). The cells are usually made from crystalline silicon material which has three forms: mono-crystalline silicon, poly-crystalline silicon, and gallium arsenide cells (P.Aghaei, 2014).

Depending on the size and structure of the system, the PV panels can be utilised in various applications on a small or large scale. The system can also operate upon grid-connected or stand-alone systems (P.Aghaei, 2014). On a grid-connected method, the PV system consists of three main elements:

- Solar panels
- Inverter
- Conventional power line.

The PV system produces the electrical energy, which is then transferred to the national power grid. An inverter connected to the network adjusts the voltage and frequency of the electrical energy produced by the PV, and makes them suitable to meet the voltage, frequency and characteristics of the grid. In basic terms this is a conversion process from DC to AC power (Lopez,J.Agustin, 2006). Figure 13 displays the operation of the PV system based on a grid-connected method.

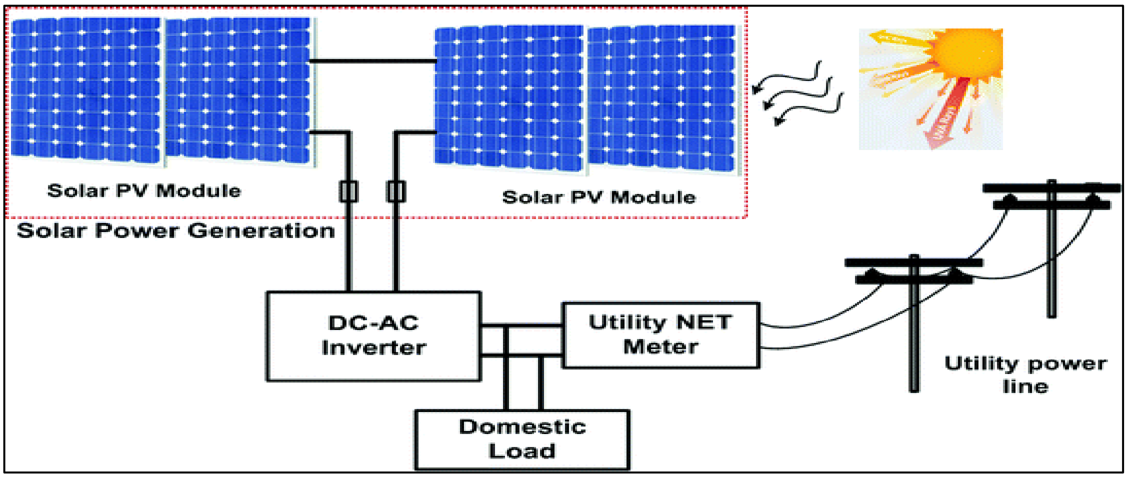


Figure 13: Grid-Connected PV System (Karthikeyan Et Al.,2017)

Additionally, in cases when there is a minimal electricity grid network in the town, the PV system can then operate on a Stand-alone method. The main components of the stand-alone PV system are:

- Solar panels
- Charge controller
- Battery bank
- Inverter

In the stand-alone PV system, the electrical energy produced by the PV panels is used to charge a bank of batteries during the day which can be used later at night when the solar irradiance is unavailable (Chaar, 2011). These batteries are chargeable which adds more flexibility to the system. Currently, the major categories of PV batteries include lead-acid, nickel-cadmium, nickel hydride, and lithium (Solar Direct, 2016). These batteries act as an alternative option when there is no grid network at all, or if there is a grid network but there are regular grid power outages (Enter, 2019). Furthermore, these batteries are controlled by a charge controller, which is responsible for regulating the power flow from the panels and preventing batteries from being either over-charged or over-discharged. The inverter then converts the DC power from the panels and batteries to AC power for use in houses or office buildings (Chaar, 2011). Figure 14 demonstrates how the stand-alone PV system operates.

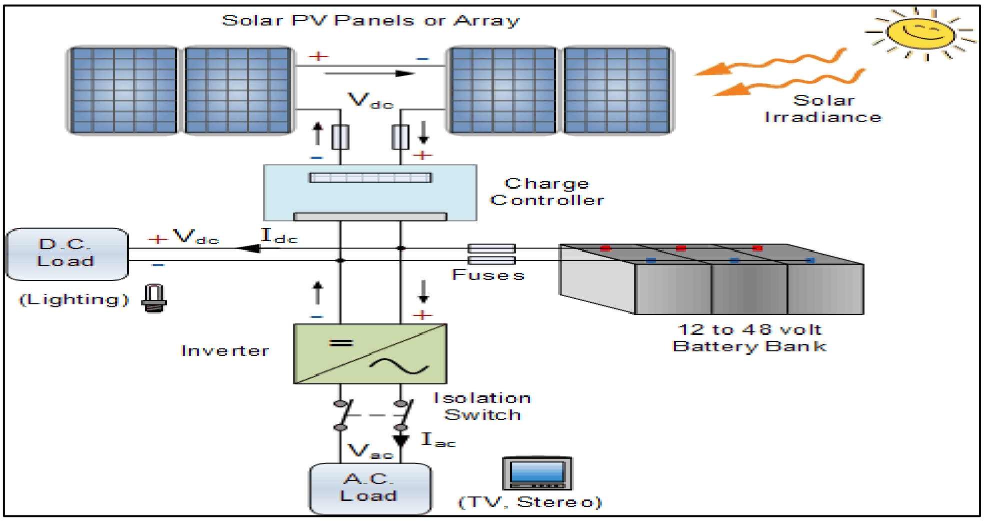


Figure 14: Stand-Alone PV System (Alternative Energy Tutorials, 2019)

There is no doubt that the PV system has significant utilisation potential as part of an integrated renewable energy system, to reliably supply power to East Soba. However, there are some factors affecting the efficiency and performance of the PV system which should also be taken into consideration. These factors include:

High Temperature: According to an article presented by Fox (2017), a high temperature above 25 degrees would decline the efficiency of electrical energy conversion by the solar cells to almost 10-25%.

Dirt and Dust: These have a negative impact on PV panels by blocking sunlight, outlined in a study conducted by Meral and Dinçer (2011). It was estimated that accumulation of some dirt or dust on a 100 KW PV module, as example, will reduce the efficiency of the PV to about 79 KW.

DC to AC Conversion: During the power conversion process by the inverter from DC to AC, there are some conversion and wiring losses; projected to be around 10-12% according to a study published by Chaar (2011).

2.4.1.2 The Anaerobic Digestion (AD)

- **Overview of The Anaerobic Digestion**

AD is the biological process of breaking down organic waste by micro-organisms in the absence of oxygen, producing biogas (Biogas, 2019). The process of converting the waste to biogas takes a place in sealed tank called a “Digester”, and continues for a period of 14 to 60 days depending on the complexity of feedstock, the digester temperature and micro-organism population (Ferris, 2015)

This produced biogas contains 50-65% Methane (CH4), 30-45% Carbon dioxide (CO2), and a small amount of Hydrogen Sulphide (H2S) (Yasar et al., 2015). The biogas is then converted to heat and electricity through a Combined Heat and Power (CHP) unit. The indigestible remaining materials which called “digestate” are often stored to be used as bio-fertiliser for agricultural land (Biarnes, 2019). Figure 15 presents an overview of the AD system process.

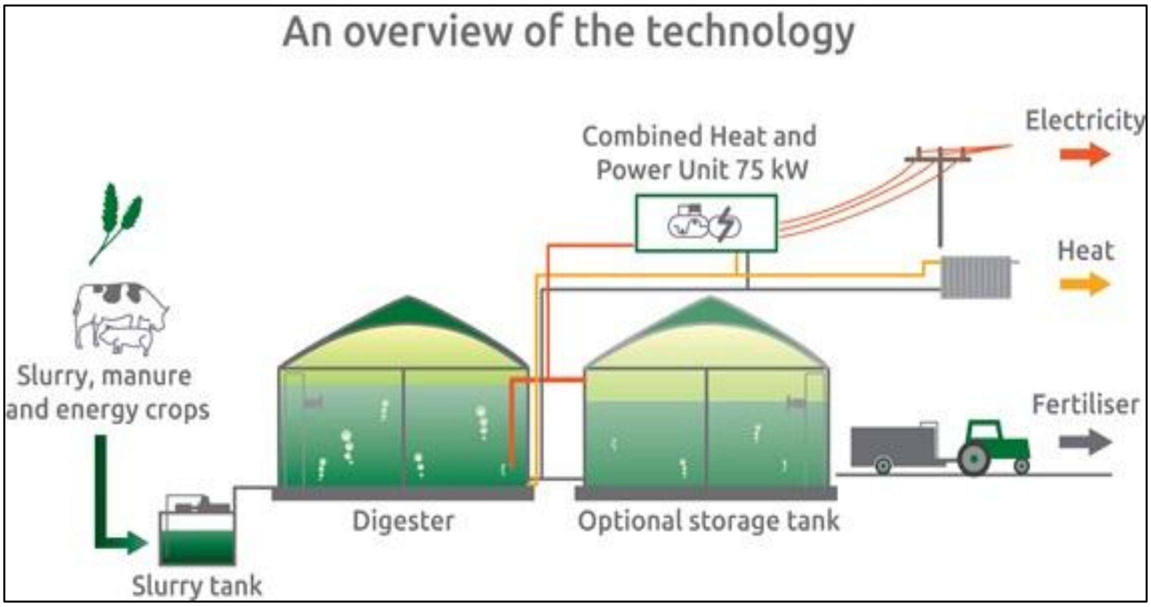


Figure 15: Anaerobic Digestion System Overview

- **The Microbial Process of The AD System**

The process of breaking down organic waste through micro-organism, to produce methane as by-product, consists of four main steps: Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis.

1. Hydrolysis is a chemical reaction which breaks down the complex organic polymers into smaller molecules such as simple sugars, fatty acids and amino acids (Biogasman, 2019).
2. Acidogenesis involves a further breakdown of the remaining components by fermentative bacteria, resulting in a creation of an acidic environment in the digestion tank along with other by-products such as ammonia, carbon dioxide, and hydrogen sulphide (Biogasman, 2019).
3. Acetogenesis is the process of producing acetic acid, carbon dioxide and hydrogen through a further digestion by acetogenic bacteria. These micro-organisms catabolise many of the products created in the acidogenesis stage (Biarnes, 2019).
4. Methanogenesis is the final process, in which methane is generated by methanogens after exploiting products from previous stages. The final product is not only methane but also includes carbon dioxide (Spuhler, 2010).

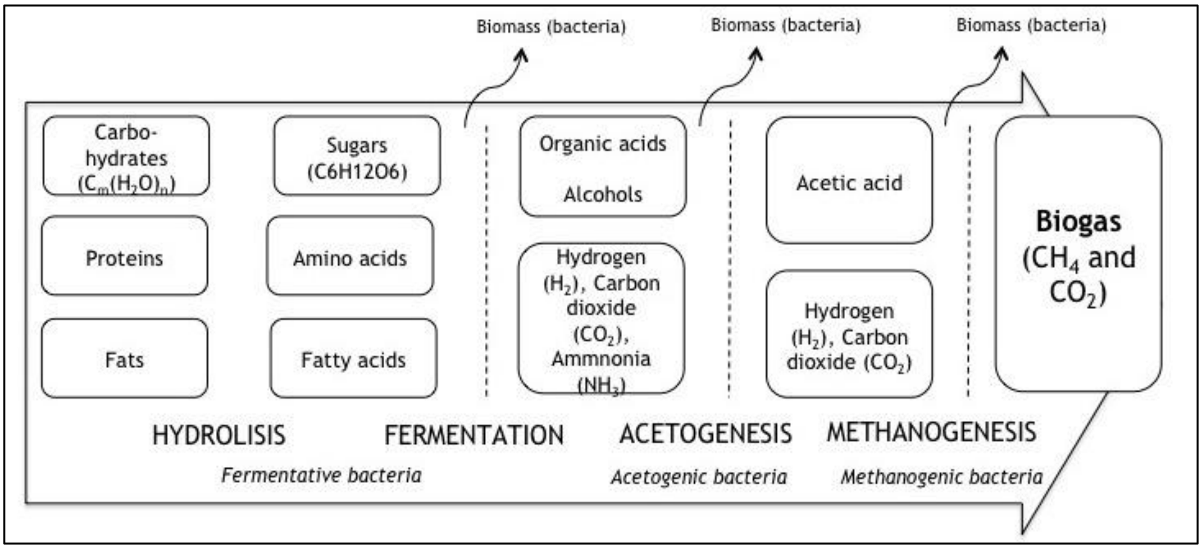


Figure 16: Four-Step Process of Breaking Down Complex Organic Molecules and Generating Biogas (Spuhler, 2010)

- **Types of AD System**

AD can be divided into two fundamental systems based on the temperature inside the digester tank. These are mesophilic and thermophilic digestion systems. In the mesophilic digestion, feedstock is digested at a temperature of 25-35 degrees, and the process takes between 15 and 30 days. Although the mesophilic digestion is the most commonly used process, it tends to produce less biogas and requires additional sanitation (Geraghty,2006).

In the thermophilic digestion, the average digester’s temperature is 49-60 degrees, and the feedstock remains in the digester for a period of 12 to 14 days. The noteworthy benefit of this type is a higher and a faster production of biogas, however, it is an expensive system to run and requires a lot of energy and control (Geraghty,2006).

- **AD System Design**

AD systems can range from a small digester tank with a tube allowing the flow of biogas, to big AD power plants with full facilities. In this project, the focus will be on small scale AD with municipal household, animal, and agriculture waste collected together as feedstock. A study conducted by Clegg (2018) evaluated the potential of installing a small-scale AD system for a rural Scottish community. The study divided the main components of the AD system into:

- Pre-treatment unit (sorting, screening, and pasteurising of the feedstock)
- Digestion tank
- Mixer/agitator
- Pumps
- Feeding systems for solid biomass
- CHP unit or bio-methane converter
- Digestate storage.

Full details of an AD system's components, processing feedstocks which come from various organic sources, can be shown below in Figure 17.

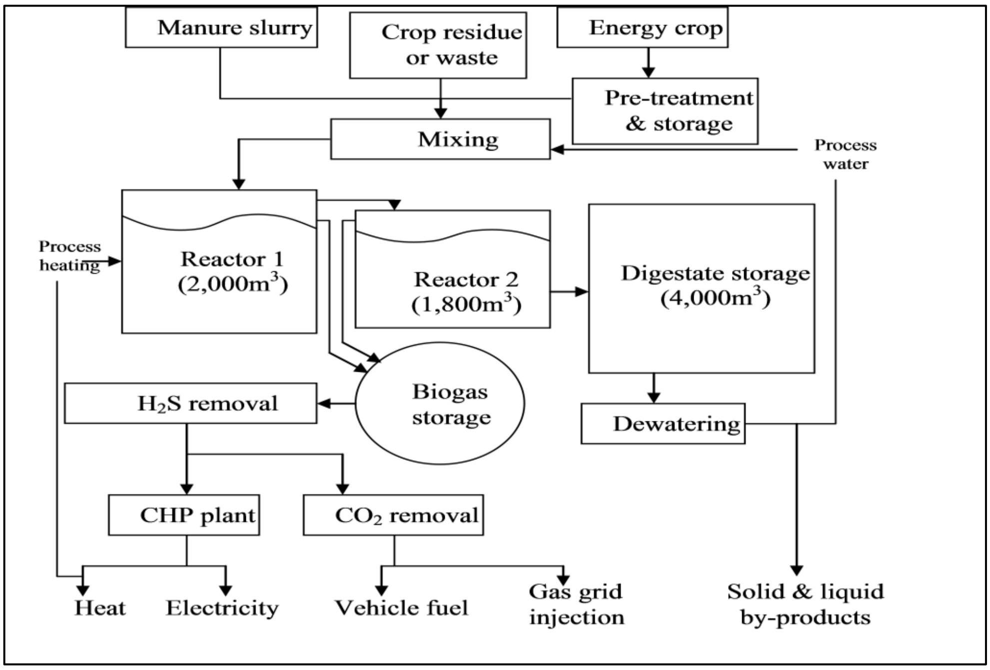


Figure 17: Typical AD System With its Components (G.Wilkinson, 2011)

With regards to the energy conversion of biogas, the biogas is converted to electricity through the use of an engine and generator. It is been suggested from comparative studies that one cubic meter of biogas can typically generate 6.7KWh of electricity (Uddin et al., 2016) - but only if the biogas contains 100% methane which is an unrealistic consideration. However, with a more realistic average of a content of 60% methane, one cubic meter of biogas can be estimated to generate 2KWh of electrical energy (BiogasInfo, 2019). In other words, 30-40% of the biogas is converted to electricity, 40-45% to heat, and the remaining 10-15% is lost.

- **Potential Benefits & Drawbacks of AD System in East Soba**

The AD system has potential benefits and drawbacks which affect its surrounding environment, energy security, commercial activity, and community sectors in the town. Here are some reviews from several case-studies.

Wilkinson (2011) analysed the environmental impact of adopting an AD system in Germany. He discovered that a small AD system can improve a town's waste and recycling infrastructure by diverting most of its municipal household waste from becoming landfill. He pointed out that many industrialised cities produce a high volume of household waste, suggesting the need for an AD system as a promising waste disposal technology.

Moreover, AD's ability to handle a significant amount of organic waste can be environmentally and economically beneficial to organic farms in the community, as stated by Fagerström et al. (2018). The study offered the idea that the organic digestate from AD can be retained as an alternative, sustainable and cheap fertiliser for those farms.

The demand for alternative energy to reduce the reliance on fossil fuel has made the output products from AD such as heat and electricity the perfect example of 100% renewable products (Bond and Templeton, 2011). Furthermore, AD has commercial benefits which are embellished in a study presented by Geraghty et al. (2004). AD has the capability to generate income through the sale of its output products - electricity, heat, gas, and digestate, charging gate fees, and avoiding landfill payment.

However, there are also some disadvantages associated with the AD system; for instance, it requires a high capital cost for investment. Also, there is a risk of an odour nuisance during the treatment of the waste. In addition, there are some safety concerns, such as the possibility of methane explosion and the risk of spillages on-site or during the transportation of waste (Geraghty, 2006).

To conclude, the AD system has big potential for implementation within an integrated renewable system for the town of East Soba, particularly considering the lack of existing case-studies for AD systems (both small and large scale) in Sudan. This can be highlighted as a gap of knowledge.

2.4.2 Review of the System Operational Style

The system is classified by its operational mode, either grid-connected (GC) or stand-alone (SA).

2.4.2.1 Grid-Connected System Concept

A study presented by Kaundinya el at. (2009) aimed to review a decentralized power system in both the presence and absence of the grid. The study defined the grid-connected energy system as an independent decentralised energy system, which is connected to the transmission and distribution systems (referred to as the main grid) prioritising the supply of electricity from the decentralised system (PV, wind turbine or anaerobic digestion) directly to the demand in the town. With this system, when there is an electricity surplus, it will be fed into the grid. The study emphasised that it is crucial to distinguish grid-connected energy systems from utility scale systems, where decentralized stations are managed by the utilities in the same way as large electric power plants. The output of these power generators will be fed into the central grid without paying any attention to the town’s specific need. In another similar case study performed in Spain by Lopez and Agustin (2006), grid-connected photovoltaic systems were evaluated in a more comprehensive way. They concluded that it is viable to operate the solar PV system based on a grid-connected concept.

2.4.2.2 Stand-Alone System Concept

The same study presented by Kaundinya el at. (2009) stated that a stand-alone system is an independent decentralised mechanism to supply electricity without any grid connection. It is particularly suited to remote villages where there is no grid connection at all. This system operates on renewable energy like solar and wind, and it is important to have battery storage for this type of system due to the seasonal variability of these resources.

2.4.2.3 The Optimal System Approach for East Soba

It can be summarised that, in the grid-connected system, the utility grid functions as a backup battery with an unlimited storage capacity. This means that any amount of power surplus from the renewable system will be stored, not wasted or lost, which confirms an overall system efficiency. In the stand-alone system the battery is needed to retain any surplus power, as there is no wider grid available in this scenario.

By reflecting upon those two operational concepts in regard to this research study, and taking into account the fact that East Soba is well connected to the national grid, it can be concluded that the proposed renewable energy system of PV-AD for the town would ideally operate as a grid-connected system, however in some special circumstances in the future, storage battery can be added as alternative to the unreliable grid, which then the hybrid system can operate entirely off-grid.

2.4.3 Review the System Modelling and Performance

Several comparable case-studies reported on the analysis and evaluation of integrated renewable energy systems in various developing countries; some are investigated in this section of the literature review. The review of these systems is based on the components, main features, technical and economic performances of each system.

A study conducted by Türkay and Telli (2011) evaluated different hybrid system configurations based on a grid-connected method for a region in Turkey. The study found that a hybrid of PV-hydrogen, with a capacity of 40KW and 20KW fuel cell, was the optimal system. The system achieved technical-economic viability: covering 75% of the region's demand with the cost of electricity at around 0.307$/kWh. However, the scale of the project and its capital cost were huge compared with the means of a city or small town. Further, González et al. (2015) modelled a PV-Wind Turbine hybrid system, based on a grid-connected method, for a small rural town in Spain. Although the system managed to satisfy the town's total demand of 4 GWh/year with 105KW capacity output, it required an initial investment of $10million, which would be considered as an obstacle if implemented similarly in East Soba.

Another hybrid configuration, of a PV-Wind Turbine system, integrated with a diesel generator and storage battery, was investigated by Bekele and Palm (2010) for a hypothetical community in Ethiopia. The study was based on a stand-alone system considering 5KW PV, and 20KW wind turbine capacities. Despite the fact that the system was stated to be technically feasible, with a renewable penetration of 51%, it was not the most cost-effective option.

Another study presented by Sen and Bhattacharyya (2014) examined various off-grid hybrid system configurations for a remote village in India. The study concluded that a hybrid of PV-hydropower-diesel generator-battery was able to meet the village's demand, with a reasonable capital cost of $238,000, and COE of $0.42/KWh. However, it was observed that 71% of the hybrid power output comes from the hydropower element, but there was a lack of adequate water flow in winter months, which put concerns on the system's capacity to provide power throughout the year.

There are several other comparable studies focused particularly on PV and anaerobic digestion as parts of different integrated systems. For instance, in a study published by Neto et al. (2010), the feasibility of a combined system of PV and a biogas generator fed by goat's manure was examined, to meet the thermal and electrical demand for a small rural community in Brazil. The study considered the system as viable after analysing the availability of high solar and organic waste resources in the community, however, the study didn't provide many techno-economic details.

Furthermore, Rahman et al. (2014) developed a model of a PV-AD off-grid hybrid system for small-scale households in Bangladesh. The study analysed 0.2KW of PV, a 0.6KW digester gas engine, and 3 batteries - each 360 amperes and 6 voltage. The system met the thermal demand and half of the electrical load. However, it wasn't completely reliable, and required every household to have at least 3 cattle to ensure supply consistency. Another PV-AD off-grid hybrid system demonstrated by Pradhan et al. (2013), was developed for a remote household with a total daily demand of 20KWh in Pakistan. It was concluded that the PV can meet 62%, and AD can meet 38%, of the total demand. The results showed the system is financially viable based on a 12-year payback period. However, the system was proposed for only one house, not a community.

Shahzad et al. (2017) optimized a hybrid off-grid system of 10KW PV, 8KW AD, and 32 storage batteries to meet the electrical load of an agricultural farm and group of households in Pakistan. Although results expressed that the system was cost-effective, with a total capital cost of PKR 2.64M, electricity production cost of 5.51 PKR/kWh, and net present cost of PKR 4.48M, the scale of the system was very small, covering just 6 houses. In addition, Ahmad et al. (2018) conducted a study of a grid-connected hybrid system of PV-Wind-AD for a district area of the Punjab region, Pakistan. The system was constructed from 20MW of PV, 15MW wind turbines, and a 15MW biogas generator. The system resulted in meeting the total load of the district area 189 GWh annual, with an average of 58% renewable penetration, 19,976.607 kg annual of CO2 saving and 0574 $/kWh electricity production cost. Even though the proposed system was considered to be technically feasible, the capital cost was calculated to be $190 million. This is unrealistically high without a significant governmental subsidy or foreign investment. Table 7 summarises the selected hybrid system case-studies.

Case Study	Country	Hybrid Configuration	Operational Method	System Features	System Assessment
Türkay and Telli (2011)	Turkey	PV-Hydrogen	Grid-Connected System	40kW PV 20kw Fuel Cell	75% Meeting of The Region Demand 0.307$/KWh Electricity Production Cost Large Regional Scale-Not Suitable for Community or Small Town
González Et Al. (2015)	Spain	PV-Wind Turbine	Grid-Connected System	102.22kW PV 3.6MW Of Wind Turbine	100 % Meeting of Town's Demand 18 Years Payback Period $10M Initial Investment- Not Cost Effective
Bekele and Palm (2010)	Ethiopia	PV-Wind Turbine	Stand-Alone System	5KW PV 20KW Wind	Technically Feasible Renewable Penetration Of 51%

					Not the Most Cost-Effective Option
Sen And Bhattacharyya (2014)	India	PV-Hydro-Diesel Generator-Battery	Stand-Alone System	20KW PV, 30 KW Small Hydro, 10kw Biodiesel And 40KW Battery	Reasonable Capital Cost Of $238,000 $0.420/KWh Electricity Production Cost Unreliable in Winter Months Due to Limited Water Flow for The Hydro Not Cost-Effective If the Hydro Replaced by Wind Turbine
Neto Et Al. (2010)	Brazil	PV-AD	Stand-Alone System	-	High Potential to Meet the Community Demand No Techno-Economic Details
Rahman Et Al. (2014)	Bangladesh	PV-AD	Stand-Alone System	0.2kW PV 0.6kw Digester Gas Engine 3 Batteries-Each 360 Ah, And 6 V	100% Meeting of Cooking Demand, And 50% Of The Electrical Load Every Household Required to Have 3 Cattle To Ensure Power Consistency
Pradhan Et Al. (2013)	Pakistan	PV-AD	Stand-Alone System	Annual 6292kWh from PV Annual 3845kWh from AD	Feasible and Cost-Effective 62% Demand Meeting From PV 38% Demand Meeting From AD 12 Years Payback Period Very Small Scale- Proposed for Only One House, Not Even A Community
Shahzad Et Al. (2017)	Pakistan	PV-AD- Battery	Stand-Alone System	10kW PV 8.0kw Digester Gas 32 Storage Batteries	Feasible and Cost Effective 100% Meeting the Demand Total Capital Cost of PKR 2.64M Electricity Production Cost Of 5.51 PKR/KWh Net Present Cost of PKR 4.48M 9.5 Years Payback Period Very Small Scale- Covering 6 Houses
Ahmad Et Al. (2018)	Pakistan	PV-AD-Wind Turbine	Grid-Connected System	20MW PV 15MW Wind Turbine 15MW Digester Gas	Feasible and Cost-Effective 100% Meeting the Demand 58% Renewable Penetration 19,976.607kg Annual of CO2 Saving Electricity Production Cost 0574 $/KWh $180M- High Capital Cost

Table 7: List of Previous Studies Showing Various Hybrid Energy Systems and Their Performances

2.4.4 Literature Review Summary

Through this literature review, it has been illustrated that there is limited comparable demand data from other studies, with little or no consideration of appliance performance or sectors other than the residential sector. This motivated a much more thorough and detailed demand data estimation and analysis on East Soba for this project.

Following a comprehensive review of various case-studies presenting integrated energy systems and other non-existing studies, to the best of the author's knowledge, none of these studies have considered or fully analysed grid-connected PV-AD hybrid system on a town scale. Most of the studies evaluated either other hybrid systems configurations or explored PV-AD systems but on a very small scale – a couple of houses/farms - without full techno-economic investigation.

However, other studies have supported this project by performing evaluations of various modelling software – they led to a decision that HOMER and the AD Excel spreadsheet calculators would be used in this study.

Various operational modes investigated through this literature review are grid-connected systems or off-grid systems. According to this, the author's proposed PV-AD system for East Soba will ideally operate as a grid-connected system, however there is potential for an alternative of a storage battery to be added instead in special circumstances.

Additionally, studies evaluating Sudan's natural resources have indicated that solar irradiance and organic waste offer the best opportunity for renewable energy generation. Thus, Solar Photovoltaic and Anaerobic Digestion systems were the obvious choices for investigation in East Soba.

3 ENERGY DEMAND AND SUPPLY ANALYSIS

The purpose of this section is to examine the energy demand and supply options of the town in more systematic steps, in order to finally choose the most appropriate hybrid energy system. These steps can be divided into: Demand data collection and optimization, assessment of renewable resources in the town, and modelling the demand and supply.

3.1 Data Collection & Demand Optimisation

The town of East Soba consists of 4000 houses and some other commercial and public services premises, with an estimated population of around 20,000 inhabitants. Table 8 shows the breakdown of the residential, commercial and public services premises.

Premises	Number
Residential Sector (Houses)	4000
Schools	3
Restaurants	5
Mosques	4
Supermarkets	4
Medical Centres	1
Pharmacies	2
Police Stations	1

Table 8: The Premises in East Soba

This data has relayed on qualitative and quantitative surveys as well as expert opinion. A telephone interview was held with an expert engineer from the Sudanese Electricity Distribution Company Mr Azhari (Azhari, 2019), and his estimate of the average electrical consumption for the premises of East Soba can be classified in Table 9 as follows:

Sectors	Monthly Average Consumption in Summer KWh	Monthly Average Consumption in Winter KWh
Residential	550-750	350-400
Schools	2000 - 2400	1000 - 1600
Medical Centres	7000-7500	5700-6000
Supermarkets	1450 - 1750	1100 - 1400
Mosques	2100 - 2550	700 - 1300
Restaurants	1600 - 1950	1600- 1950
Police stations	1700-1900	1000-1300
Pharmacies	800-1000	650-850

Table 9: The Estimated Average Electrical Consumption Via Expert Consultation for East Soba, Sudan

In fact, the vast majority of East Soba's electrical consumption is accounted for by the residential sector, with nearly half of the town's total consumption. This is followed by the services and industry/commercial sectors with approximately 25% and 16% respectively. The agriculture sector consumes a small amount of electricity with only 5%. The transportation sector is powered with diesel and petrol engines, and therefore there is no electrical demand for this sector in Sudan. Figure 18 below illustrated the demand percentage in East Soba by different sectors (Rabah et al., 2016).

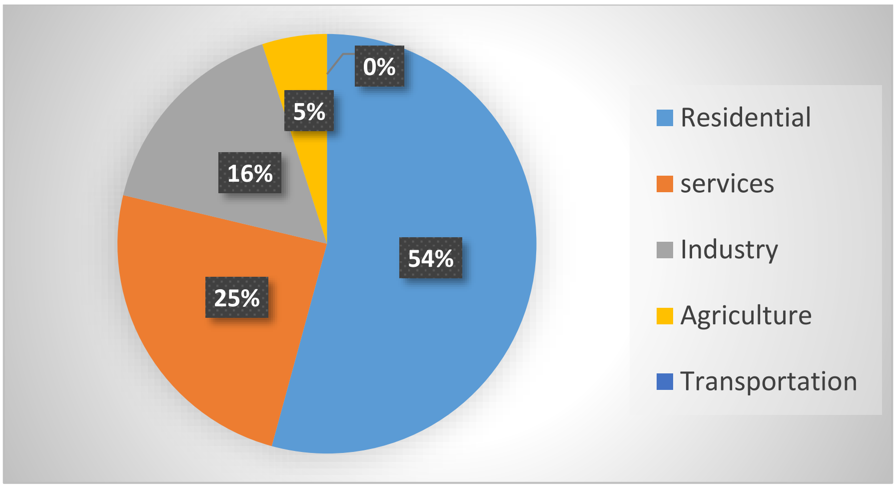


Figure 18: Breakdown of Electricity Consumption Sectors in East Soba from the Initial Collected Data

3.1.1 The Residential Sector

Quantitative and qualitative surveys were carried out to identify precise electrical demands in the residential sector in East Soba. Data was gathered from 11 houses in the town, including information such as ongoing electricity purchase receipts, in order to find the average monthly residential demand. This data encompassed:

- Electricity bills for the last 12 months
- Household appliances
- Consumption behaviour

From the quantitative survey, the average electrical consumption of these 11 houses varies from 550 to 750KWh in summer, and from 350 to 500KWh in winter. According to some inhabitants, the demand in summer is always higher than in the winter. The Qualitative Survey gathered information about the main appliances used in the houses. It became clear that air conditioners, ceiling fans, fluorescent lamps and fridges were among the most common appliances. Table 10 below demonstrates the data which was gathered through both surveys.

House Number	Monthly Average Consumption in Summer KWh	Monthly Average Consumption in Winter KWh	Common Appliances
House 1	750	500	Air Conditioner Washing Machine Ceiling Fan Fluorescent Lamps Computer TV Fridge Freezer Oven Tungsten Lamp Microwave
House 2	730	480	
House 3	700	450	
House 4	600	400	
House 5	570	380	
House 6	690	440	
House 7	500	350	
House 8	580	395	
House 9	625	405	
House 10	650	425	
Home 11	670	466	

Table 10: Housing Data Gathered Through Quantitative and Qualitative Surveys

The survey illustrated that most of the houses have a roughly similar number of bedrooms. It was then estimated that an average house in the town consists of two bedrooms, a kitchen, a living room and two bathrooms. To take into account human behavior, the qualitative survey also involved the operating times of appliances in the houses, and the power rating was careful considered from the manufacturers' websites (CSE, 2019) (DaftLogic, 2017). Table 11 below shows an example of a typical house with its appliances and their operating times.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours of Usage/Day	Daily Demand (Wh)	Daily Demand (kWh)
Air Conditioner	2500	1	2500	4	10000	10
Washing Machine	1200	1	1200	1.8	2160	2.16
Ceiling Fan	70	4	280	12	3360	3.36
Fluorescent lamps	18	6	108	6	648	0.648
Computer	115	1	115	2	230	0.23
TV	120	1	120	3	360	0.36
Fridge	80	1	80	24	1920	1.92
Freezer	150	1	150	6	900	0.9
Oven	2100	1	0	0	0	0
Tungsten lamp	75	1	75	3	225	0.225
Microwave	1000	1	1000	1	1000	1
Total Demand: 20 KWh/day						

Table 11: Typical House from The Survey with Its Appliances and Their Operating Times for One Day

Residential Demand Data Optimisation

The demand generated by the houses was observed during the day and night in summer and winter, based on the consumption behaviour data from some residents in the town which was collected through the survey. In summer, peak hours from midday to 6pm were shown to be the highest consumption period, with approximately 70-80% higher energy demand than the night times, which was due to the extreme usage of air-conditioners. In winter, the demand for cooling is less; air-conditioners are not used at all. Figure 19 and 20 below demonstrate an hourly demand performance in summer and winter for a typical house in East Soba.

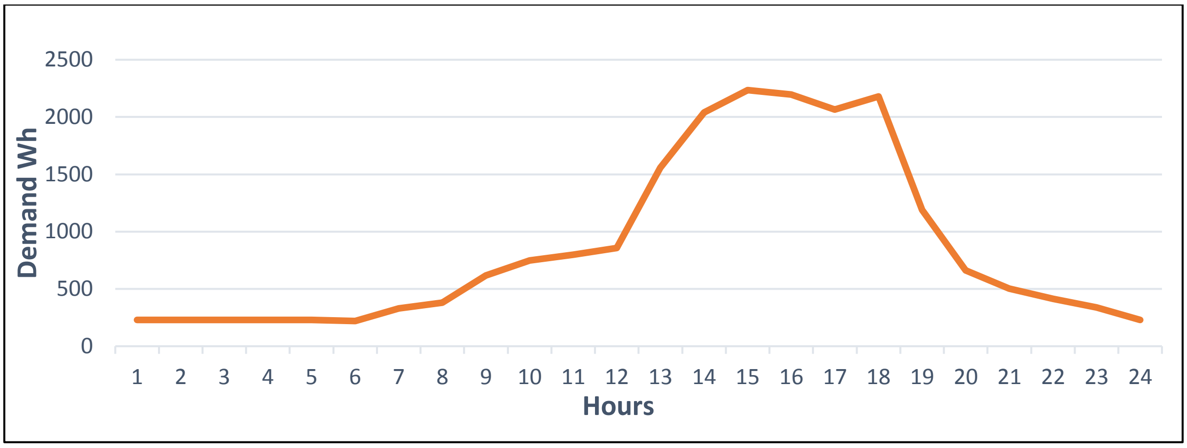


Figure 19: Estimated Hourly Demand Performance for the House in a Typical Summer Day (June)

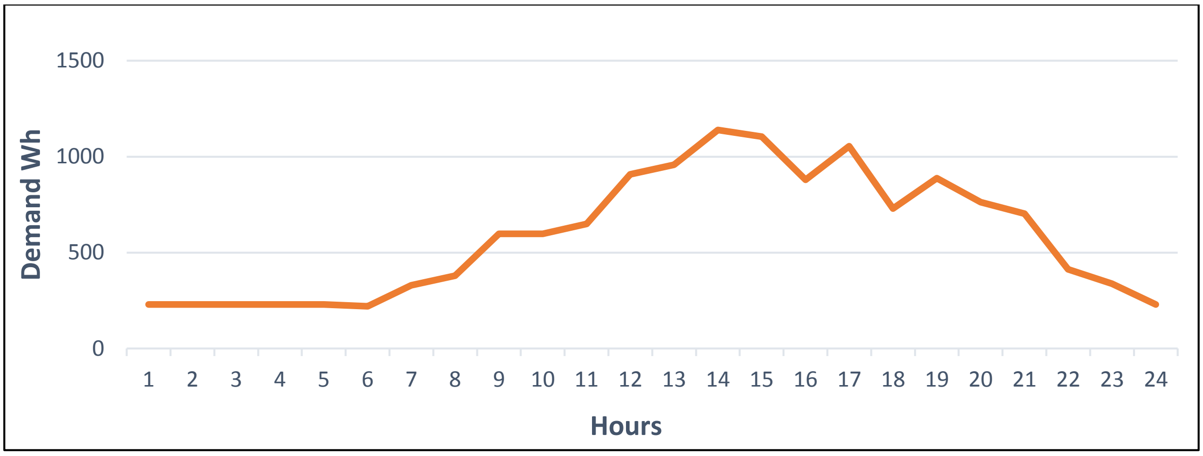
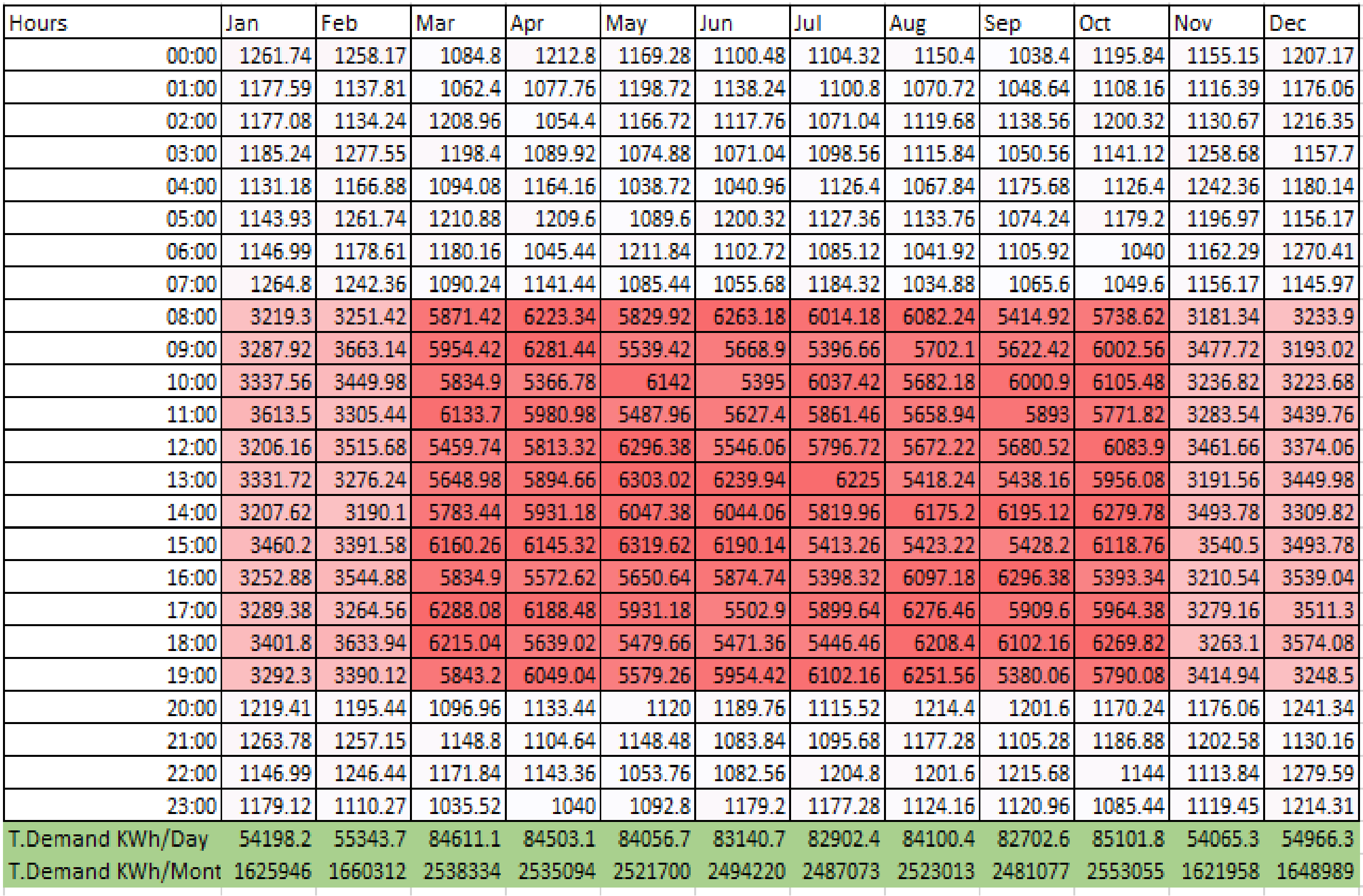


Figure 20: Estimated Hourly Demand Performance for the House in a Typical Winter Day (February)

The quantitative survey confirmed that the average electric demand for houses in summer is between 550-750KWh/month, and for the winter is between 350 –500KWh/month. Consequently, to optimize and create an hourly consumption values range for the entire year, interquartile mathematical calculation method was accomplished. The interquartile values range for the summer and winter were measured to be between 0.8-0.95KWh, and 0.54-0.62KWh, respectively.

It is also important to point out that in Sudan, the summer months are March until October, and the winter is considered to be from November until February. Taking above-mentioned elements into account, with a consideration that that the town of East Soba has around 4,000 houses with an estimated similar average size, appliances and operating times. Therefore, the totals Hourly electric demand for all houses throughout the year can be calculated below in Table 12.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	1261.74	1258.17	1084.8	1212.8	1169.28	1100.48	1104.32	1150.4	1038.4	1195.84	1155.15	1207.17
01:00	1177.59	1137.81	1062.4	1077.76	1198.72	1138.24	1100.8	1070.72	1048.64	1108.16	1116.39	1176.06
02:00	1177.08	1134.24	1208.96	1054.4	1166.72	1117.76	1071.04	1119.68	1138.56	1200.32	1130.67	1216.35
03:00	1185.24	1277.55	1198.4	1089.92	1074.88	1071.04	1098.56	1115.84	1050.56	1141.12	1258.68	1157.7
04:00	1131.18	1166.88	1094.08	1164.16	1038.72	1040.96	1126.4	1067.84	1175.68	1126.4	1242.36	1180.14
05:00	1143.93	1261.74	1210.88	1209.6	1089.6	1200.32	1127.36	1133.76	1074.24	1179.2	1196.97	1156.17
06:00	1146.99	1178.61	1180.16	1045.44	1211.84	1102.72	1085.12	1041.92	1105.92	1040	1162.29	1270.41
07:00	1264.8	1242.36	1090.24	1141.44	1085.44	1055.68	1184.32	1034.88	1065.6	1049.6	1156.17	1145.97
08:00	3219.3	3251.42	5871.42	6223.34	5829.92	6263.18	6014.18	6082.24	5414.92	5738.62	3181.34	3233.9
09:00	3287.92	3663.14	5954.42	6281.44	5539.42	5668.9	5396.66	5702.1	5622.42	6002.56	3477.72	3193.02
10:00	3337.56	3449.98	5834.9	5366.78	6142	5395	6037.42	5682.18	6000.9	6105.48	3236.82	3223.68
11:00	3613.5	3305.44	6133.7	5980.98	5487.96	5627.4	5861.46	5658.94	5893	5771.82	3283.54	3439.76
12:00	3206.16	3515.68	5459.74	5813.32	6296.38	5546.06	5796.72	5672.22	5680.52	6083.9	3461.66	3374.06
13:00	3331.72	3276.24	5648.98	5894.66	6303.02	6239.94	6225	5418.24	5438.16	5956.08	3191.56	3449.98
14:00	3207.62	3190.1	5783.44	5931.18	6047.38	6044.06	5819.96	6175.2	6195.12	6279.78	3493.78	3309.82
15:00	3460.2	3391.58	6160.26	6145.32	6319.62	6190.14	5413.26	5423.22	5428.2	6118.76	3540.5	3493.78
16:00	3252.88	3544.88	5834.9	5572.62	5650.64	5874.74	5398.32	6097.18	6296.38	5393.34	3210.54	3539.04
17:00	3289.38	3264.56	6288.08	6188.48	5931.18	5502.9	5899.64	6276.46	5909.6	5964.38	3279.16	3511.3
18:00	3401.8	3633.94	6215.04	5639.02	5479.66	5471.36	5446.46	6208.4	6102.16	6269.82	3263.1	3574.08
19:00	3292.3	3390.12	5843.2	6049.04	5579.26	5954.42	6102.16	6251.56	5380.06	5790.08	3414.94	3248.5
20:00	1219.41	1195.44	1096.96	1133.44	1120	1189.76	1115.52	1214.4	1201.6	1170.24	1176.06	1241.34
21:00	1263.78	1257.15	1148.8	1104.64	1148.48	1083.84	1095.68	1177.28	1105.28	1186.88	1202.58	1130.16
22:00	1146.99	1246.44	1171.84	1143.36	1053.76	1082.56	1204.8	1201.6	1215.68	1144	1113.84	1279.59
23:00	1179.12	1110.27	1035.52	1040	1092.8	1179.2	1177.28	1124.16	1120.96	1085.44	1119.45	1214.31
T.Demand KWh/Day	54198.2	55343.7	84611.1	84503.1	84056.7	83140.7	82902.4	84100.4	82702.6	85101.8	54065.3	54966.3
T.Demand KWh/Mont	1625946	1660312	2538334	2535094	2521700	2494220	2487073	2523013	2481077	2553055	1621958	1648989

Table 12: Total Estimated Electricity Consumption for the Residential Sector in East Soba, Sudan

3.1.2 Public Services Sector

3.1.2.1 Schools

The electrical loads of schools were investigated according to data collected by the survey. The town has 3 primary schools - however the survey only covered one school due to difficulties in getting in touch with the other two, therefore their electrical loads have been estimated.

AL-Asba Primary School was assessed through the survey. The school consists of eight classrooms, three offices, one canteen, ten toilets and a large front yard. There were three important factors which were considered when calculating the electrical demand for the school:

- Appliances and their operating times
- School working times
- Summer holidays.

The electrical demand for a typical day was initially evaluated at a range of 2000-2400KWh/month in summer and 1000-1600KWh/Month in winter. These figures were reached after considering appliances within the school, their operating times, and the power rates of each appliance (DaftLogic, 2017), as shown in Table 13.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours of Usage/Day	Daily Demand (Wh)	Daily Demand (kWh)	Demand (%)
Air Conditioner	2500	3	7500	5	37500	37.5	51
Photocopier	1265	2	2530	1	2530	2.53	3
Ceiling Fan	70	19	1330	8	10640	10.64	14
Fluorescent Lamps	18	38	684	8	5472	5.472	7
Computer	115	10	1150	5	5750	5.75	8
Fridge	80	2	160	24	3840	3.84	5
Freezer	150	1	150	24	3600	3.6	5
Electrical Bell	20	1	0	0.5	10	0.01	0
Tungsten Lamp	75	10	750	3	2250	2.25	3
Microphone Stereo-System	400	1	400	1	400	0.4	1
Kettle	1200	3	3600	0.5	1800	1.8	2
Total Demand: 73 KWh/day							

Table 13: AL-Asba School with its appliances and their operating times for a typical working day

School Demand Data Optimisation

The hourly electrical demand optimization process was carefully carried out based on the data that was collected from the survey. The first factor which was measured is the peak working hours. According to the Al-Asba Primary School's headmistress Faiza Al-Saideeg, the electrical consumption during the peak working time from 8am to 4pm is 70% higher than at other times, such as the evening or early morning, when the school is mainly shut down; excepting a low level of demand from basic appliances (Al-Saideeg, 2019)

The second factor is the summer holiday, which was also evaluated in this optimization. The summer holiday has a duration of three months in Sudan, from the start of March to the end of May every year. The demand during the summer holiday is usually 85% less than the days where students attend the school (Al-Saideeg, 2019). Figures 21 and 22 show the estimated hourly demand performance for the school attendance day in summer and winter based on the appliances and the working hours.

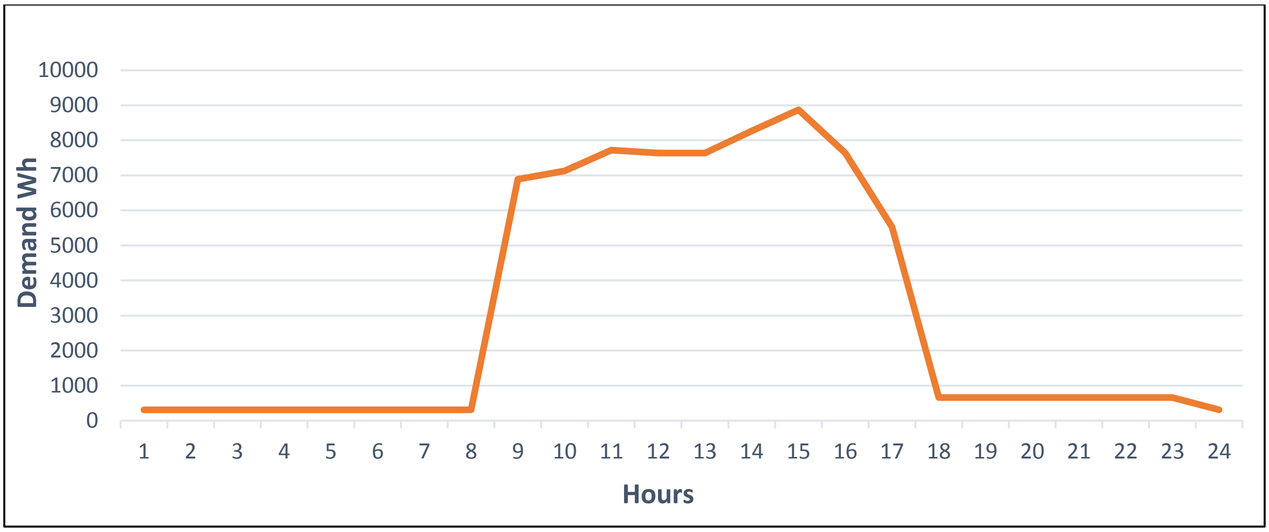


Figure 21: Estimated Hourly Demand Performance for Al-Asba Primary School in a Typical summer Day (June)

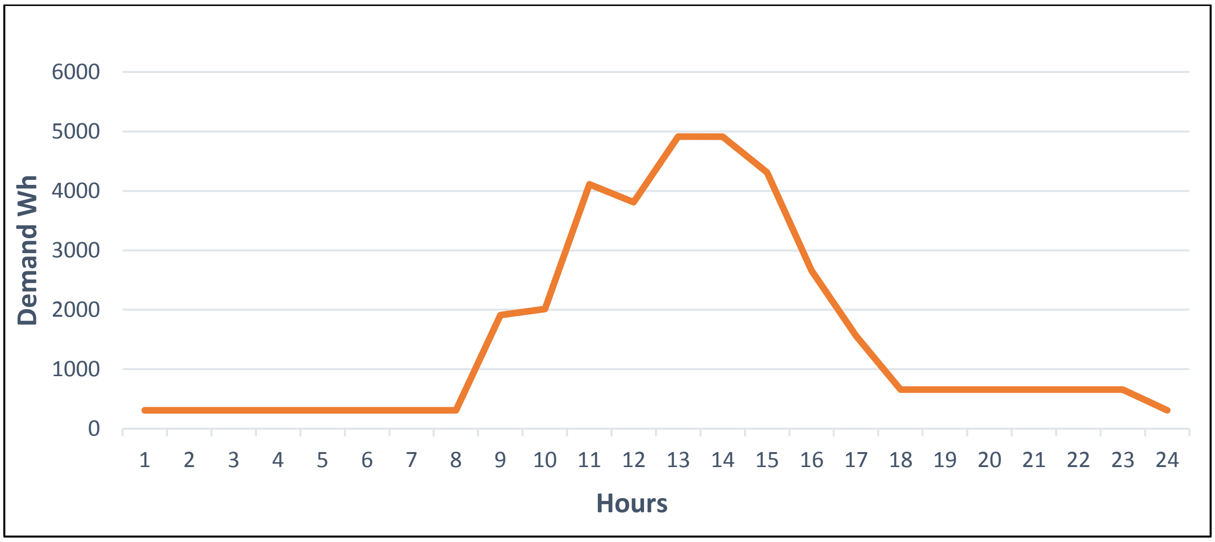
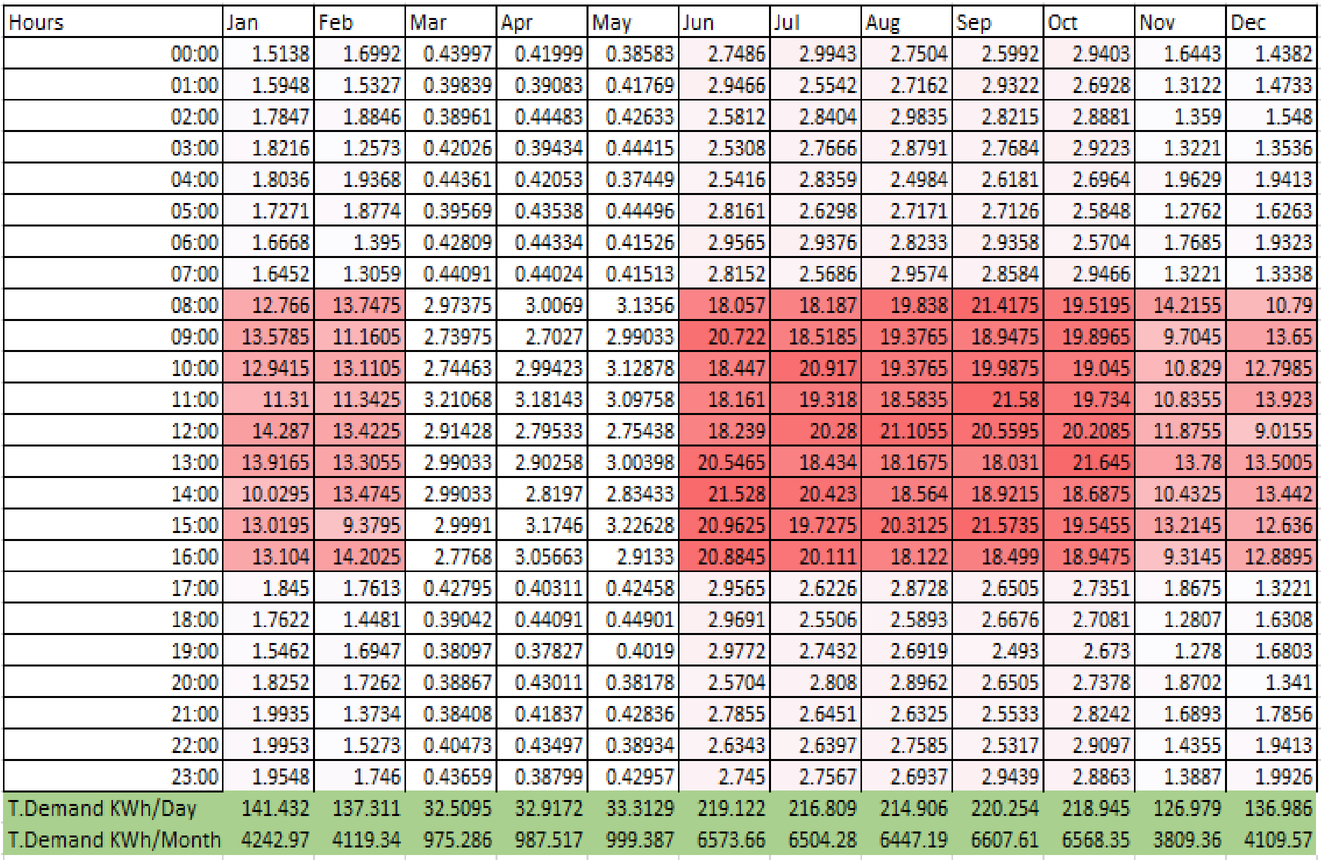


Figure 22: Estimated Hourly Demand Performance for Al-Asba Primary School in a Typical winter Day (November)

It was also mentioned earlier that the other two schools were estimated to have similar electrical demands to Al-Asba Primary school in terms of the appliances, classroom numbers and working times. As result, the total hourly demand for the three schools throughout the year was calculated and displayed below in Table 14.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	1.5138	1.6992	0.43997	0.41999	0.38583	2.7486	2.9943	2.7504	2.5992	2.9403	1.6443	1.4382
01:00	1.5948	1.5327	0.39839	0.39083	0.41769	2.9466	2.5542	2.7162	2.9322	2.6928	1.3122	1.4733
02:00	1.7847	1.8846	0.38961	0.44483	0.42633	2.5812	2.8404	2.9835	2.8215	2.8881	1.359	1.548
03:00	1.8216	1.2573	0.42026	0.39434	0.44415	2.5308	2.7666	2.8791	2.7684	2.9223	1.3221	1.3536
04:00	1.8036	1.9368	0.44361	0.42053	0.37449	2.5416	2.8359	2.4984	2.6181	2.6964	1.9629	1.9413
05:00	1.7271	1.8774	0.39569	0.43538	0.44496	2.8161	2.6298	2.7171	2.7126	2.5848	1.2762	1.6263
06:00	1.6668	1.395	0.42809	0.44334	0.41526	2.9565	2.9376	2.8233	2.9358	2.5704	1.7685	1.9323
07:00	1.6452	1.3059	0.44091	0.44024	0.41513	2.8152	2.5686	2.9574	2.8584	2.9466	1.3221	1.3338
08:00	12.766	13.7475	2.97375	3.0069	3.1356	18.057	18.187	19.838	21.4175	19.5195	14.2155	10.79
09:00	13.5785	11.1605	2.73975	2.7027	2.99033	20.722	18.5185	19.3765	18.9475	19.8965	9.7045	13.65
10:00	12.9415	13.1105	2.74463	2.99423	3.12878	18.447	20.917	19.3765	19.9875	19.045	10.829	12.7985
11:00	11.31	11.3425	3.21068	3.18143	3.09758	18.161	19.318	18.5835	21.58	19.734	10.8355	13.923
12:00	14.287	13.4225	2.91428	2.79533	2.75438	18.239	20.28	21.1055	20.5595	20.2085	11.8755	9.0155
13:00	13.9165	13.3055	2.99033	2.90258	3.00398	20.5465	18.434	18.1675	18.031	21.645	13.78	13.5005
14:00	10.0295	13.4745	2.99033	2.8197	2.83433	21.528	20.423	18.564	18.9215	18.6875	10.4325	13.442
15:00	13.0195	9.3795	2.9991	3.1746	3.22628	20.9625	19.7275	20.3125	21.5735	19.5455	13.2145	12.636
16:00	13.104	14.2025	2.7768	3.05663	2.9133	20.8845	20.111	18.122	18.499	18.9475	9.3145	12.8895
17:00	1.845	1.7613	0.42795	0.40311	0.42458	2.9565	2.6226	2.8728	2.6505	2.7351	1.8675	1.3221
18:00	1.7622	1.4481	0.39042	0.44091	0.44901	2.9691	2.5506	2.5893	2.6676	2.7081	1.2807	1.6308
19:00	1.5462	1.6947	0.38097	0.37827	0.4019	2.9772	2.7432	2.6919	2.493	2.673	1.278	1.6803
20:00	1.8252	1.7262	0.38867	0.43011	0.38178	2.5704	2.808	2.8962	2.6505	2.7378	1.8702	1.341
21:00	1.9935	1.3734	0.38408	0.41837	0.42836	2.7855	2.6451	2.6325	2.5533	2.8242	1.6893	1.7856
22:00	1.9953	1.5273	0.40473	0.43497	0.38934	2.6343	2.6397	2.7585	2.5317	2.9097	1.4355	1.9413
23:00	1.9548	1.746	0.43659	0.38799	0.42957	2.745	2.7567	2.6937	2.9439	2.8863	1.3887	1.9926
T.Demand KWh/Day	141.432	137.311	32.5095	32.9172	33.3129	219.122	216.809	214.906	220.254	218.945	126.979	136.986
T.Demand KWh/Month	4242.97	4119.34	975.286	987.517	999.387	6573.66	6504.28	6447.19	6607.61	6568.35	3809.36	4109.57

Table 14: Total estimated electricity consumption for all three schools in the town of East Soba, Sudan

3.1.2.2 Mosques

The electrical demand of mosques has been explored based on the data collected from the survey and some other comparable studies. Currently the town of East Soba has four mosques; all share the same number of appliances and prayer rooms and have almost identical operating times. There were the three main elements which taken into consideration when the data was collected and optimized:

- The appliances and their operating times
- The five daily prayer and congregation times
- The holy month of Ramadan.

From a comparable study conducted in Saudi Arabia by Al-shaalan et al. (2017), to analysis the electrical loads of a mosque – of a similar size to those in East Soba - the average monthly summer consumption of the mosque was found to be between 2000 and 2500KWh, and between 700 and 1300KWh in winter. Appliances, their operating times and power rates (DaftLogic, 2017) in a typical mosque were identified in Table 15 below.

Appliances	Power (W)	Quantity	Total Power Dmand (W)	Hours of Usage/Day	Daily Demand (Wh)	Daily Demand (kWh)	Demand (%)
Air Conditioner	2500	5	12500	5	62500	62.5	79
Ceiling Fan	70	15	1050	8	8400	8.4	11
Fluorescent lamps	18	20	360	8	2880	2.88	4
Fridge	80	1	80	24	1920	1.92	2
Electrical Clock	5	1	5	24	120	0.12	0
Microphone Sound System	1200	2.5	3000	1	3000	3	4
Average Demand 78 KWh/day							

Table 15: The Mosque's Appliances and Their Operating Times for A Typical Working Day

The electrical demand from mosques is highly affected by daily prayer times. A mosque is usually occupied five times a day throughout the year as a reliable standard. Worshippers often come to the mosque at different times, but the maximum number of worshippers are anticipated to gather in the mosque during the performance of the five main daily prayers, which each usually last around 30-60 minutes. The demand at these prayers times is estimated to be 75% higher than in the other hours according to an expert consultation from the Sudanese Electricity Distribution Company (Azhari, 2019).

Another crucial factor that has an impact on increasing a mosque's demand, particularly its cooling requirements, is the fasting month of Ramadan. Worshippers tend to stay longer in the mosque throughout the day during this month, leading to an estimated 25% increase in electrical consumption compared to all other months (Azhari, 2019). Table 16 below highlights the five prayer times and Ramadan period in Sudan.

Prayers	Approximate Time	Ramadan Period
Fajr	5:00am	From 5 May – 4 June 2019
Zhuhr	14:00pm	
Asr	16:00pm	
Magrib	19:00pm	
Isha	21:00pm	

Table 16: The Five Daily Prayer Times and the Ramadan Period in Sudan in 2019

Mosque Demand Data Optimisation

The hourly optimization process was conducted to monitor the average electrical loads of the mosque during the summer and winter, with special consideration to the five daily prayer times as well as the holy month of Ramadan. Figure 23 displays an estimated electrical consumption based on hourly performance for the mosque in a typical day during Ramadan 2019, with obvious demand increase during the five daily prayer times.

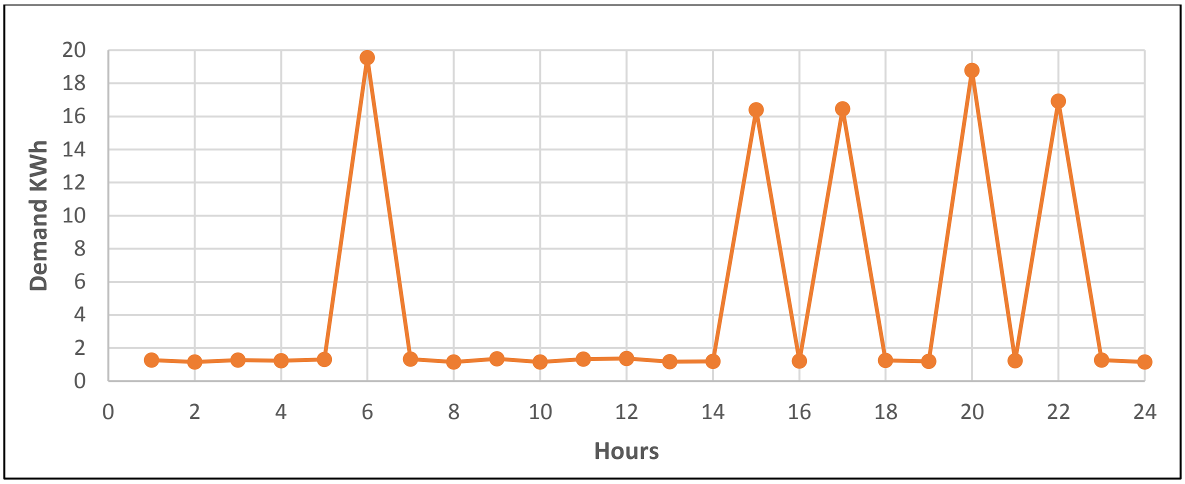
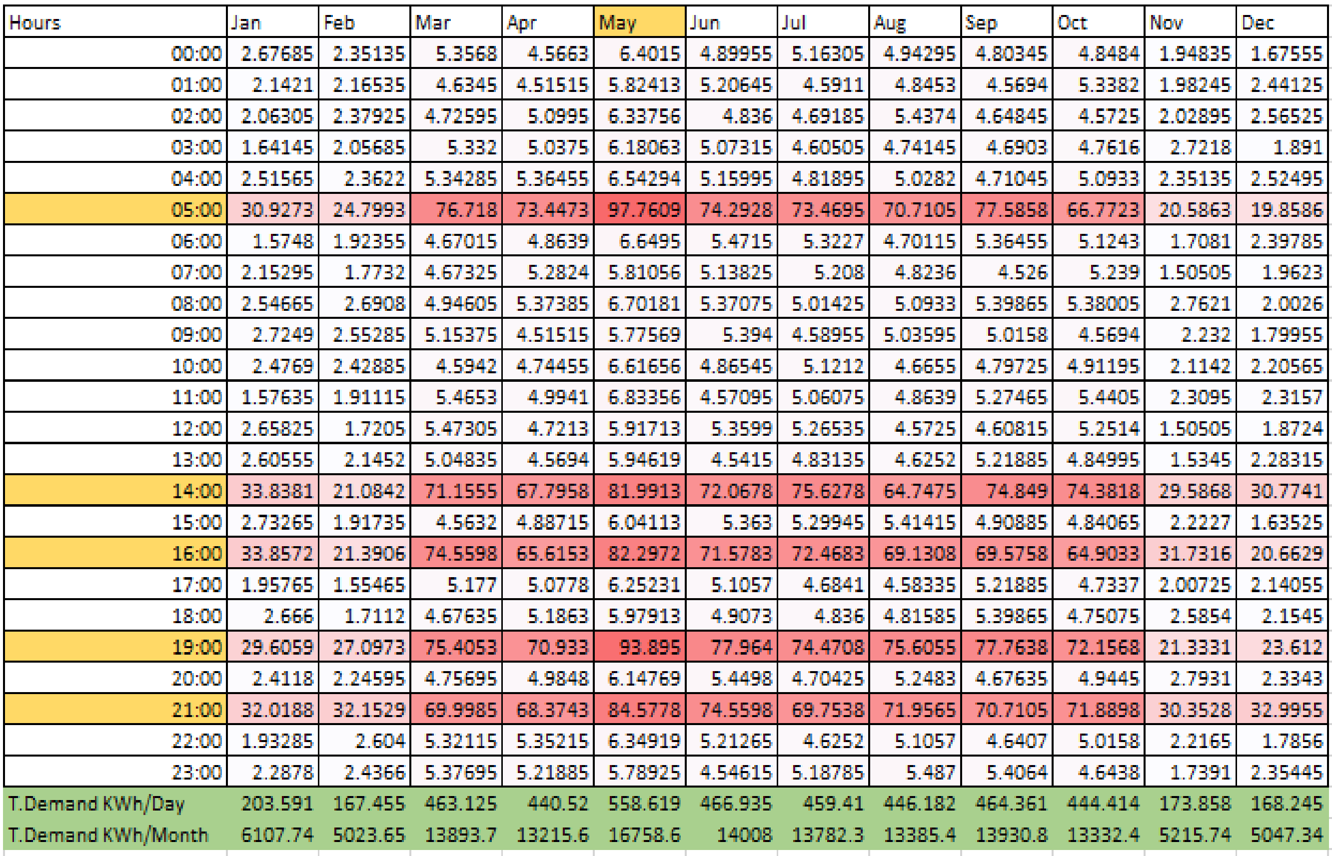


Figure 23: The Estimated Hourly Demand Performance for the Mosque in A Typical Day in Ramadan

After monitoring the hourly electrical demand during the day for one mosque, and taking into account that East Soba has four mosques, all estimated as having a similar electric demand and working times. Thus, the final total demand for the four mosques was measured in Table 17.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	2.67685	2.35135	5.3568	4.5663	6.4015	4.89955	5.16305	4.94295	4.80345	4.8484	1.94835	1.67555
01:00	2.1421	2.16535	4.6345	4.51515	5.82413	5.20645	4.5911	4.8453	4.5694	5.3382	1.98245	2.44125
02:00	2.06305	2.37925	4.72595	5.0995	6.33756	4.836	4.69185	5.4374	4.64845	4.5725	2.02895	2.56525
03:00	1.64145	2.05685	5.332	5.0375	6.18063	5.07315	4.60505	4.74145	4.6903	4.7616	2.7218	1.891
04:00	2.51565	2.3622	5.34285	5.36455	6.54294	5.15995	4.81895	5.0282	4.71045	5.0933	2.35135	2.52495
05:00	30.9273	24.7993	76.718	73.4473	97.7609	74.2928	73.4695	70.7105	77.5858	66.7723	20.5863	19.8586
06:00	1.5748	1.92355	4.67015	4.8639	6.6495	5.4715	5.3227	4.70115	5.36455	5.1243	1.7081	2.39785
07:00	2.15295	1.7732	4.67325	5.2824	5.81056	5.13825	5.208	4.8236	4.526	5.239	1.50505	1.9623
08:00	2.54665	2.6908	4.94605	5.37385	6.70181	5.37075	5.01425	5.0933	5.39865	5.38005	2.7621	2.0026
09:00	2.7249	2.55285	5.15375	4.51515	5.77569	5.394	4.58955	5.03595	5.0158	4.5694	2.232	1.79955
10:00	2.4769	2.42885	4.5942	4.74455	6.61656	4.86545	5.1212	4.6655	4.79725	4.91195	2.1142	2.20565
11:00	1.57635	1.91115	5.4653	4.9941	6.83356	4.57095	5.06075	4.8639	5.27465	5.4405	2.3095	2.3157
12:00	2.65825	1.7205	5.47305	4.7213	5.91713	5.3599	5.26535	4.5725	4.60815	5.2514	1.50505	1.8724
13:00	2.60555	2.1452	5.04835	4.5694	5.94619	4.5415	4.83135	4.6252	5.21885	4.84995	1.5345	2.28315
14:00	33.8381	21.0842	71.1555	67.7958	81.9913	72.0678	75.6278	64.7475	74.849	74.3818	29.5868	30.7741
15:00	2.73265	1.91735	4.5632	4.88715	6.04113	5.363	5.29945	5.41415	4.90885	4.84065	2.2227	1.63525
16:00	33.8572	21.3906	74.5598	65.6153	82.2972	71.5783	72.4683	69.1308	69.5758	64.9033	31.7316	20.6629
17:00	1.95765	1.55465	5.177	5.0778	6.25231	5.1057	4.6841	4.58335	5.21885	4.7337	2.00725	2.14055
18:00	2.666	1.7112	4.67635	5.1863	5.97913	4.9073	4.836	4.81585	5.39865	4.75075	2.5854	2.1545
19:00	29.6059	27.0973	75.4053	70.933	93.895	77.964	74.4708	75.6055	77.7638	72.1568	21.3331	23.612
20:00	2.4118	2.24595	4.75695	4.9848	6.14769	5.4498	4.70425	5.2483	4.67635	4.9445	2.7931	2.3343
21:00	32.0188	32.1529	69.9985	68.3743	84.5778	74.5598	69.7538	71.9565	70.7105	71.8898	30.3528	32.9955
22:00	1.93285	2.604	5.32115	5.35215	6.34919	5.21265	4.6252	5.1057	4.6407	5.0158	2.2165	1.7856
23:00	2.2878	2.4366	5.37695	5.21885	5.78925	4.54615	5.18785	5.487	5.4064	4.6438	1.7391	2.35445
T.Demand KWh/Day	203.591	167.455	463.125	440.52	558.619	466.935	459.41	446.182	464.361	444.414	173.858	168.245
T.Demand KWh/Month	6107.74	5023.65	13893.7	13215.6	16758.6	14008	13782.3	13385.4	13930.8	13332.4	5215.74	5047.34

Table 17: Total Estimated Electricity Consumption for All Four Mosques in East Soba, Sudan

3.1.2.3 Medical Centres

Currently, the town of East Soba has only one medical centre. The subsequent data was estimated based on comparable case studies as well as expert consultation. In order to identify likely appliance types and usage times in the medical centre, Dr. Alaa Mohaker, a senior doctor at Soba Hospital in Khartoum who has previously worked at this centre, was consulted through a phone interview (Mohaker, 2019). Following this consultation, the appliances were divided into five categories as in Table 18 below.

Category	Components
HVAC Appliances	Air Conditioner, Medical Fridge, Medical Freezer, Ceiling Fan
IT Appliances	Printer, Computer, Paper shredder
Lighting Appliances	Fluorescent lamp
Medical equipment	Microscope, X-ray Machine, Ultrasonic diagnostic machine
Kitchen Appliances	Microwave Oven, Kettle, Coffee Maker, Toaster Electric Cooker

Table 18: The Appliances Likely to Be Found in East Soba Medical Centre

According to a study conducted upon a teaching hospital in Norway, it is the technical medical equipment such as Microscopes, X-ray Machines, Ultrasonic diagnostic machines, Magnetic Resonance Imaging (MRI), and Positron Emission Tomography (PET), which consume most of the electric loads (Rode and Martinez, 2015).

Furthermore, according to a report from the Department of the Environment, Transport and the Regions Energy Efficiency in the UK, the monthly consumption for a typical small-scale hospital can vary from 7000-7500KWh in summer and 5700-6000KWh in winter (DETR, 1999). Based on the quantity of the equipment, its power ratings (DaftLogic, 2017), and the hours of usage during the day, the average daily demand for the medical centre in East Soba was then estimated and found to be approximately 244KWh. Table 19 reveals the analysis of appliances.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours Of Usage/Day	Daily Demand (Wh)	Daily Demand (KWh)
Air Conditioner	2500	4	10000	5	50000	50
Printer	1265	2	2530	2	5060	5.06
Ceiling Fan	70	11	770	15	11550	11.55
Fluorescent Lamps	18	22	396	15	5940	5.94
Computer	115	10	1150	10	11500	11.5
Medical Fridge	300	3	900	24	21600	21.6
Medical Freezer	200	3	600	24	14400	14.4
Paper Shredder	150	1	150	2	300	0.3
Microwave Oven	1000	2	2000	2	4000	4
Toaster	850	1	850	1	850	0.85
Cooker	790	1	790	3	2370	2.37
Kettle	1200	3	3600	0.5	1800	1.8
Coffee Maker	900	3	2700	1	2700	2.7
X-Ray Devices	2600	2	5200	10	52000	52

Ultrasonic Diagnostic Machine	2300	1	2300	10	23000	23
Microscope	1250	3	3750	10	37500	37.5
Average Demand: 244KWh/day						

Table 19: The East Soba Medical Centre's Appliances and Their Operating Times for A Typical Working Day

Following an examination of the medical Centre's appliances, the vast majority of the power was found to be consumed through the medical equipment and air conditioners. Figure 24 below illustrates the breakdown of the power consumption in the centre according to the appliances there.

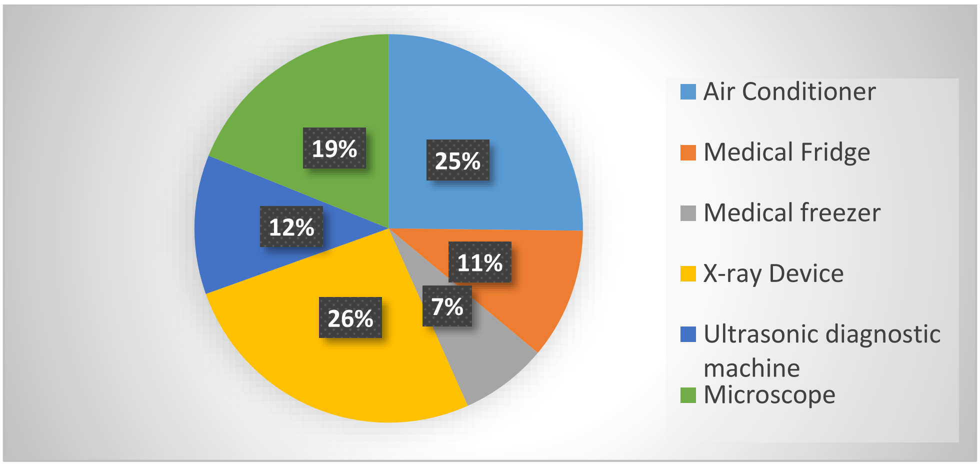


Figure 24: Breakdown of Electricity Consumption for East Soba Medical Centre, Sudan

Healthcare Centre Demand Data Optimisation

The demand optimization procedure was investigated based on the Centre's long working hours which were estimated to be from 9am to midnight according to the consultation with Dr. Mohaker (2019). During summer and winter, the demand through the peak working hours was 94% higher than non-working hours. In fact, the electricity load of the medical centre is not disturbed by climatic conditions, except that in winter the usage of air conditioners is almost zero. Figures 25 and 26 present the average hourly demand for the medical centre in summer and winter following the data optimization.

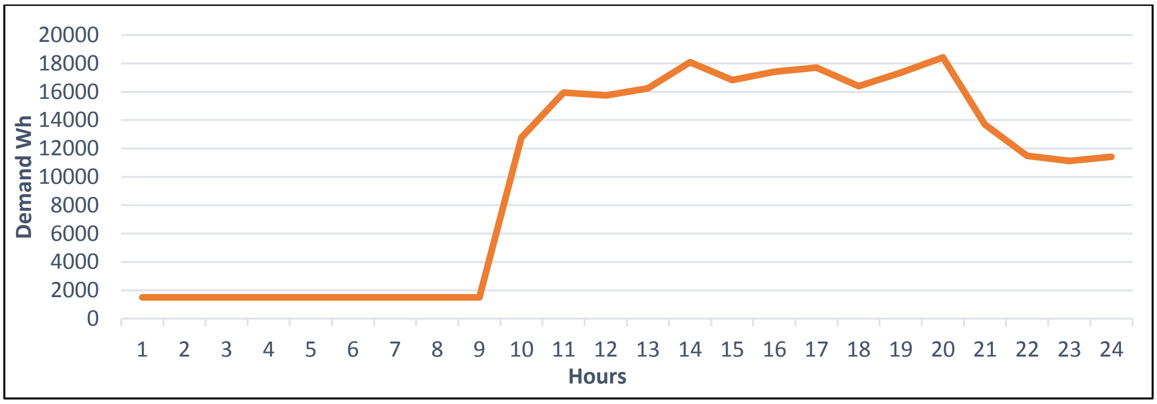


Figure 25: Estimated Hourly Demand Performance for East Soba Medical Centre in A Typical Summer Day (June)

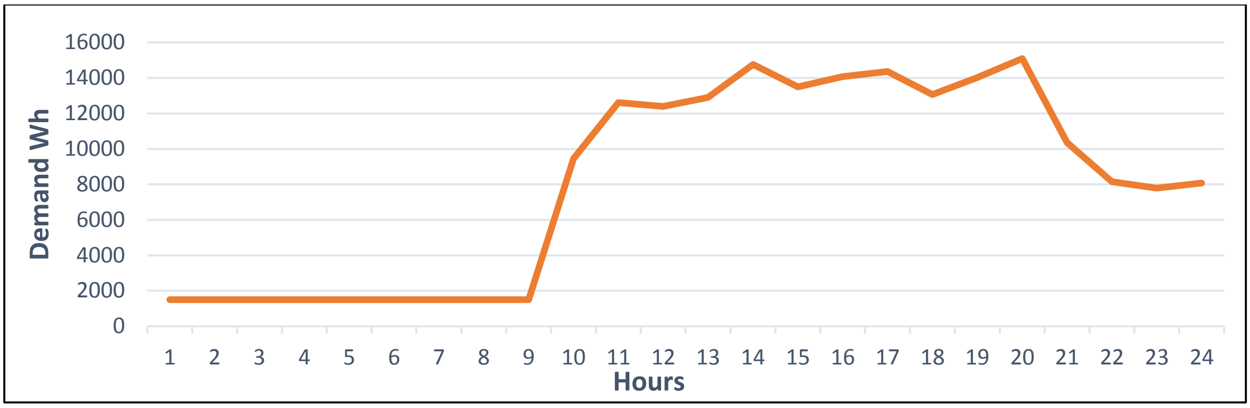
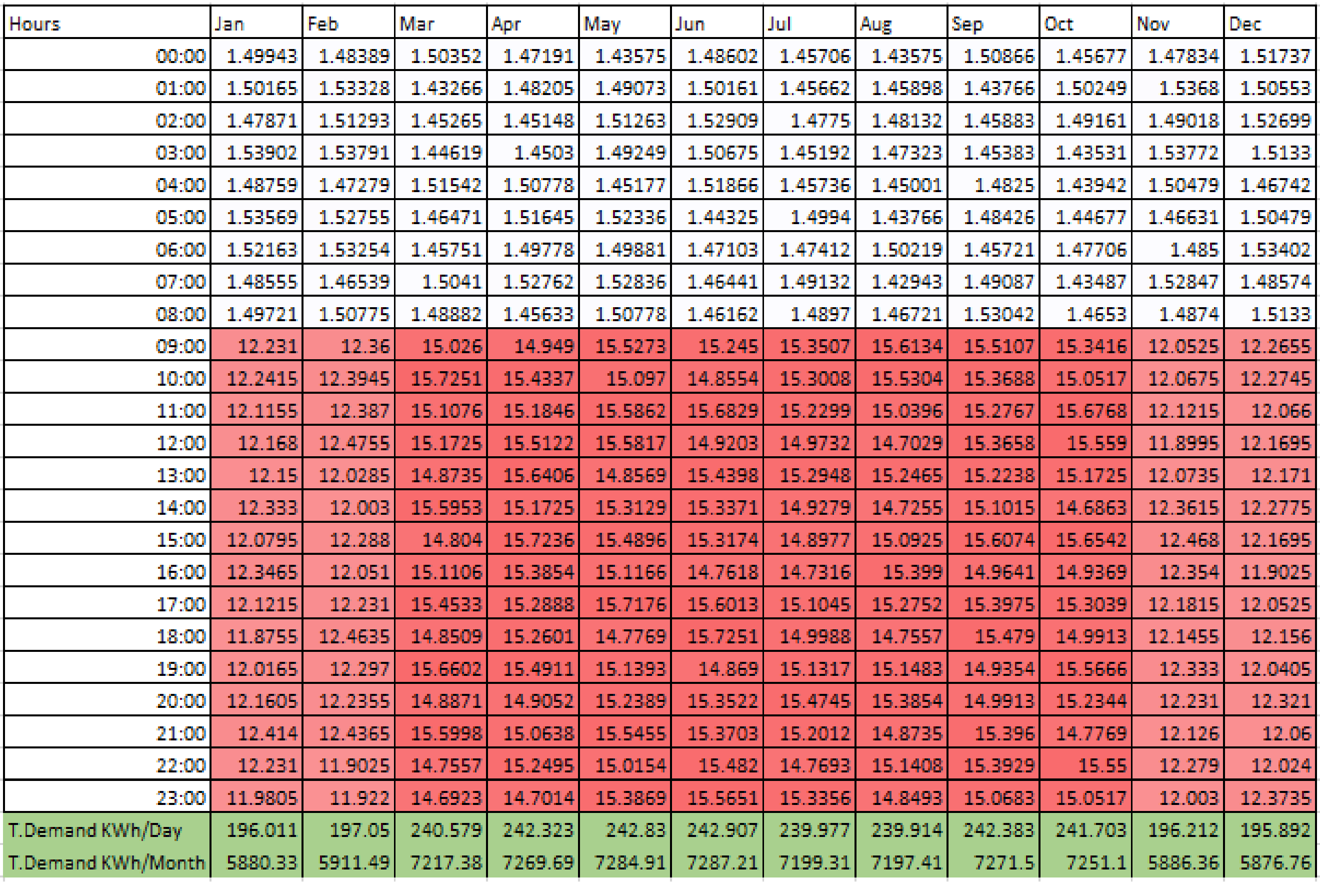


Figure 26: Estimated Hourly Demand Performance for East Soba Medical Centre in A Typical Winter Day (December)

Taking into consideration the above-mentioned analysis, the final total demand for the medical centre in East Soba was calculated beneath in Table 20.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	1.49943	1.48389	1.50352	1.47191	1.43575	1.48602	1.45706	1.43575	1.50866	1.45677	1.47834	1.51737
01:00	1.50165	1.53328	1.43266	1.48205	1.49073	1.50161	1.45662	1.45898	1.43766	1.50249	1.5368	1.50553
02:00	1.47871	1.51293	1.45265	1.45148	1.51263	1.52909	1.4775	1.48132	1.45883	1.49161	1.49018	1.52699
03:00	1.53902	1.53791	1.44619	1.4503	1.49249	1.50675	1.45192	1.47323	1.45383	1.43531	1.53772	1.5133
04:00	1.48759	1.47279	1.51542	1.50778	1.45177	1.51866	1.45736	1.45001	1.4825	1.43942	1.50479	1.46742
05:00	1.53569	1.52755	1.46471	1.51645	1.52336	1.44325	1.4994	1.43766	1.48426	1.44677	1.46631	1.50479
06:00	1.52163	1.53254	1.45751	1.49778	1.49881	1.47103	1.47412	1.50219	1.45721	1.47706	1.485	1.53402
07:00	1.48555	1.46539	1.5041	1.52762	1.52836	1.46441	1.49132	1.42943	1.49087	1.43487	1.52847	1.48574
08:00	1.49721	1.50775	1.48882	1.45633	1.50778	1.46162	1.4897	1.46721	1.53042	1.4653	1.4874	1.5133
09:00	12.231	12.36	15.026	14.949	15.5273	15.245	15.3507	15.6134	15.5107	15.3416	12.0525	12.2655
10:00	12.2415	12.3945	15.7251	15.4337	15.097	14.8554	15.3008	15.5304	15.3688	15.0517	12.0675	12.2745
11:00	12.1155	12.387	15.1076	15.1846	15.5862	15.6829	15.2299	15.0396	15.2767	15.6768	12.1215	12.066
12:00	12.168	12.4755	15.1725	15.5122	15.5817	14.9203	14.9732	14.7029	15.3658	15.559	11.8995	12.1695
13:00	12.15	12.0285	14.8735	15.6406	14.8569	15.4398	15.2948	15.2465	15.2238	15.1725	12.0735	12.171
14:00	12.333	12.003	15.5953	15.1725	15.3129	15.3371	14.9279	14.7255	15.1015	14.6863	12.3615	12.2775
15:00	12.0795	12.288	14.804	15.7236	15.4896	15.3174	14.8977	15.0925	15.6074	15.6542	12.468	12.1695
16:00	12.3465	12.051	15.1106	15.3854	15.1166	14.7618	14.7316	15.399	14.9641	14.9369	12.354	11.9025
17:00	12.1215	12.231	15.4533	15.2888	15.7176	15.6013	15.1045	15.2752	15.3975	15.3039	12.1815	12.0525
18:00	11.8755	12.4635	14.8509	15.2601	14.7769	15.7251	14.9988	14.7557	15.479	14.9913	12.1455	12.156
19:00	12.0165	12.297	15.6602	15.4911	15.1393	14.869	15.1317	15.1483	14.9354	15.5666	12.333	12.0405
20:00	12.1605	12.2355	14.8871	14.9052	15.2389	15.3522	15.4745	15.3854	14.9913	15.2344	12.231	12.321
21:00	12.414	12.4365	15.5998	15.0638	15.5455	15.3703	15.2012	14.8735	15.396	14.7769	12.126	12.06
22:00	12.231	11.9025	14.7557	15.2495	15.0154	15.482	14.7693	15.1408	15.3929	15.55	12.279	12.024
23:00	11.9805	11.922	14.6923	14.7014	15.3869	15.5651	15.3356	14.8493	15.0683	15.0517	12.003	12.3735
T.Demand KWh/Day	196.011	197.05	240.579	242.323	242.83	242.907	239.977	239.914	242.383	241.703	196.212	195.892
T.Demand KWh/Month	5880.33	5911.49	7217.38	7269.69	7284.91	7287.21	7199.31	7197.41	7271.5	7251.1	5886.36	5876.76

Table 20: Total Estimated Electricity Consumption for East Soba Medical Centre, Sudan

3.1.2.4 The Police station

East Soba police station consists of three offices, two custody rooms, a reception room and four toilets. The monthly power consumption in the station was predicted to be 1700-1900KWh in summer and 1000-1300KWh in winter, according to expert consultation through a phone call from Yousif Azhari, an engineer at the Sudanese Electricity Distribution Company (Azhari, 2019).The demand in East Soba police station depends heavily on the type of the electrical appliances there, as well as the working hours, which are considered to be 24-hours a day.

To check that the above-mentioned information is right, the daily demand was explored according to various appliances, their power rating (DaftLogic, 2017), and hours of usage during the day. Table 21 below notes the average daily demand can reach up to 61KWh/day in summer, and 32KWh/day in winter, when air conditioners are not used.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours of Usage/Day	Daily Demand (Wh)	Daily Demand (kWh)
Air Conditioner	2500	2	5000	5	25000	25
Printer	1265	1	1265	2	2530	2.53
Ceiling Fan	70	7	490	24	11760	11.76
Fluorescent Lamps	18	10	180	24	4320	4.32
Computer	115	4	460	24	11040	11.04
Fridge	80	1	80	24	1920	1.92
Freezer	150	1	150	24	3600	3.6
Microwave Oven	1000	1	1000	0.5	500	0.5
Kettle	1200	1	1200	0.5	600	0.6
Average Demand: 61KWh/day						

Table 21: The police station with its appliances and their operating times for a typical working day

It is important to outline that; air conditioners are key appliances within the police station. They represent almost 41% of the total demand, followed by ceiling fans and computers at 20% and 18% respectively. Figure 27 expresses the breakdown of the power consumption by the type of appliance at East Soba police station.

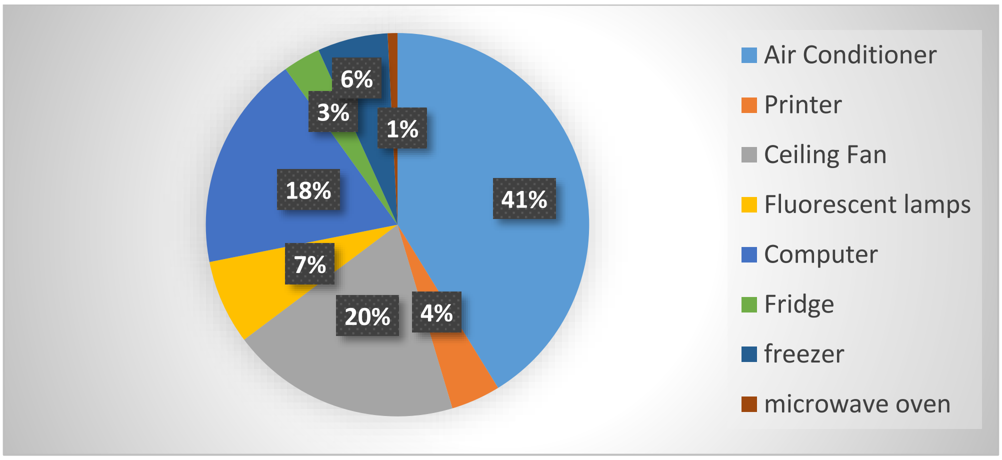


Figure 27: Breakdown of electricity consumption for the Police Station, East Soba, Sudan

East Soba Police Station Demand Data Optimisation

In order to get an accurate measurement, the demand data was optimized on an hourly basis during the summer and winter. This optimization was carried out based on the consumption of appliances over 24 hours, as working times for the police station. For the summer, the consumption was estimated to be almost double the consumption in winter because of the air conditioner loads. Figures 28 and 29 demonstrate a full explanation of the demand for a typical working day in summer, and in winter, at East Soba Police station.

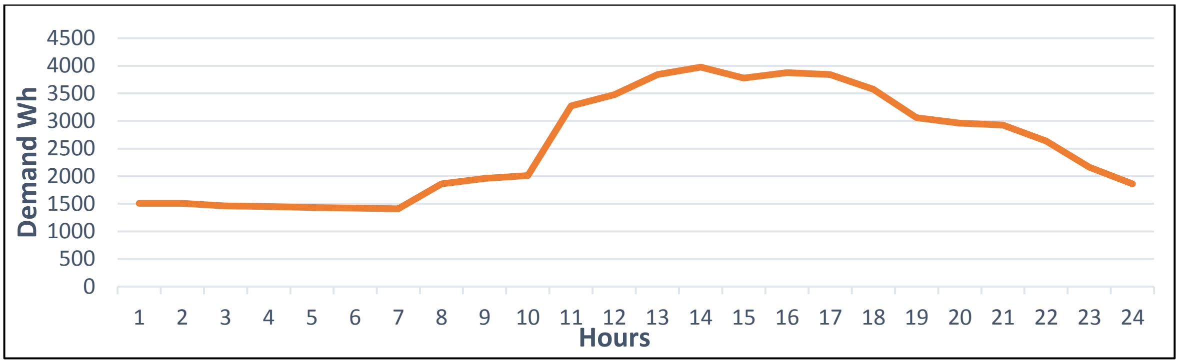


Figure 28: Estimated Hourly Demand Performance for the police station in A Typical Summer Day (June)

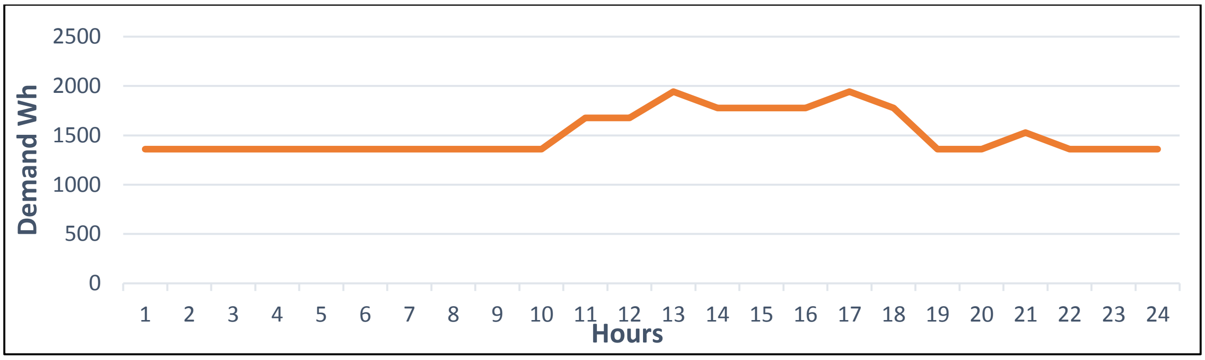
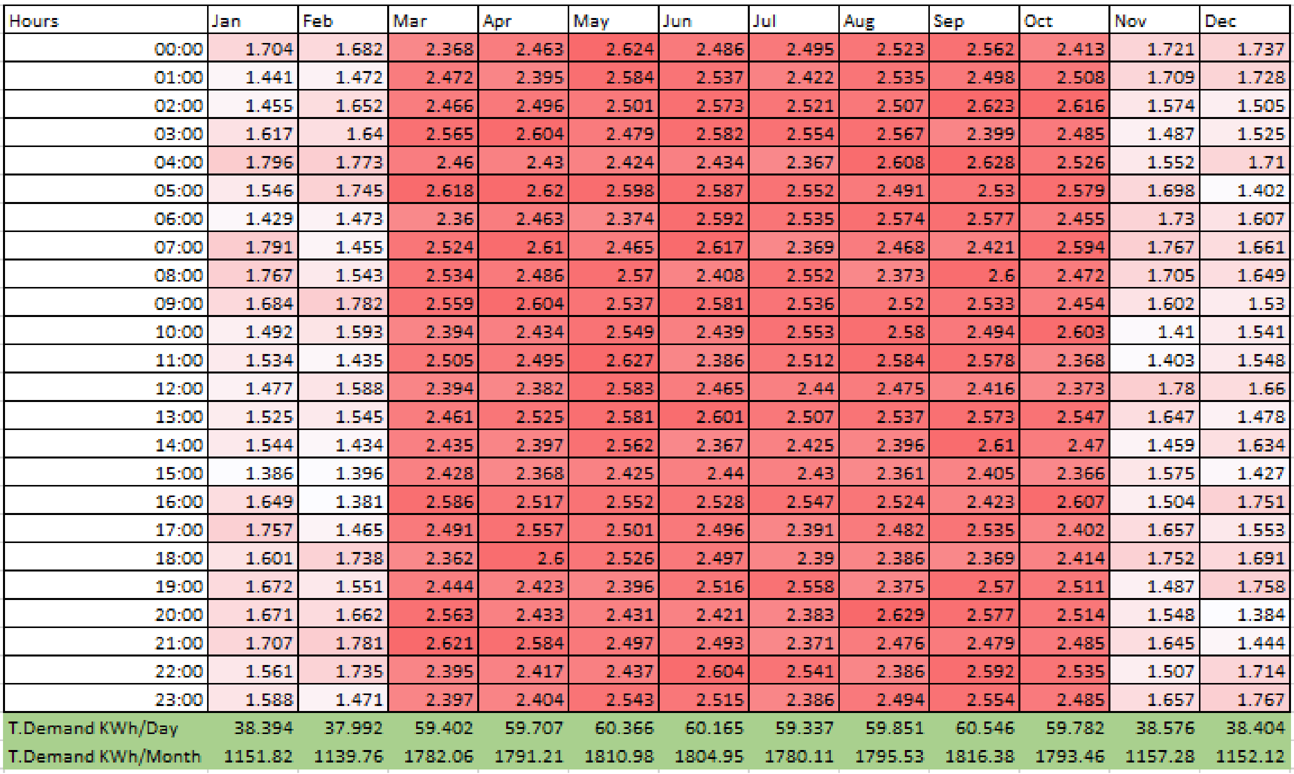


Figure 29: Estimated Hourly Demand Performance for the police station in A Typical winter Day (February)

Following the demand monitoring process for a typical working day, the final total demand can then be generated on an hourly basis for the entire year. See Table 22.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	1.704	1.682	2.368	2.463	2.624	2.486	2.495	2.523	2.562	2.413	1.721	1.737
01:00	1.441	1.472	2.472	2.395	2.584	2.537	2.422	2.535	2.498	2.508	1.709	1.728
02:00	1.455	1.652	2.466	2.496	2.501	2.573	2.521	2.507	2.623	2.616	1.574	1.505
03:00	1.617	1.64	2.565	2.604	2.479	2.582	2.554	2.567	2.399	2.485	1.487	1.525
04:00	1.796	1.773	2.46	2.43	2.424	2.434	2.367	2.608	2.628	2.526	1.552	1.71
05:00	1.546	1.745	2.618	2.62	2.598	2.587	2.552	2.491	2.53	2.579	1.698	1.402
06:00	1.429	1.473	2.36	2.463	2.374	2.592	2.535	2.574	2.577	2.455	1.73	1.607
07:00	1.791	1.455	2.524	2.61	2.465	2.617	2.369	2.468	2.421	2.594	1.767	1.661
08:00	1.767	1.543	2.534	2.486	2.57	2.408	2.552	2.373	2.6	2.472	1.705	1.649
09:00	1.684	1.782	2.559	2.604	2.537	2.581	2.536	2.52	2.533	2.454	1.602	1.53
10:00	1.492	1.593	2.394	2.434	2.549	2.439	2.553	2.58	2.494	2.603	1.41	1.541
11:00	1.534	1.435	2.505	2.495	2.627	2.386	2.512	2.584	2.578	2.368	1.403	1.548
12:00	1.477	1.588	2.394	2.382	2.583	2.465	2.44	2.475	2.416	2.373	1.78	1.66
13:00	1.525	1.545	2.461	2.525	2.581	2.601	2.507	2.537	2.573	2.547	1.647	1.478
14:00	1.544	1.434	2.435	2.397	2.562	2.367	2.425	2.396	2.61	2.47	1.459	1.634
15:00	1.386	1.396	2.428	2.368	2.425	2.44	2.43	2.361	2.405	2.366	1.575	1.427
16:00	1.649	1.381	2.586	2.517	2.552	2.528	2.547	2.524	2.423	2.607	1.504	1.751
17:00	1.757	1.465	2.491	2.557	2.501	2.496	2.391	2.482	2.535	2.402	1.657	1.553
18:00	1.601	1.738	2.362	2.6	2.526	2.497	2.39	2.386	2.369	2.414	1.752	1.691
19:00	1.672	1.551	2.444	2.423	2.396	2.516	2.558	2.375	2.57	2.511	1.487	1.758
20:00	1.671	1.662	2.563	2.433	2.431	2.421	2.383	2.629	2.577	2.514	1.548	1.384
21:00	1.707	1.781	2.621	2.584	2.497	2.493	2.371	2.476	2.479	2.485	1.645	1.444
22:00	1.561	1.735	2.395	2.417	2.437	2.604	2.541	2.386	2.592	2.535	1.507	1.714
23:00	1.588	1.471	2.397	2.404	2.543	2.515	2.386	2.494	2.554	2.485	1.657	1.767
T.Demand KWh/Day	38.394	37.992	59.402	59.707	60.366	60.165	59.337	59.851	60.546	59.782	38.576	38.404
T.Demand KWh/Month	1151.82	1139.76	1782.06	1791.21	1810.98	1804.95	1780.11	1795.53	1816.38	1793.46	1157.28	1152.12

Table 22: Total Estimated Electricity Consumption for the Police Station in East Soba, Sudan

3.1.3 *Commercial Sector*

The town has five restaurants, four supermarkets and two pharmacies. The demand data of each was estimated through consultation from the Sudanese electricity distribution company (Azhari, 2019). The consultation indicated that the average monthly demand for a single restaurant in East Soba fluctuates year-round between 1600-1950KWh. In addition, the average monthly consumption for a supermarket is 1450-1750KWh in summer, and 1100-1400KWh in winter.

Furthermore, the average monthly consumption estimation for the pharmacies is 800-1000KWh in summer, and 650-850KWh in winter. However, two crucial factors have been taken into consideration when collecting data from the commercial sector:

- Appliances and cooking facilities with their operating times
- Opening hours of each premises.

3.1.3.1 Restaurants

The majority of the electrical consumption in a restaurant typically comes from the cooking facilities. Commercial fridges and freezers were found to consume nearly 60% of a restaurant's total electrical loads. Figure 30 below reveals the breakdown of power consumption in a restaurant.

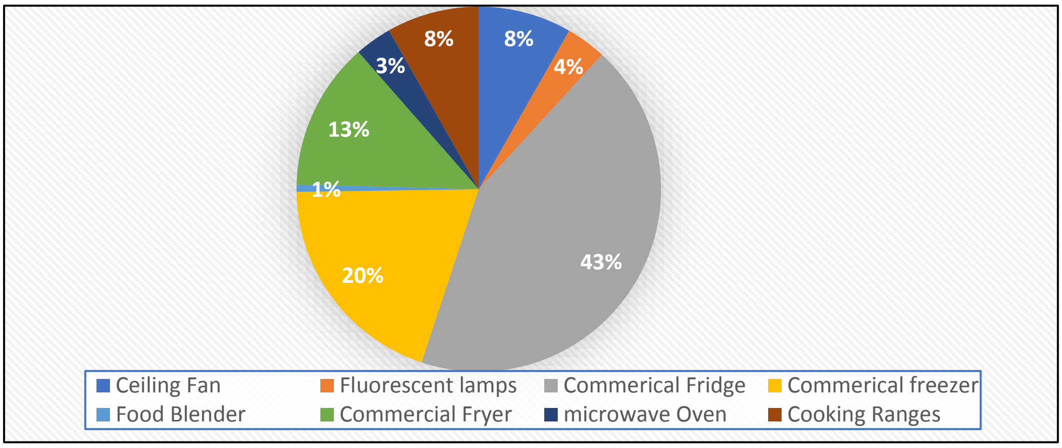


Figure 30: Breakdown of Average Electricity Consumption in the Restaurant, East Soba, Sudan

The operating times for appliances were estimated and analysed for a typical day based on the collected data. The average daily consumption is around 60KWh, expanded on below in Table 23.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours of Usage/Day	Daily Demand (Wh)	Daily Demand (kWh)
Ceiling Fan	70	6	420	12	5040	5.04
Fluorescent lamps	18	10	180	12	2160	2.16
Commercial Fridge	550	2	1100	24	26400	26.4
Freezer	500	1	500	24	12000	12
Food Blender	390	1	390	1	390	0.39
Commercial Fryer	2000	1	2000	4	8000	8
Microwave Oven	1000	1	1000	2	2000	2
Cooking Range	1250	1	1250	4	5000	5
Average demand: 60KWh/day						

Table 23: The Restaurant with Its Appliances and Their Operating Times for A Typical Working Day

Restaurant Demand Data Optimisation

The demand optimization process was held by monitoring the performance of the cooking facilities on an hourly basis throughout the day in the summer and winter. The performance was estimated to be similar in both summer and winter as the average restaurant's capacity and customer numbers were not found to be affected by the weather conditions. Unlike other business premises, Sudanese restaurants traditionally have open-air dining areas, so their cooling loads do not vary widely between summer and winter. The restaurants in East Soba have very similar working hours; all five of them operate largely between 9am and 9pm with little to no variation throughout the year. From the optimization analysis, the demand during the peak working hours from 9am to 9pm was revealed to be almost 68% higher than when the restaurant is shut down. Figure 31 clarifies the average hourly demand in a typical day for the restaurant.

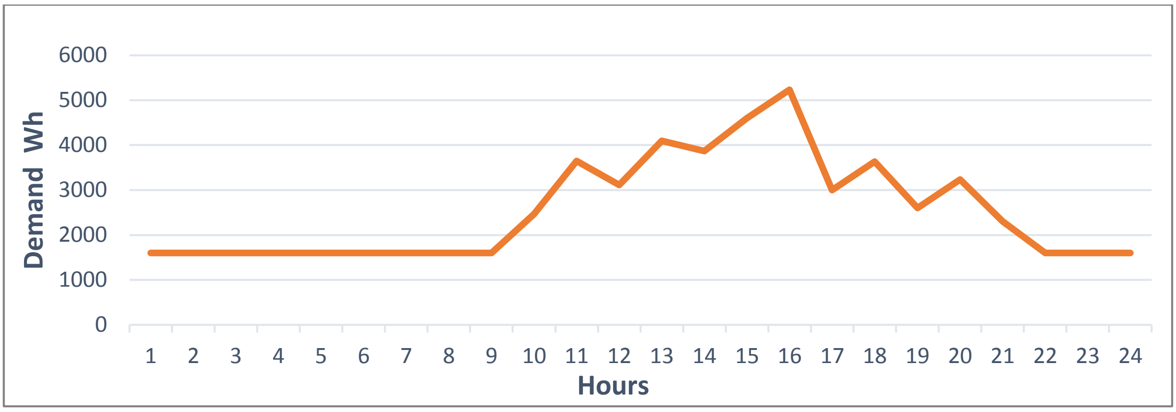
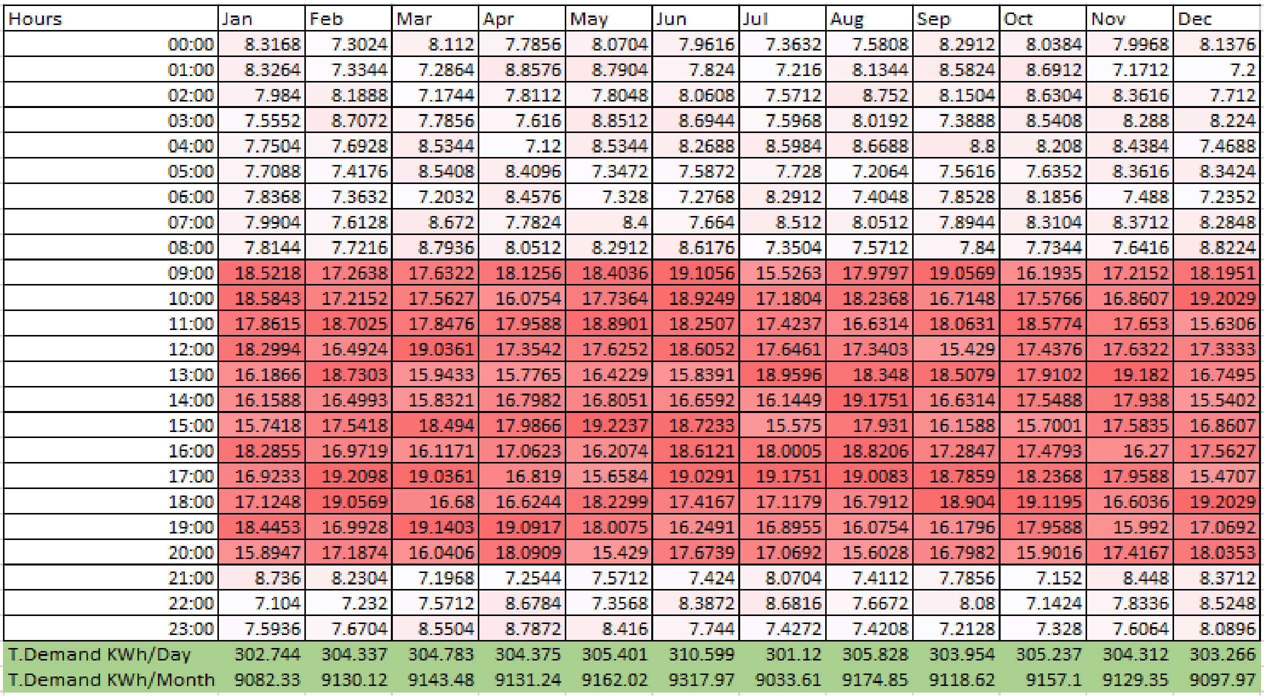


Figure 31: Estimated Hourly Demand Performance for the restaurant in a typical working day

After considering the appliances, peak working hours, and hourly demand in the day, with a consideration that the East Soba has five restaurants which they share a similar electrical demand. Consequently, the final total hourly demand for all restaurants thought the year was calculated, as shown in Table 24.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	8.3168	7.3024	8.112	7.7856	8.0704	7.9616	7.3632	7.5808	8.2912	8.0384	7.9968	8.1376
01:00	8.3264	7.3344	7.2864	8.8576	8.7904	7.824	7.216	8.1344	8.5824	8.6912	7.1712	7.2
02:00	7.984	8.1888	7.1744	7.8112	7.8048	8.0608	7.5712	8.752	8.1504	8.6304	8.3616	7.712
03:00	7.5552	8.7072	7.7856	7.616	8.8512	8.6944	7.5968	8.0192	7.3888	8.5408	8.288	8.224
04:00	7.7504	7.6928	8.5344	7.12	8.5344	8.2688	8.5984	8.6688	8.8	8.208	8.4384	7.4688
05:00	7.7088	7.4176	8.5408	8.4096	7.3472	7.5872	7.728	7.2064	7.5616	7.6352	8.3616	8.3424
06:00	7.8368	7.3632	7.2032	8.4576	7.328	7.2768	8.2912	7.4048	7.8528	8.1856	7.488	7.2352
07:00	7.9904	7.6128	8.672	7.7824	8.4	7.664	8.512	8.0512	7.8944	8.3104	8.3712	8.2848
08:00	7.8144	7.7216	8.7936	8.0512	8.2912	8.6176	7.3504	7.5712	7.84	7.7344	7.6416	8.8224
09:00	18.5218	17.2638	17.6322	18.1256	18.4036	19.1056	15.5263	17.9797	19.0569	16.1935	17.2152	18.1951
10:00	18.5843	17.2152	17.5627	16.0754	17.7364	18.9249	17.1804	18.2368	16.7148	17.5766	16.8607	19.2029
11:00	17.8615	18.7025	17.8476	17.9588	18.8901	18.2507	17.4237	16.6314	18.0631	18.5774	17.653	15.6306
12:00	18.2994	16.4924	19.0361	17.3542	17.6252	18.6052	17.6461	17.3403	15.429	17.4376	17.6322	17.3333
13:00	16.1866	18.7303	15.9433	15.7765	16.4229	15.8391	18.9596	18.348	18.5079	17.9102	19.182	16.7495
14:00	16.1588	16.4993	15.8321	16.7982	16.8051	16.6592	16.1449	19.1751	16.6314	17.5488	17.938	15.5402
15:00	15.7418	17.5418	18.494	17.9866	19.2237	18.7233	15.575	17.931	16.1588	15.7001	17.5835	16.8607
16:00	18.2855	16.9719	16.1171	17.0623	16.2074	18.6121	18.0005	18.8206	17.2847	17.4793	16.27	17.5627
17:00	16.9233	19.2098	19.0361	16.819	15.6584	19.0291	19.1751	19.0083	18.7859	18.2368	17.9588	15.4707
18:00	17.1248	19.0569	16.68	16.6244	18.2299	17.4167	17.1179	16.7912	18.904	19.1195	16.6036	19.2029
19:00	18.4453	16.9928	19.1403	19.0917	18.0075	16.2491	16.8955	16.0754	16.1796	17.9588	15.992	17.0692
20:00	15.8947	17.1874	16.0406	18.0909	15.429	17.6739	17.0692	15.6028	16.7982	15.9016	17.4167	18.0353
21:00	8.736	8.2304	7.1968	7.2544	7.5712	7.424	8.0704	7.4112	7.7856	7.152	8.448	8.3712
22:00	7.104	7.232	7.5712	8.6784	7.3568	8.3872	8.6816	7.6672	8.08	7.1424	7.8336	8.5248
23:00	7.5936	7.6704	8.5504	8.7872	8.416	7.744	7.4272	7.4208	7.2128	7.328	7.6064	8.0896
T.Demand KWh/Day	302.744	304.337	304.783	304.375	305.401	310.599	301.12	305.828	303.954	305.237	304.312	303.266
T.Demand KWh/Month	9082.33	9130.12	9143.48	9131.24	9162.02	9317.97	9033.61	9174.85	9118.62	9157.1	9129.35	9097.97

Table 24: Total Estimated Electricity Consumption for All Five Restaurants in East Soba, Sudan

3.1.3.2 Supermarkets

In the average small supermarket in Sudan, the consumption is dominated by fridges and freezers, reaching almost 42% and 28% of the supermarket's total demand respectively. Air conditioners have the third highest load portion during opening hours, at approximately 20% of the total electrical demand. Figure 32 displays the breakdown of consumption in a typical small supermarket in East Soba, Sudan.

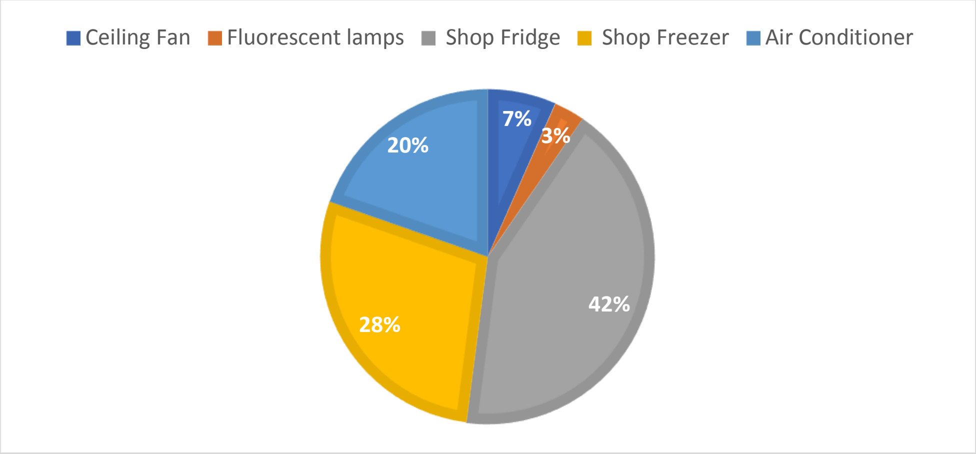


Figure 32: Breakdown of Electricity Consumption in the Supermarket

East Soba has four of these small supermarkets, all estimated to have similar appliances, working hours and therefore a similar electrical demand. The daily demand for one supermarket has been estimated after calculating the power rating (DaftLogic, 2017), and the hours of usage of every appliance. The average demand for a working day was measured to be 50KWh in summer and 40KWh in winter. Table 25 expresses the estimated daily demand for one supermarket based on its appliances.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours Of Usage/Day	Daily Demand (Wh)	Daily Demand (KWh)
Ceiling Fans	70	4	280	12	3360	3.36
Fluorescent Lamps	18	7	126	12	1512	1.512
Shop Fridges	300	3	900	24	21600	21.6
Shop Freezer	200	3	600	24	14400	14.4
Air Conditioner	2500	1	2500	4	10000	10
Average Demand: 50KWh/day						

Table 25: The Supermarket with Its Appliances and Their Operating Times for A Typical Working Day

Supermarket Demand Data Optimisation

To ensure that the demand data is more precise, an hourly demand analysis was performed in the summer and winter based on the opening times of the supermarket, which are generally from 9am to 9pm. During the shop's working hours in summer, the electrical demand was 65% higher than the non-working hours. In the winter the demand increased by 55% during the same opening hours. Figures 33 and 34 explain the average hourly demand for the shop in a typical day in summer and winter following the data optimization.

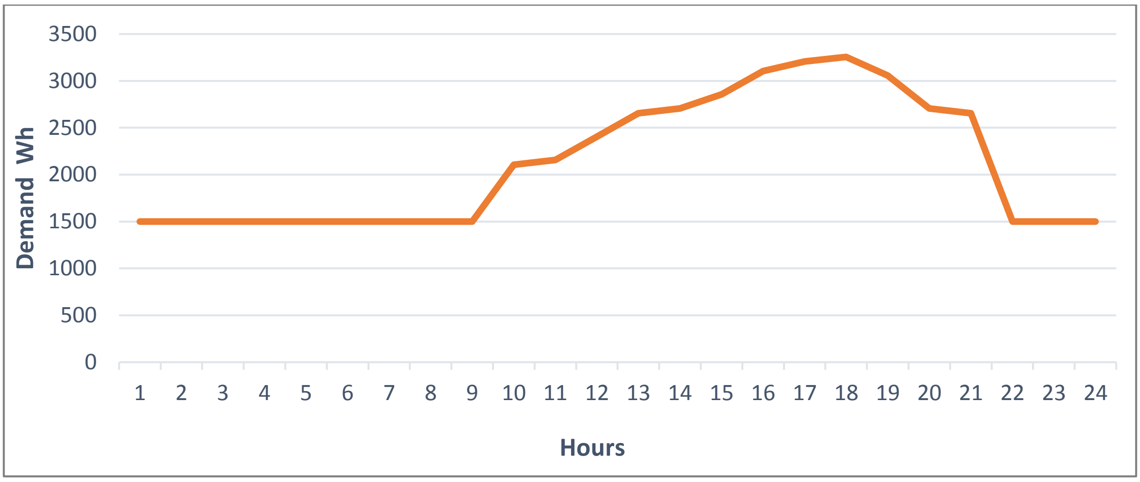


Figure 33: Estimated Hourly Demand Performance for the Supermarket in A Typical Summer Day (June)

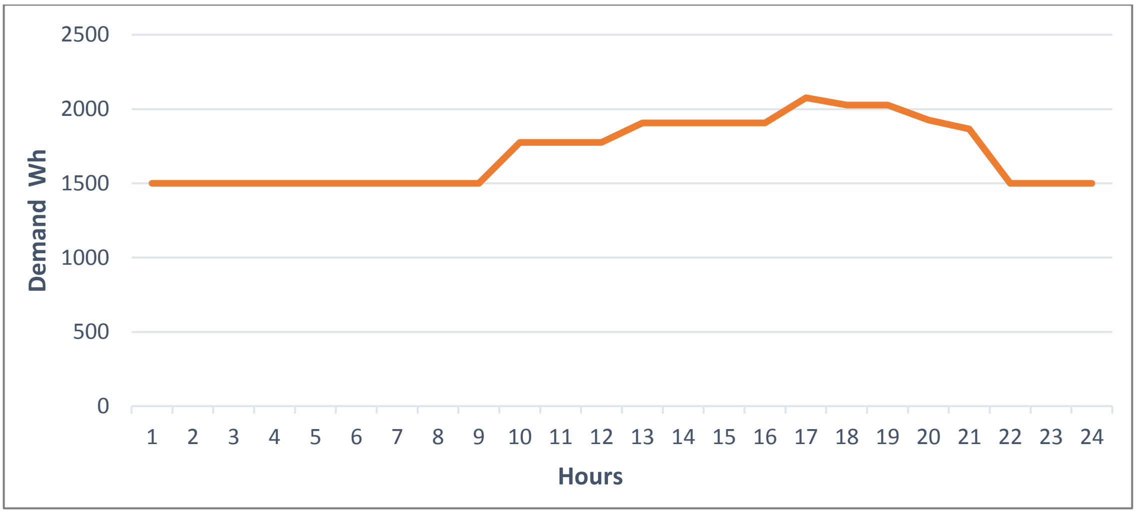
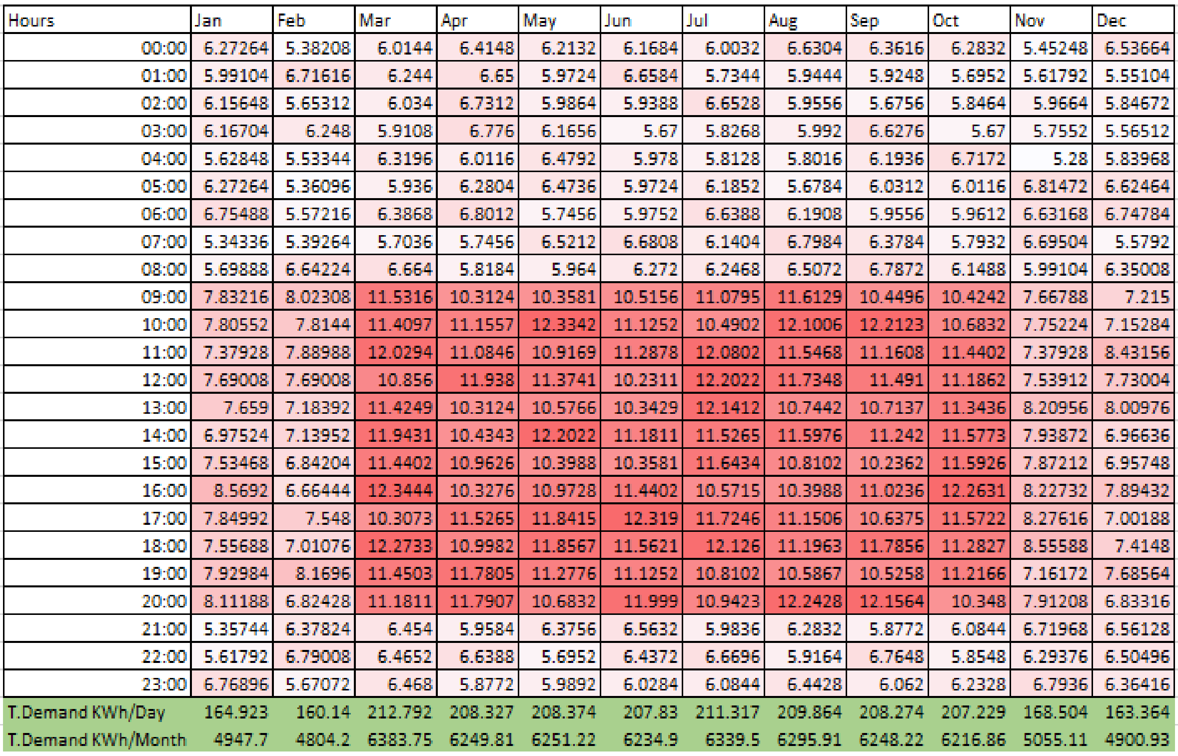


Figure 34: Estimated Hourly Demand Performance for the Supermarket in A Typical Winter Day (December)

After full consideration of the hourly demand performance in summer and winter for one supermarket, and the fact that East Soba has four of these small supermarkets, therefore a comprehensive demand calculation was completed to consider all the four shops which can be shown below in Table 26.



Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	6.27264	5.38208	6.0144	6.4148	6.2132	6.1684	6.0032	6.6304	6.3616	6.2832	5.45248	6.53664
01:00	5.99104	6.71616	6.244	6.65	5.9724	6.6584	5.7344	5.9444	5.9248	5.6952	5.61792	5.55104
02:00	6.15648	5.65312	6.034	6.7312	5.9864	5.9388	6.6528	5.9556	5.6756	5.8464	5.9664	5.84672
03:00	6.16704	6.248	5.9108	6.776	6.1656	5.67	5.8268	5.992	6.6276	5.67	5.7552	5.56512
04:00	5.62848	5.53344	6.3196	6.0116	6.4792	5.978	5.8128	5.8016	6.1936	6.7172	5.28	5.83968
05:00	6.27264	5.36096	5.936	6.2804	6.4736	5.9724	6.1852	5.6784	6.0312	6.0116	6.81472	6.62464
06:00	6.75488	5.57216	6.3868	6.8012	5.7456	5.9752	6.6388	6.1908	5.9556	5.9612	6.63168	6.74784
07:00	5.34336	5.39264	5.7036	5.7456	6.5212	6.6808	6.1404	6.7984	6.3784	5.7932	6.69504	5.5792
08:00	5.69888	6.64224	6.664	5.8184	5.964	6.272	6.2468	6.5072	6.7872	6.1488	5.99104	6.35008
09:00	7.83216	8.02308	11.5316	10.3124	10.3581	10.5156	11.0795	11.6129	10.4496	10.4242	7.66788	7.215
10:00	7.80552	7.8144	11.4097	11.1557	12.3342	11.1252	10.4902	12.1006	12.2123	10.6832	7.75224	7.15284
11:00	7.37928	7.88988	12.0294	11.0846	10.9169	11.2878	12.0802	11.5468	11.1608	11.4402	7.37928	8.43156
12:00	7.69008	7.69008	10.856	11.938	11.3741	10.2311	12.2022	11.7348	11.491	11.1862	7.53912	7.73004
13:00	7.659	7.18392	11.4249	10.3124	10.5766	10.3429	12.1412	10.7442	10.7137	11.3436	8.20956	8.00976
14:00	6.97524	7.13952	11.9431	10.4343	12.2022	11.1811	11.5265	11.5976	11.242	11.5773	7.93872	6.96636
15:00	7.53468	6.84204	11.4402	10.9626	10.3988	10.3581	11.6434	10.8102	10.2362	11.5926	7.87212	6.95748
16:00	8.5692	6.66444	12.3444	10.3276	10.9728	11.4402	10.5715	10.3988	11.0236	12.2631	8.22732	7.89432
17:00	7.84992	7.548	10.3073	11.5265	11.8415	12.319	11.7246	11.1506	10.6375	11.5722	8.27616	7.00188
18:00	7.55688	7.01076	12.2733	10.9982	11.8567	11.5621	12.126	11.1963	11.7856	11.2827	8.55588	7.4148
19:00	7.92984	8.1696	11.4503	11.7805	11.2776	11.1252	10.8102	10.5867	10.5258	11.2166	7.16172	7.68564
20:00	8.11188	6.82428	11.1811	11.7907	10.6832	11.999	10.9423	12.2428	12.1564	10.348	7.91208	6.83316
21:00	5.35744	6.37824	6.454	5.9584	6.3756	6.5632	5.9836	6.2832	5.8772	6.0844	6.71968	6.56128
22:00	5.61792	6.79008	6.4652	6.6388	5.6952	6.4372	6.6696	5.9164	6.7648	5.8548	6.29376	6.50496
23:00	6.76896	5.67072	6.468	5.8772	5.9892	6.0284	6.0844	6.4428	6.062	6.2328	6.7936	6.36416
T.Demand KWh/Day	164.923	160.14	212.792	208.327	208.374	207.83	211.317	209.864	208.274	207.229	168.504	163.364
T.Demand KWh/Month	4947.7	4804.2	6383.75	6249.81	6251.22	6234.9	6339.5	6295.91	6248.22	6216.86	5055.11	4900.93

Table 26: Total Estimated Electricity Consumption for All Four Supermarkets in East Soba, Sudan

3.1.3.3 Pharmacies

The town has two main pharmacies. The demand relies principally on the main appliances, as well as the peak working times, which are 8am to 10pm every day for both premises. The appliances of both pharmacies were estimated to be almost identical in terms of type, quantity, power rating and operating time.

From the expert consultation, the monthly consumption for a typical pharmacy in summer is roughly 800-1100KWh, and 500-750KWh in winter (Azhari, 2019). To corroborate the accuracy of this estimation, an appliances analysis was performed in order to calculate the average daily demand for one pharmacy in East Soba. The demand was discovered to be around 32 KWh/day during the hotter summer, and 20 KWh/day in winter when there is less or no usage of air conditioning. See Table 27.

Appliances	Power (W)	Quantity	Total Power Demand (W)	Hours Of Usage/Day	Daily Demand (Wh)	Daily Demand (KWh)
Air Conditioner	2500	1	2500	5	12500	12.5
Ceiling Fan	70	3	210	14	2940	2.94
Fluorescent lamps	18	8	144	14	2016	2.016
Computer	115	2	230	14	3220	3.22
Medical Fridge	300	1	300	24	7200	7.2
Medical Freezer	200	1	200	24	4800	4.8
Average demand: 32KWh/day						

Table 27: The Pharmacy with Its Appliances and Their Operating Times for A Typical Working Day

Undoubtedly, cooling appliances such as air conditioners, medical refrigerators and freezers consume the highest amount of energy; see the breakdown of power consumption by these appliances in Figure 35. This is due to the fact that all medicines in a pharmacy have consistent cooling requirements – they must always be stored either in cold conditions (between 2-8°C) or storage that is not above 25°C (Care Inspectorate, 2016).

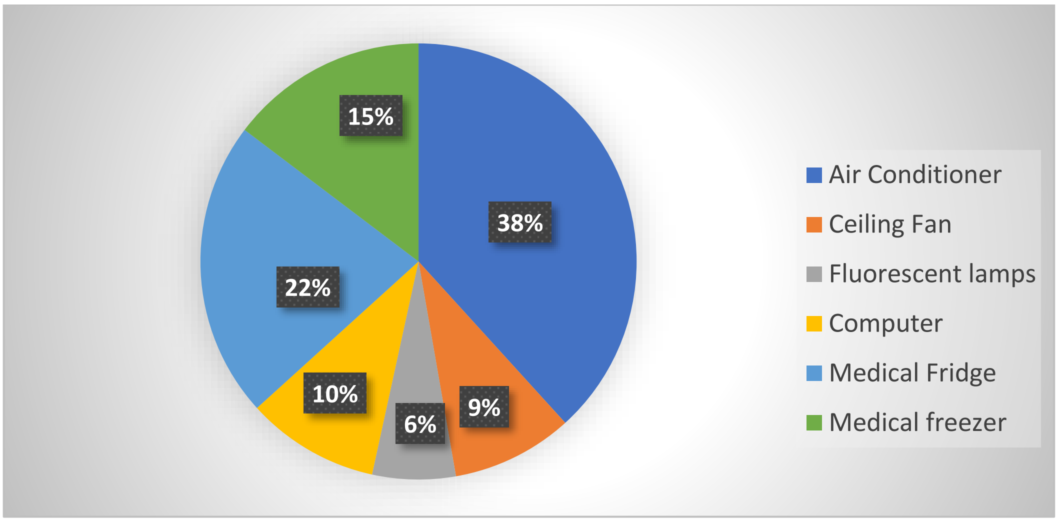


Figure 35: Breakdown of Electricity Consumption in the Pharmacy

Pharmacy Demand Data Optimisation

The hourly demand was monitored during both summer and winter in order to achieve the clearest possible understanding of the pharmacy's electric loads. The analysis was based on the pharmacy's opening hours, 8am-10pm. For both the summer and winter cases, the demand during peak working hours was found to be higher by 75% than the demand in the non-working hours. Figures 36 and 37 describe the hourly demand performance for the pharmacy in summer and winter following the data optimization.

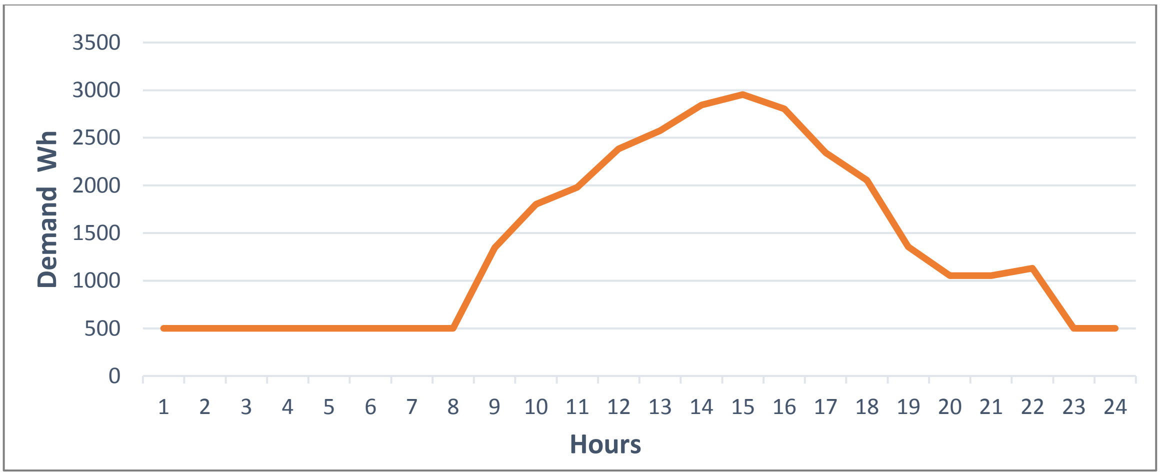


Figure 36: Estimated Hourly Demand Performance for the Pharmacy in A Typical Summer Day (August)

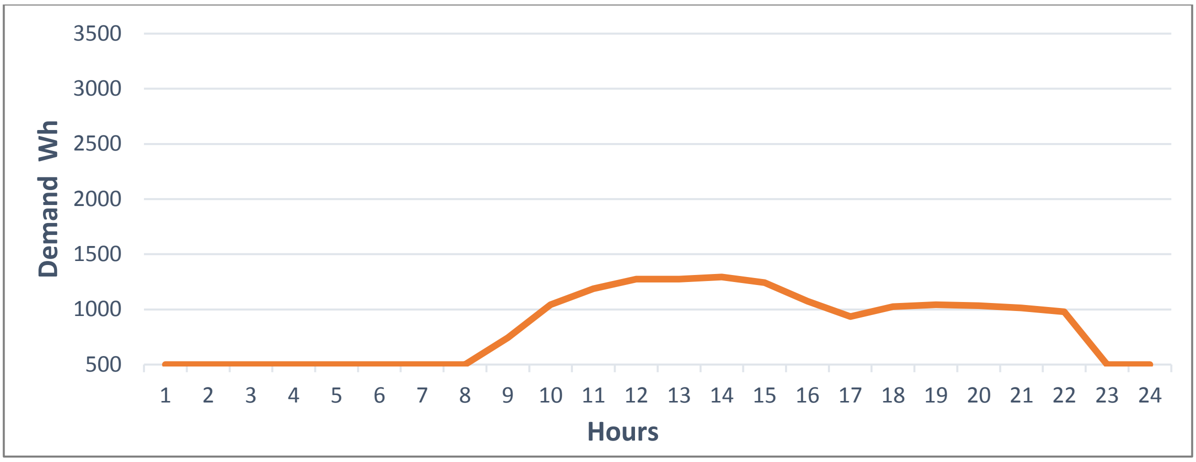
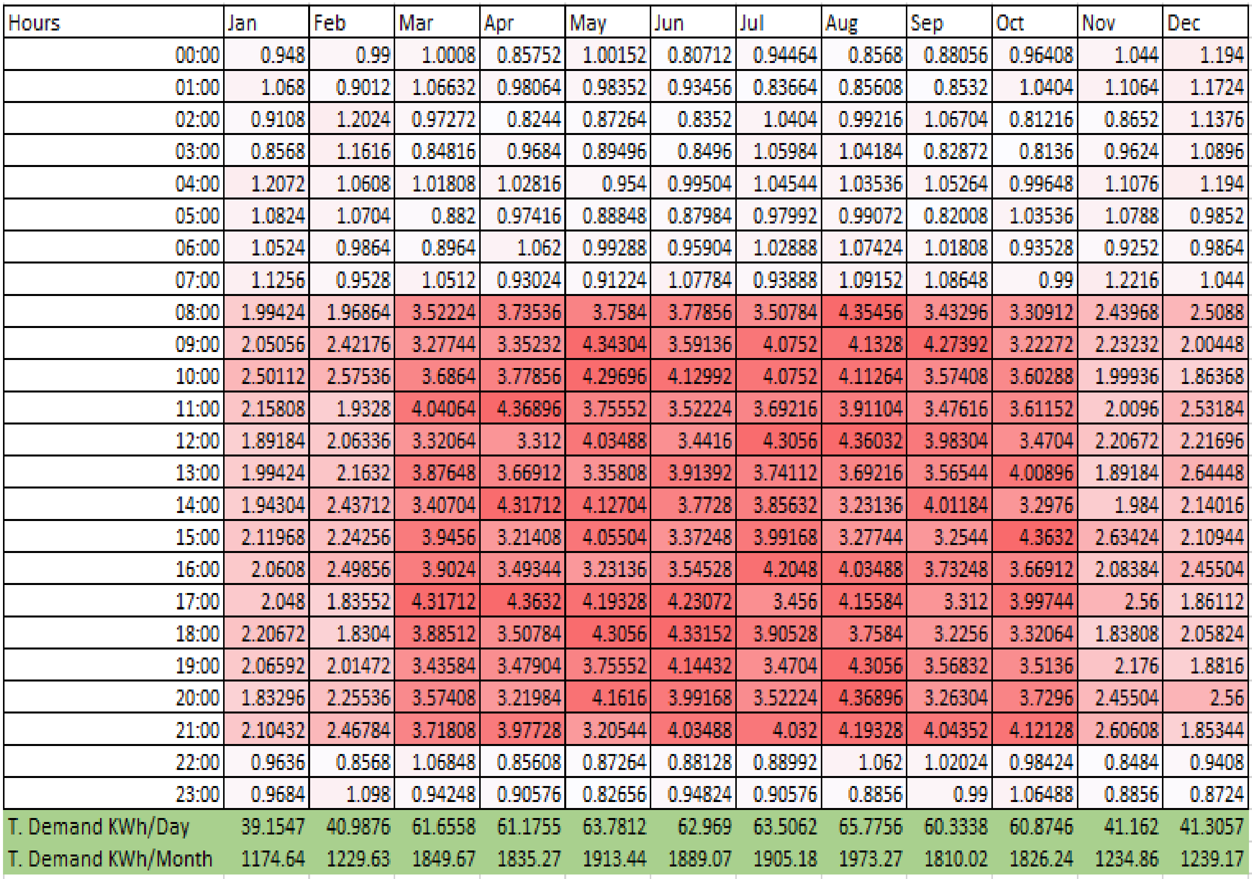


Figure 37: Estimated Hourly Demand Performance for the Pharmacy in A Typical Winter Day (December)

The final total estimated demand of the two pharmacies throughout the year, calculated from the original hourly data, is displayed below in Table 28.



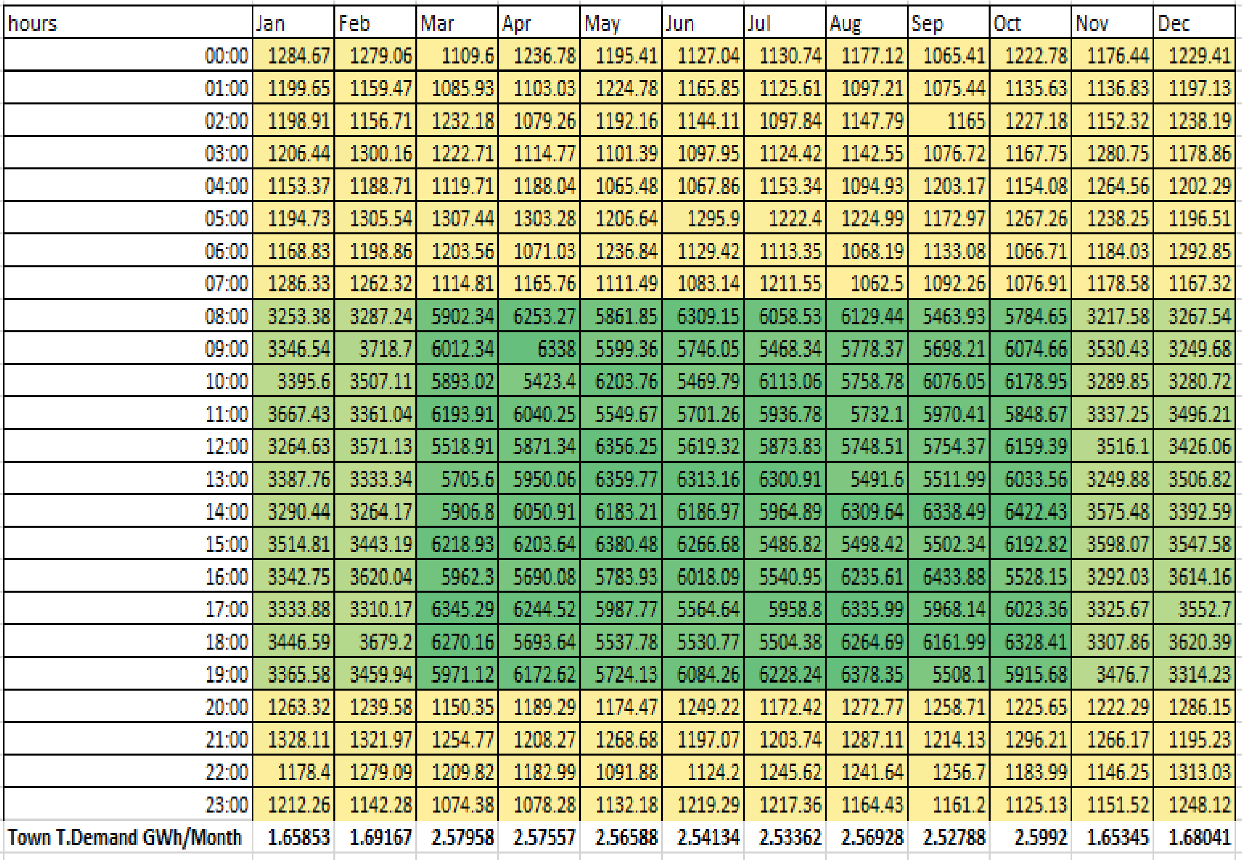
Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	0.948	0.99	1.0008	0.85752	1.00152	0.80712	0.94464	0.8568	0.88056	0.96408	1.044	1.194
01:00	1.068	0.9012	1.06632	0.98064	0.98352	0.93456	0.83664	0.85608	0.8532	1.0404	1.1064	1.1724
02:00	0.9108	1.2024	0.97272	0.8244	0.87264	0.8352	1.0404	0.99216	1.06704	0.81216	0.8652	1.1376
03:00	0.8568	1.1616	0.84816	0.9684	0.89496	0.8496	1.05984	1.04184	0.82872	0.8136	0.9624	1.0896
04:00	1.2072	1.0608	1.01808	1.02816	0.954	0.99504	1.04544	1.03536	1.05264	0.99648	1.1076	1.194
05:00	1.0824	1.0704	0.882	0.97416	0.88848	0.87984	0.97992	0.99072	0.82008	1.03536	1.0788	0.9852
06:00	1.0524	0.9864	0.8964	1.062	0.99288	0.95904	1.02888	1.07424	1.01808	0.93528	0.9252	0.9864
07:00	1.1256	0.9528	1.0512	0.93024	0.91224	1.07784	0.93888	1.09152	1.08648	0.99	1.2216	1.044
08:00	1.99424	1.96864	3.52224	3.73536	3.7584	3.77856	3.50784	4.35456	3.43296	3.30912	2.43968	2.5088
09:00	2.05056	2.42176	3.27744	3.35232	4.34304	3.59136	4.0752	4.1328	4.27392	3.22272	2.23232	2.00448
10:00	2.50112	2.57536	3.6864	3.77856	4.29696	4.12992	4.0752	4.11264	3.57408	3.60288	1.99936	1.86368
11:00	2.15808	1.9328	4.04064	4.36896	3.75552	3.52224	3.69216	3.91104	3.47616	3.61152	2.0096	2.53184
12:00	1.89184	2.06336	3.32064	3.312	4.03488	3.4416	4.3056	4.36032	3.98304	3.4704	2.20672	2.21696
13:00	1.99424	2.1632	3.87648	3.66912	3.35808	3.91392	3.74112	3.69216	3.56544	4.00896	1.89184	2.64448
14:00	1.94304	2.43712	3.40704	4.31712	4.12704	3.7728	3.85632	3.23136	4.01184	3.2976	1.984	2.14016
15:00	2.11968	2.24256	3.9456	3.21408	4.05504	3.37248	3.99168	3.27744	3.2544	4.3632	2.63424	2.10944
16:00	2.0608	2.49856	3.9024	3.49344	3.23136	3.54528	4.2048	4.03488	3.73248	3.66912	2.08384	2.45504
17:00	2.048	1.83552	4.31712	4.3632	4.19328	4.23072	3.456	4.15584	3.312	3.99744	2.56	1.86112
18:00	2.20672	1.8304	3.88512	3.50784	4.3056	4.33152	3.90528	3.7584	3.2256	3.32064	1.83808	2.05824
19:00	2.06592	2.01472	3.43584	3.47904	3.75552	4.14432	3.4704	4.3056	3.56832	3.5136	2.176	1.8816
20:00	1.83296	2.25536	3.57408	3.21984	4.1616	3.99168	3.52224	4.36896	3.26304	3.7296	2.45504	2.56
21:00	2.10432	2.46784	3.71808	3.97728	3.20544	4.03488	4.032	4.19328	4.04352	4.12128	2.60608	1.85344
22:00	0.9636	0.8568	1.06848	0.85608	0.87264	0.88128	0.88992	1.062	1.02024	0.98424	0.8484	0.9408
23:00	0.9684	1.098	0.94248	0.90576	0.82656	0.94824	0.90576	0.8856	0.99	1.06488	0.8856	0.8724
T. Demand KWh/Day	39.1547	40.9876	61.6558	61.1755	63.7812	62.969	63.5062	65.7756	60.3338	60.8746	41.162	41.3057
T. Demand KWh/Month	1174.64	1229.63	1849.67	1835.27	1913.44	1889.07	1905.18	1973.27	1810.02	1826.24	1234.86	1239.17

Table 28: Total Estimated Electricity Consumption for the Two Pharmacies in East Soba, Sudan

3.1.4 Total Demand of East Soba Town

After examining the demand of the residential, commercial, and public services buildings, a fair estimate of the town’s total demand has been accomplished. This will be utilised later in the modelling software as a load profile to enable selection of the optimal renewable energy supply options. The overall demand estimate is subject to a difference in value of 5-10%, which incorporates any feasible fluctuations in the consumption data. The total demand in the town of East Soba was estimated to be around 27GWh annually.

Table 29 and Figure 38 below, outline the total estimated annual electricity demand (GWh) of East Soba on both an hourly and monthly breakdown.



hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	1284.67	1279.06	1109.6	1236.78	1195.41	1127.04	1130.74	1177.12	1065.41	1222.78	1176.44	1229.41
01:00	1199.65	1159.47	1085.93	1103.03	1224.78	1165.85	1125.61	1097.21	1075.44	1135.63	1136.83	1197.13
02:00	1198.91	1156.71	1232.18	1079.26	1192.16	1144.11	1097.84	1147.79	1165	1227.18	1152.32	1238.19
03:00	1206.44	1300.16	1222.71	1114.77	1101.39	1097.95	1124.42	1142.55	1076.72	1167.75	1280.75	1178.86
04:00	1153.37	1188.71	1119.71	1188.04	1065.48	1067.86	1153.34	1094.93	1203.17	1154.08	1264.56	1202.29
05:00	1194.73	1305.54	1307.44	1303.28	1206.64	1295.9	1222.4	1224.99	1172.97	1267.26	1238.25	1196.51
06:00	1168.83	1198.86	1203.56	1071.03	1236.84	1129.42	1113.35	1068.19	1133.08	1066.71	1184.03	1292.85
07:00	1286.33	1262.32	1114.81	1165.76	1111.49	1083.14	1211.55	1062.5	1092.26	1076.91	1178.58	1167.32
08:00	3253.38	3287.24	5902.34	6253.27	5861.85	6309.15	6058.53	6129.44	5463.93	5784.65	3217.58	3267.54
09:00	3346.54	3718.7	6012.34	6338	5599.36	5746.05	5468.34	5778.37	5698.21	6074.66	3530.43	3249.68
10:00	3395.6	3507.11	5893.02	5423.4	6203.76	5469.79	6113.06	5758.78	6076.05	6178.95	3289.85	3280.72
11:00	3667.43	3361.04	6193.91	6040.25	5549.67	5701.26	5936.78	5732.1	5970.41	5848.67	3337.25	3496.21
12:00	3264.63	3571.13	5518.91	5871.34	6356.25	5619.32	5873.83	5748.51	5754.37	6159.39	3516.1	3426.06
13:00	3387.76	3333.34	5705.6	5950.06	6359.77	6313.16	6300.91	5491.6	5511.99	6033.56	3249.88	3506.82
14:00	3290.44	3264.17	5906.8	6050.91	6183.21	6186.97	5964.89	6309.64	6338.49	6422.43	3575.48	3392.59
15:00	3514.81	3443.19	6218.93	6203.64	6380.48	6266.68	5486.82	5498.42	5502.34	6192.82	3598.07	3547.58
16:00	3342.75	3620.04	5962.3	5690.08	5783.93	6018.09	5540.95	6235.61	6433.88	5528.15	3292.03	3614.16
17:00	3333.88	3310.17	6345.29	6244.52	5987.77	5564.64	5958.8	6335.99	5968.14	6023.36	3325.67	3552.7
18:00	3446.59	3679.2	6270.16	5693.64	5537.78	5530.77	5504.38	6264.69	6161.99	6328.41	3307.86	3620.39
19:00	3365.58	3459.94	5971.12	6172.62	5724.13	6084.26	6228.24	6378.35	5508.1	5915.68	3476.7	3314.23
20:00	1263.32	1239.58	1150.35	1189.29	1174.47	1249.22	1172.42	1272.77	1258.71	1225.65	1222.29	1286.15
21:00	1328.11	1321.97	1254.77	1208.27	1268.68	1197.07	1203.74	1287.11	1214.13	1296.21	1266.17	1195.23
22:00	1178.4	1279.09	1209.82	1182.99	1091.88	1124.2	1245.62	1241.64	1256.7	1183.99	1146.25	1313.03
23:00	1212.26	1142.28	1074.38	1078.28	1132.18	1219.29	1217.36	1164.43	1161.2	1125.13	1151.52	1248.12
Town T.Demand GWh/Month	1.65853	1.69167	2.57958	2.57557	2.56588	2.54134	2.53362	2.56928	2.52788	2.5992	1.65345	1.68041

Table 29: Total Hourly Estimated Demand for East Soba, Sudan

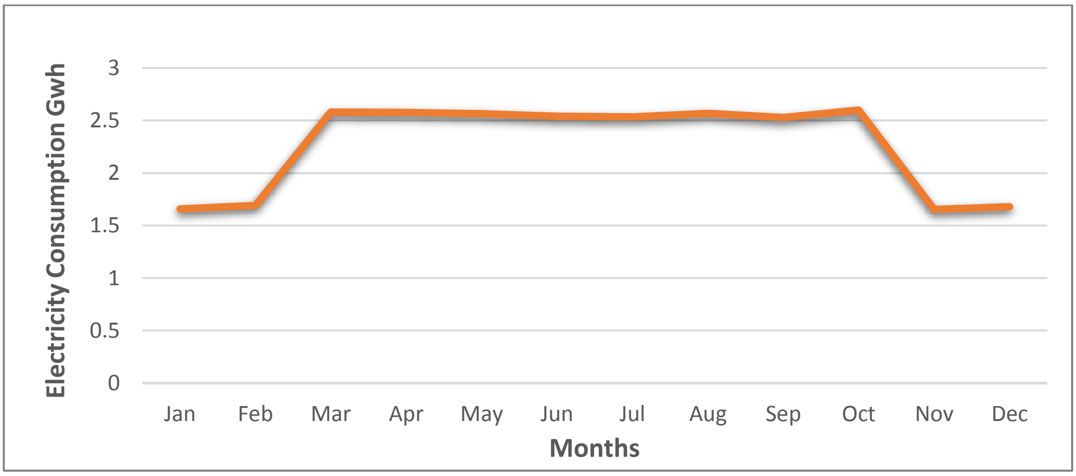


Figure 38: The Total Monthly Estimated Electricity Consumption for East Soba, Sudan

3.2 Analysing the Town's Renewable Resources

Four different renewable energy generation options have been examined for the supply analysis as previously discussed in the literature review. Energy generation from wind and hydro were not nominated to be analysed further since they present poor potential in the town and construction difficulties. Solar energy and anaerobic digestion were selected since they present good potential, due to the excellent solar resource and availability of waste in the area.

The daily average solar global horizontal irradiance in East Soba was shown to be 6.3 KWh/m2/day. The average monthly solar global horizontal irradiance, and clearness index, were taken from Solar Energy Database and NASA Surface Meteorology, after considering the longitudes of 32° 41' 03.8” East, and latitudes of 15° 30' 05.0" North (NASA, 2019). Full illustration is shown below in Figure 39.

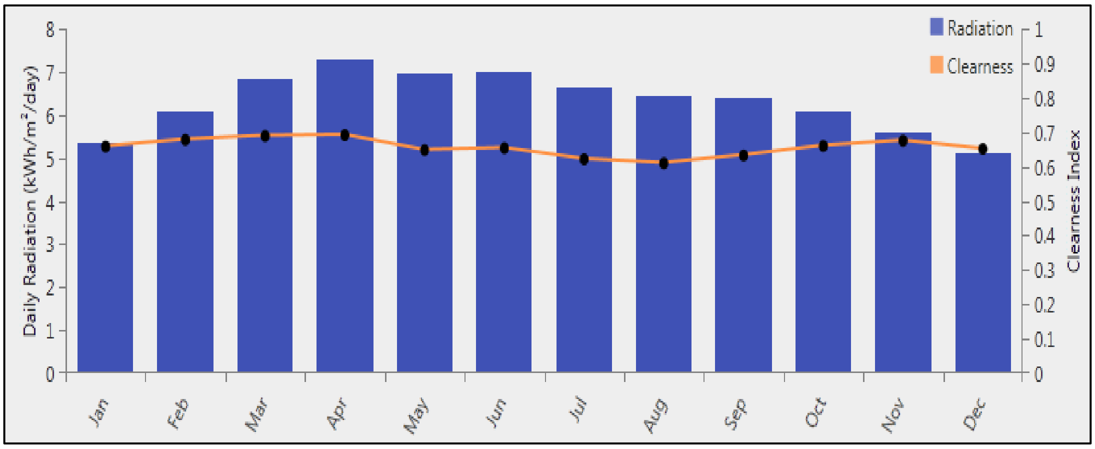


Figure 39: Monthly Average Solar Global Horizontal Irradiance for East Soba, Sudan (NASA, 2019)

The organic waste in the town was analysed and estimated from various comparable case-studies which have geographical, agricultural and climatic similarities. It was found that the majority of the waste is municipal household, agricultural, and animal manure, based upon a total annual average of 5,258 Tonnes. This was calculated after taking into account the town’s population of 20,000 people, 200 animals including cows, sheep and poultry, and 20 agricultural plantations, producing mainly maize and wheat (Rabah et al 2016). Moreover, each inhabitant in the town was estimated to produce an average of 0.3kg waste per day, each animal producing an average of 17kg manure per day, and each crop field was predicted to generate 250kg waste per day (The world bank, 2010). Full description of the total feedstock is demonstrated below in Table 30.

Types	Municipal Household Waste	Animal Manure	Farmlands Waste
Contains	Food residue, vegetable residue, baking and cheese residue	Fresh cattle muck, sheep muck, poultry excrement	Maize grain silage, Wheat straw
Amount of Waste (Ton/Year)	2,190	1,241	1,826
Total Feedstock (Ton/Year)	5,258		

Table 30: Full Description of the Total Feedstock in East Soba, Sudan

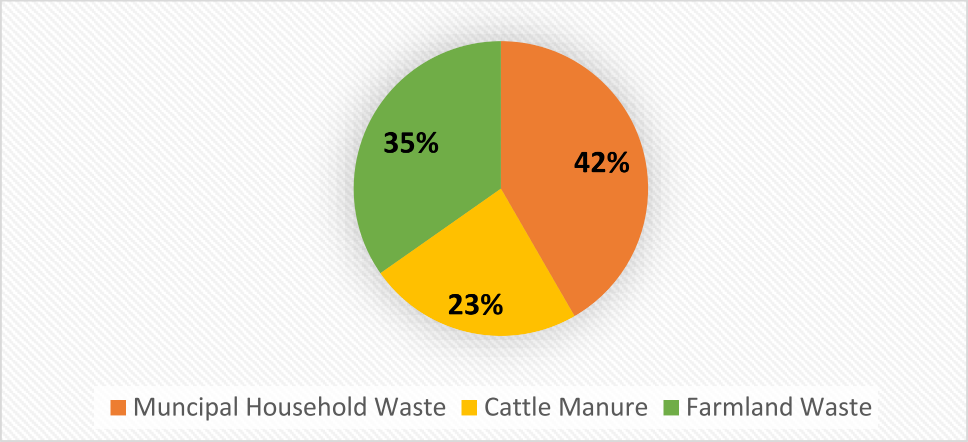


Figure 40: Breakdown of East Soba Feedstock by Percentage

3.3 Modelling of Energy Demand and Supply

3.3.1 Simulation Tools

Various energy modelling tools have been evaluated in the literature chapter. Only three were found as the most appropriate tools for this integrated energy system. These tools were found to have the capability to perform technical and economical measurements for the system. These tools are: HOMER, the AD calculator developed by Geraghty et al. (2004), and The Anaerobic Digestion Economic Assessment Tool.

3.3.2 Modelling of the Existing Energy System

Currently, the town is supplied entirely by a non-renewable energy system, which is the main grid. However, there is a daily average of 8 hours of scheduled load-shedding during the summer months, which are March until October every year. This load-shedding lasts from approximately 9am until 5pm according to information from The Sudanese Electricity Distribution Company (SEDC, 2015).

In light of this, the town's total electricity demand was estimated after considering the residential, commercial and public services sectors. The total annual electricity demand is calculated to be around 27GWh. The daily electrical demand was estimated to be 75,491KWh with a peak of 10,525KW, accounting for a 5-10% reserve margin. Figure 41 below displays a schematic model of the current energy system in the town, and Figure 42 expresses the town's total current electrical demand throughout the year.

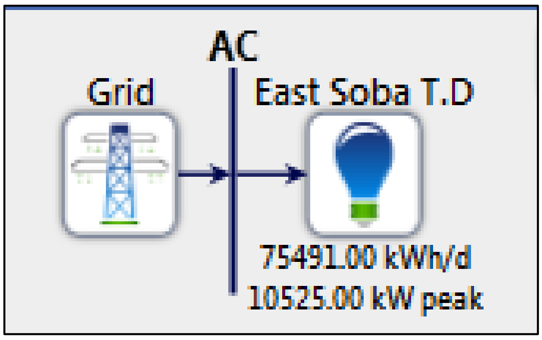


Figure 41: Schematic of East Soba's Current Energy System

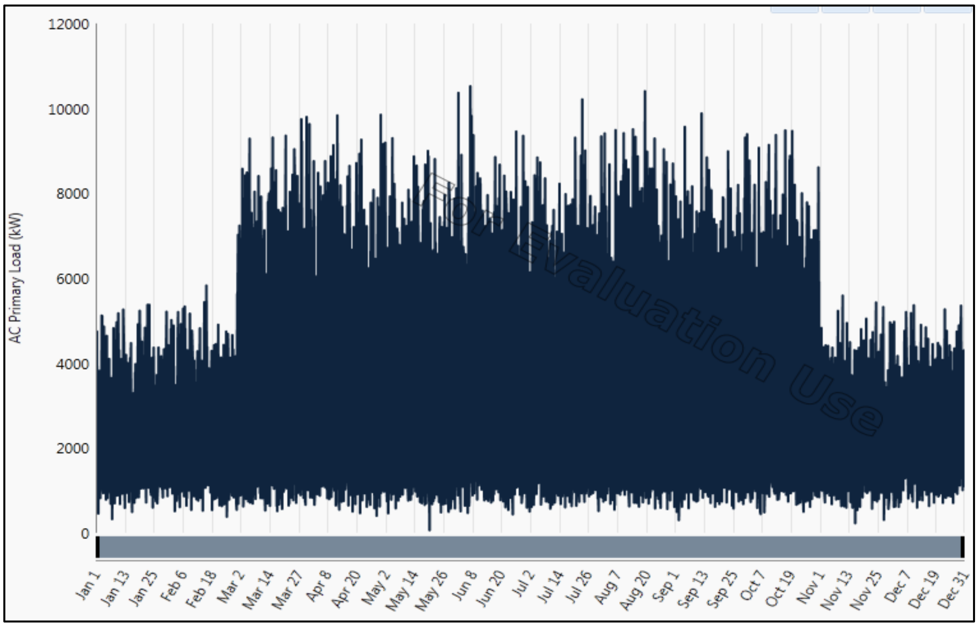


Figure 42: East Soba's Total Current Electrical Demand and Peak Throughout the Year

3.3.2.1 Base Model Configuration Description

Components	Capacity (KW)	Production (GWh/Year)	Capacity Factor (%)	Renewable Penetration (%)	Surplus Energy (%)
Grid	999,999	27.55	100	0	0

Table 31: Current Base Model Configuration Details

3.3.2.2 Base Model Results

Modelling the current existing grid energy system through HOMER, certain features have been evaluated, explained below in Table 32. Currently, as shown, there is no renewable penetration in this system. The current average electricity price in Sudan has been estimated as 0.16 $/KWh (RCREEE, 2012), which is an unsustainably high price for citizens. The CO2 level was found to be roughly 17,414 annual tonnes, this was calculated by multiplying the current estimated CO_2 emissions 632 g/KWh, by the total annual electrical production 27.55GWh.

Features of the Current Existing Grid System	Values
COE ($/kWh)	0.16
Grid CO_2 emissions (g/KWh)	632
Total annual CO_2 emissions (Ton/year)	17,414

Table 32: East Soba's Current Existing Energy System Features

3.3.2.3 Base Model Performance

In summer, June was found to be the month with the highest energy consumption, with a typical June day peaking at 9000-1000KW. Moreover, in winter, December is the month with the lowest power consumption, peaking at 4000-5000KW approximately. Thus, for more accurate modelling analysis, two typical days in June and December were selected to allow accurate measurements of the system's performance in this project via HOMER. Figure 43 below illustrates a typical day's grid supply in June, which clearly highlights that there is no electricity provided by the grid from 9am-5pm.

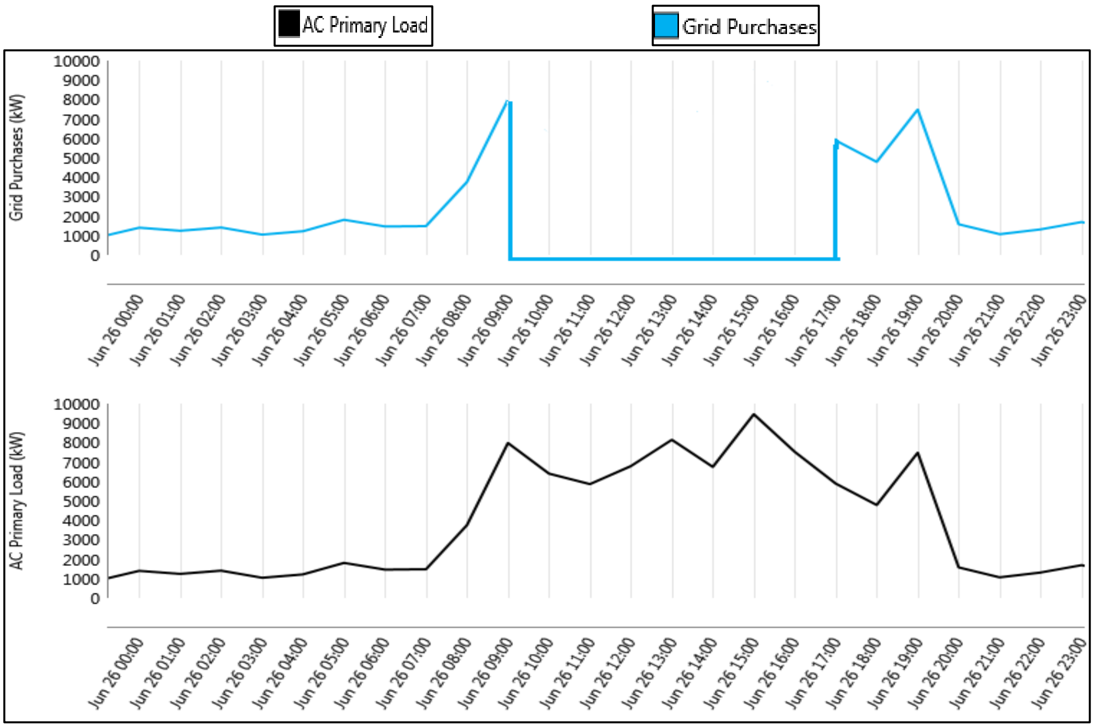


Figure 43: The Performance of the Power Output for the Base Model in Summer (26th June)

However, during the winter months, which are typically November, December, January and February, the current exiting grid energy system doesn't usually experience any sort of load-shedding at any time. Therefore, the town's demand during this period is completely met through the main grid without any issues, as shown below in Figure 44 which displays the grid performance of a typical winter day in East Soba.

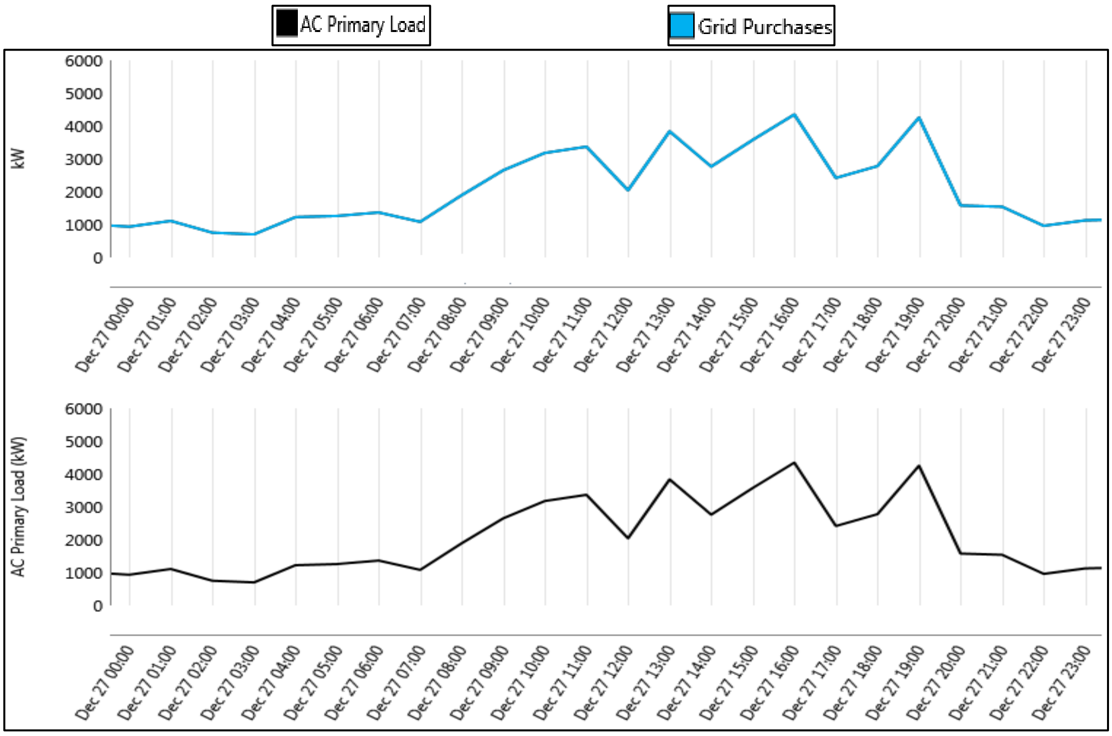


Figure 44: The Performance of the Power Output for the Base Model in Winter (27th December)

3.3.3 Modelling of Alternative Energy Systems

The objective of this modelling was to develop a hybrid energy system that can supply reliable and sustainable power to the town of East Soba. Seven main criteria were identified as standard for checking the feasibility of the system – the system's load-shedding coverage ability during summer months, the total renewable fraction, the cost of electricity (COE), the net present cost (NPC), the system's capital cost, the payback period, and the carbon dioxide emissions level.

The core components of this proposed hybrid system were solar Photovoltaic panels (PV), an Anaerobic Digestion (AD) plant, a converter, and/or a storage battery. Each of these components has various essential input parameters and assumptions, which impacted on the modelling results. Some parameters had to be estimated as there were difficulties adjusting them when using HOMER and the AD spreadsheet Excel calculator. Therefore, subsequently, each component will be explained, recognizing pertaining parameters relevant to simulation.

3.3.3.1 Photovoltaic System

The main drive for the selection of PV for analysis, was, firstly, the excellent solar irradiance in East Soba throughout the year. Secondly, PV is easy to implement because certain national problems such as political instability, financial constraints, and legal frameworks can be bypassed; PV have a low capital cost. However, there are some drawbacks related to the PV technology; energy generation for this technology is restricted to hours where there is sunlight. Also, a relatively large area is needed to implement the solar panels as a PV farm, for town energy production scale.

There are different types of solar PV panels, desponding on the size and the type of cells used; PV panels vary at an output of 150-345w per panel. The panel model Canadian Solar Dymond CS6K-285M-FG was chosen for the HOMER modelling. The technical specifications of this panel are summarised below in Table 33.

PV Technical Specifications	Value
Name	Canadian Solar Dymond CS6K-285M-FG
Type	Flat plate
Manufacturer	Canadian Solar
Cell type	Mono-crystalline
Rated Capacity (kW)	0.285
Panel Efficiency (%)	17.33
Temperature Coefficient	- 0.41
Operating Temperature C°	45
Derating Factor (%)	88
Ground Reflection (%)	20
Lifetime (years)	25

Table 33: PV Technical Specifications

With regards to the financial parameters of PV energy generation, the capital cost was estimated to be around \$1388/KW, which was based on a report published by IRENA (2018). Furthermore, the PV O&M cost was considered to be 14 \$/KW; this price includes the inverter maintenance cost as well, and was based on a study conducted in the USA by the National Renewable Energy Laboratory (NREL), reported on the New Energy Update website (2019). In addition, IRENA (2018) assumed that the replacement cost of the PV system is approximately 50% of the capital cost. Full description of PV financial elements is displayed below in Table 34.

PV Cost Specifications	Value
Capital cost (\$/KW)	1,388
O&M (\$/KW/year)	14
Replacement cost (\$)	50% of the capital cost
Interest rate (%)	6
Discount rate (%)	6

Table 34: PV Financial Specifications

3.3.3.2 Anaerobic Digestion System

An Anaerobic Digestion plant is an essential component of this proposed integrated energy system. To simulate it in further detail, the Economic Assessment Excel spreadsheet was run; this checked the possibility of biogas, and electrical power from AD. Three main types of the town's organic waste have been identified and analysed in the literature chapter, which are: municipal household waste 42%, farmlands waste 35%, and cattle manure 23%. The total feedstock was estimated to be around 5,258 tonnes/year. Following the input of this feedstock into the AD simulation tool, the potential biogas product is predicted as below in Table 35.

Feedstock	Amount of Feedstock (Ton /Year)	Biogas Production (m^3 /Year)	Biogas Yield (m^3/Ton)
Livestock Manures	1,242	82,904	67
Farmlands Waste	1,826	678,399	372
Municipal Household Waste	2,190	1,030,771	471
Total	**5,258**	**1,792,074**	**341**

Table 35: The AD System - Biogas Output

The table above highlights that feeding the digester with a combination of several types of feedstock, will increase the production of the biogas yield, which was calculated to be 341m^3/ton. Also, the annual total biogas production was found to be 1.79 million m^3 , after multiplying the total amount of feedstock and the total biogas yield. It is also important to point out that, the Biogas yield was calculated after considering the standard biogas potential per tonnes in every component of the current feedstock, this is shown below in Figure 45.

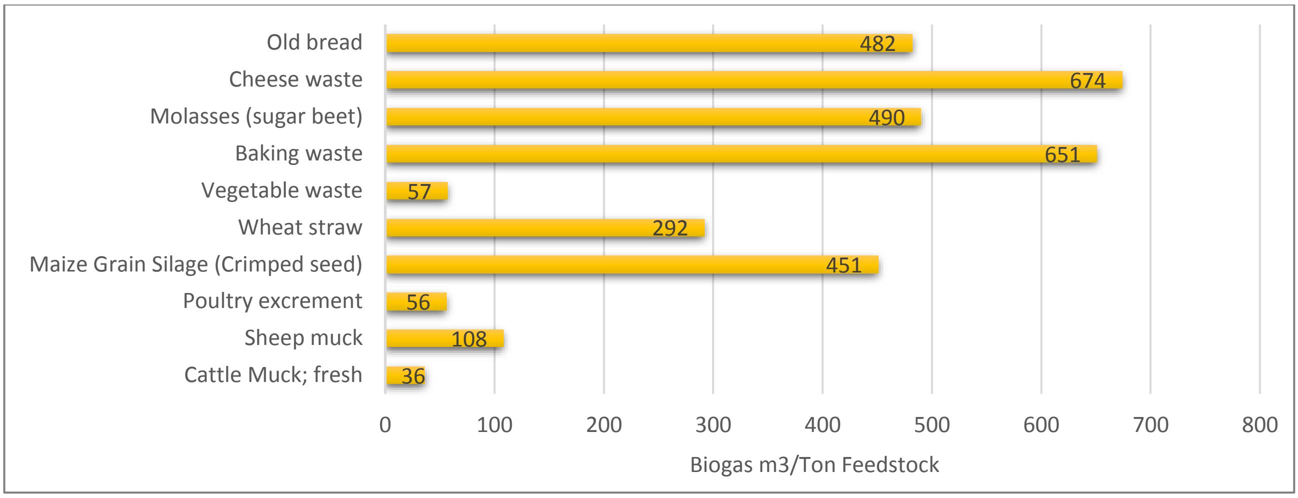


Figure 45: Typical Biogas Yields (m3/ton) for the Current Feedstock's Components

A digester with a capacity of 650m^3 ,was selected as most appropriate for the system; it was designed based on the monthly volume of feedstock, and the retention time. Retention time is defined as the period required for the digester to process the feedstock - in this analysis the retention time has been estimated at around 45 days. The capacity of the digester was calculated from the following equation:

$$\text{The Digester Capacity} \Rightarrow \frac{\text{Total annual feedstock} \div 365\text{ (days)} =}{\text{Retention time (days)}} \quad \frac{5{,}258 \div 365}{45} = \underline{650\text{m}^3}$$

It was assumed that if there is a constant volume of feedstock supplying the digester every month, which has a potential value, if gathered from the local area, of around 438 tonnes, then the production of biogas every month would be constant as well. This monthly biogas output was therefore calculated to be 149,339 m^3. Figure 46 below demonstrates the monthly allocation of feedstock and biogas generation.

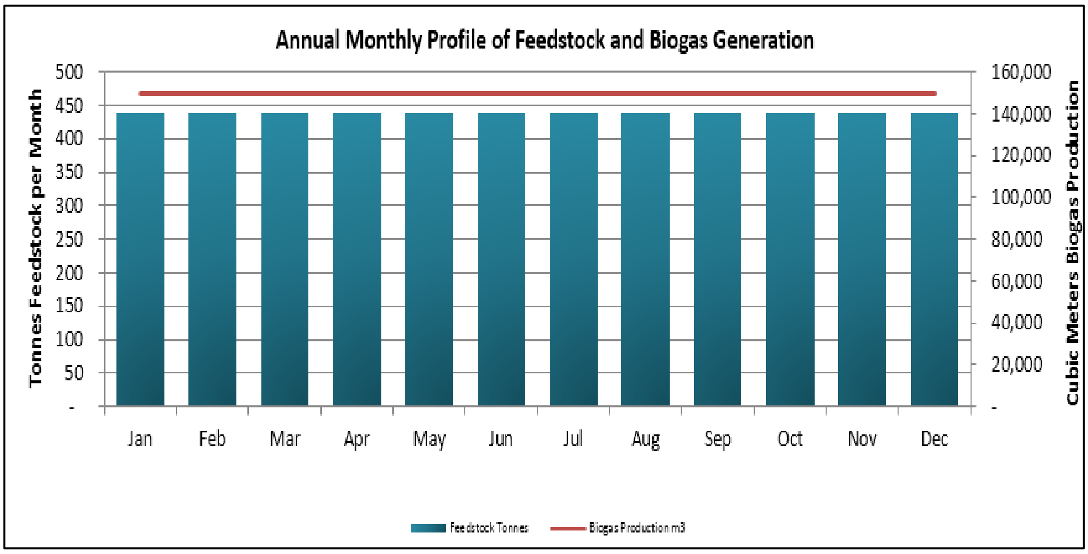


Figure 46: The Monthly Allocation of Feedstock and Biogas Generation

This produced biogas is then converted to electricity through a combination of heat and power (CHP). The electrical power from the AD was calculated through the AD excel spreadsheet tool as shown in table. . However, some important specifications were taken into consideration before the conversion process. Firstly, it was estimated that one cubic meter of biogas can generate 2.66 KWh of electrical energy, taking into account that the biogas has an average content of 60% methane. Secondly, the electrical efficiency of CHP was considered to be 45%, and losses and inefficiencies were 12%, according to the Andersons centre (2010). Table 36 below presents the electrical output of the AD system.

Total Annual Electricity Generation (GWh)	Electricity Generation Capacity (KW)
4.76	**544**

Table 36: The Electrical Output of the AD System

It is significant that East Soba has a total annual electricity demand of 27GWh, whereas the total annual electricity generation from the AD would be 4.7GWh; therefore, the percentage of the town's total demand which the AD can cover is only around 18%. Additionally, other AD technical specifications and assumptions had to be taken into consideration, these are summarised below in Table 37.

AD Technical Specifications	Value
Minimum Digester Capacity (m^3)	650
Digester Type	Mesophilic
Digester Temperature (C °)	35
Retention Time (Days)	45
Feedstock Dry Matter (%)	57
Overall Biogas Yields (M3/Ton)	341
Estimated Methane Content of Biogas (%)	60
Energy Content of Biogas (KWh/ m^3)	2.66
CHP Losses and Inefficiency (%)	12
CHP Electrical Efficiency (%)	45
Required Parasitic Load (KWh/Ton Feedstock)	6

Table 37: AD Technical Specifications and Assumptions Summary

Regarding the financial side of AD, it was estimated that a typical AD system has a standard capital cost of 3,000 - $6,000 per KW capacity, according to report from the Andersons centre (2010). In this AD analysis, an average of $3,636/KW has been estimated as a likely capital cost. The capital cost typically includes building and infrastructure costs, and any CHP machinery costs. The maintenance cost was predicted to be 1% of the capital cost according to a comparable case-study conducted by Clegg (2017): the operating and running costs include transportation, labour, general management, land and insurance.

Moreover, the current Sudanese price for selling electricity is approximately $0.16/KWh, taken as an average of peak and off-peak selling prices. The interest rate was taken to be 6%, based on the Sudan Central Bank, with a Repayment Loan Payback period of 15 years; the lifetime of an AD plant is usually around 25 years.

Furthermore, due to lack of information about any feedstock prices in Sudan, it was inferred that there will be no feedstock charge. The Table below shows the full list of AD financial specifications. Following that, AD financial analysis has been performed using the AD Excel spreadsheet tool. Table 38 below breaks down the results in detail.

AD Financial Specifications	Value
Capacity (KW)	544
Renewable fraction (%)	17%
Capital Cost ($Millions)	1.97
Maintenance Cost ($/Year)	19,779
Running Cost ($/Year)	456,765
Electricity Selling Price ($/KWh)	0.16
COE ($/KWh)	0.13
Payback Period (Years)	10
Total Income ($)	519,868
Total NPC (($Millions)	1.68
Accumulative NPV ($)	128,605
Feedstock Price ($)	0
Gate fees ($)	0
Lifetime of AD (Years)	25
Interest Rate (%)	6
Discount Rate (%)	6
CHP Replacement Time (Years)	10-12

Table 38: AD Financial Specifications

3.3.3.3 Converter

A Converter is the device that converts the AC current to DC current, or vice versa. It is important to point out that in the integrated system, the AD produces an AC current, but the Solar PV produces a DC current – therefore, a converter is required for the system.

The converter has been sized based on the power capacity of PV, and the round-trip efficiency of the converter which was considered as 96% (Shahzad et al.,2017). see equation below.

Converter capacity (KW) = PV capacity (KW) × 100/96

The converter related cost and technical specifications are listed below in Table 39.

Converter Specifications	Value
Type	Leonics GTP519S 900KW 700Vdc
Manufacturer	Leonics
Nominal Capacity (KW)	900
Capital Cost ($/KW)	300
Replacement Cost ($/KW)	50% of Capital Cost
O&M ($/Year)	Included Within PV O&M Cost
Inverter Efficiency (%)	96
Lifetime (Years)	25
Rectifier Efficiency (%)	96

Table 39: Converter Specifications

3.3.3.4 Lithium-ion Battery

Due to the stochastic power output from renewable energy sources, dependent on changeable weather conditions, the lithium-ion battery storage was explored in the modelling as a support to the hybrid combination. The Lithium-ion battery will add more stability to the system, and ensure that excess energy is stored, so it can be used during peak loads. The only drawback of a Lithium-ion battery is the high capital cost, in fact, the price reached 1160 $/KWh in 2010, however the cost dropped significantly in 2018 to 176$/KWh, according to a report from Bloomberg NEF (Baker, 2019). Also, it was projected that the replacement cost of the battery system is approximately 50% of the capital cost (IRENA, 2018). Full assumptions and specifications of a li-ion battery are stated below in Table 40.

Battery Specifications	Value
Type	Li-Ion Battery
Typical Nominal Capacity (MWh)	1
Capital Cost ($/MWh)	176,000
Replacement Cost ($)	50% of the Capital Cost
O&M ($/Year)	2% of the Capital Cost
Roundtrip Efficiency (%)	90
Lifetime (Years)	15
Nominal Voltage (V)	600

Table 40: Li-ion Battery Specifications

4 MODELLING RESULTS AND EVALUATION

The current existing grid energy system in East Soba was modelled and used as a base comparison to the modelled alternative integrated energy system. A number of prospective design configurations for the integrated system have been simulated through HOMER software. After examining every design, four main system scenarios have been chosen for assessment, which can be divided as follow:

- A combination of Solar Photovoltaic and the main grid
- A combination of Anaerobic digestion and the main grid
- A combination of Solar Photovoltaic, Anaerobic digestion, and the main grid
- A combination of Solar Photovoltaic, Anaerobic digestion, and battery storage.

The optimisation was carried out for each scenario by varying the capacities of each component, excepting the AD, which was considered to have the same capacity in each scenario, due to waste limitations. Moreover, each scenario was fully modelled and examined based on technical, environmental, and financial criteria, consisting of:

- **Load-Shedding**

This is important to check the ability of scenarios to cover the town's daily 8-hour power outages which last from 9am-5pm during summer months.

- **Renewable Fraction**

The renewable fraction factor can be defined as the fraction of the energy delivered to the town's load that originated from renewable power sources, as in the equation below. The criteria were set to check the capability of scenarios to satisfy at least 50% renewable fraction level.

$$Renewable\ Fraction\ (\%) = 1 - \frac{Non\ renewable\ Production\ (kWhyear)}{Total\ electrical\ Load\ Served\ (kWhyear)}$$

- **Reduction of Carbon Dioxide Emissions**

The carbon emissions that are associated with the grid can be calculated by multiplying the net grid purchases (in KWh) by the CO_2 emission factor (in g/kWh). This was assumed to be 632 kg of CO_2 in HOMER Software (Montero, 2018).

- **Cost of the System**

The cost factor can be divided into cost of electricity (COE), Net present cost (NPC), capital cost and payback period. The cost of electricity produced (COE) is calculated by dividing the total annual cost - which includes maintenance, operation, and loan repayment - over the total electrical energy produced from the system.

Moreover, the Net present cost (NPC) is the present value of all the costs involved in the project such as, installation and operation of any component(s) over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the total net present cost by summing the total discounted cash flow in each year of the project lifetime (Homerenergy.com, 2019).

Furthermore, the payback period is a crucial element of the analysis, as it specifies the time expected for the project to take, before an investment will be returned in the form of income. The payback period is estimated by calculating the Net present value for each year, as previously explained, then calculating the accumulative net present value (Net present value year 1 + Net present value year 2 + Net present value year 3, etc..). This is accumulated by year until the accumulative net present value is a positive number, that year is the payback year (Williams et al., 2012).

4.1 Scenario 1 (PV-Grid)

This scenario investigates the possibility to supply reliable power to the town, with an integrated system of solar PV and the main grid. This scenario consists of a converter device with both AC and DC connections, to ensure that the DC output power from the solar PV can be converted to AC power and reach the town's total demand. The system operates based on a grid-connected method, therefore, any surplus power from the PV will not be wasted, rather it will be directed to the main grid line. Figure 47 below presents a simple schematic of the system in this scenario.

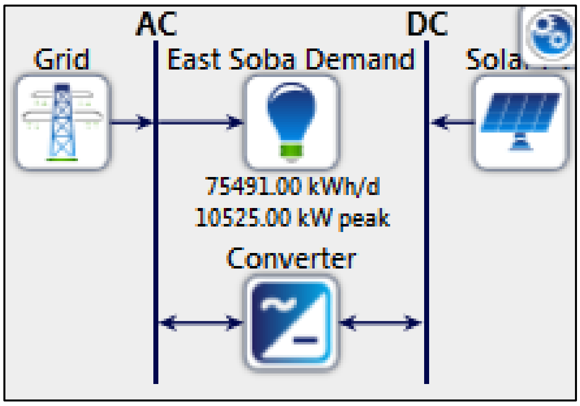


Figure 47: Schematic of Scenario 1

4.1.1 *Scenario 1 Technical Configuration Details*

After sizing various PV capacities, two options were preferred, these are: 15MW PV, and 25MW PV. The technical outcome of both options is described as below in Tables 41 and 42:

Components	Capacity (MW)	Production (GWh/Year)	Capacity Factor (%)	Surplus Sent Back To Grid (GWh/Year)	Renewable Fraction (%)	Load-Shedding Coverage (Hours)	Wasted Energy (%)
PV	15	28.43	73.2	10.17 (27%)	72	1.5	zero
Grid	999,999	10.43	26.8				
Converter	15	-	-				

Table 41: Technical Configuration Outcomes of Scenario 1, Option 1

Components	Capacity (MW)	Production (GWh/Year)	Capacity Factor (%)	Surplus Sent Back to Grid (GWh/Year)	Renewable Fraction (%)	Load-Shedding Coverage (Hours)	Wasted Energy (%)
PV	25	47.39	84.3	26.76	83	6	zero
Grid	999,999	8.82	15.7	(49 %)			
Converter	20	-	-				

Table 42: Technical Configuration Outcomes of Scenario 1, Option 2

4.1.2 Scenario 1 Carbon Emissions & Financial Outcomes

Features	15MW PV + Grid	25MW PV + Grid
Total Annual Co2 Emissions (Ton/Year)	6,595	5,574
Reduction of CO2 Emissions (%)	(62%)	(68%)
COE ($/KWh)	0.077	0.077
Total NPC ($Millions)	30.1	50.2
Initial Capital Cost ($Millions)	25.3	42.1
O&M Cost ($/Year)	210,000	350,000
Payback Period (Years)	8	8

Table 43: Carbon Emissions & Financial Outcomes of Scenario 1

4.1.3 Scenario 1 Power Performance in Summer & Winter

Option 1: 15MW PV + Grid

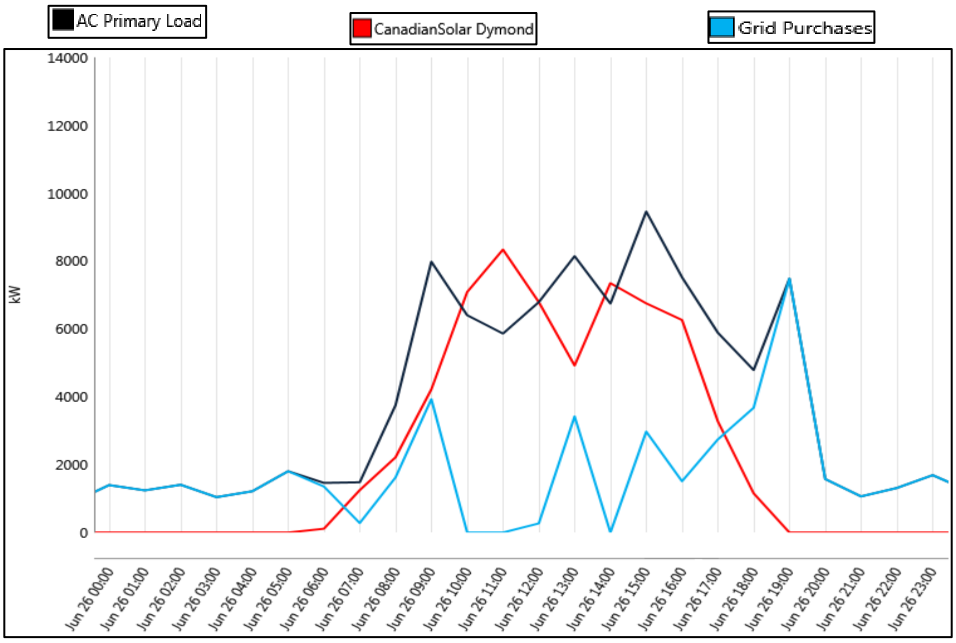


Figure 48: The Performance of the Power Output for Scenario 1, Option 1 in Summer (26th June)

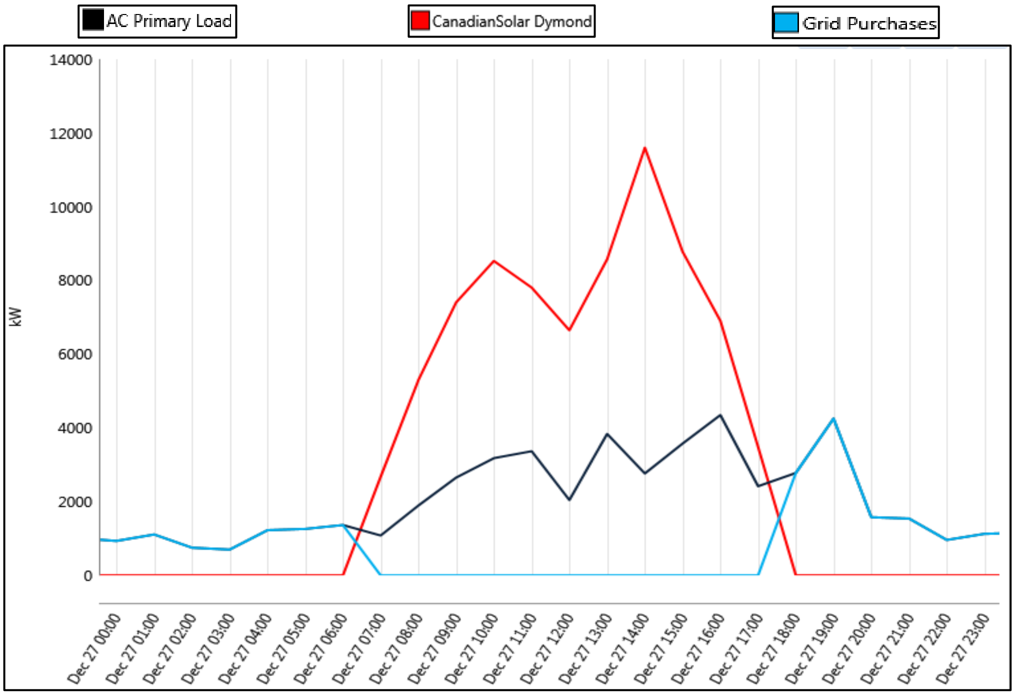


Figure 49: The Performance of the Power Output for Scenario 1, Option 1 in Winter (27th December)

Option 2: 25MW PV + Grid

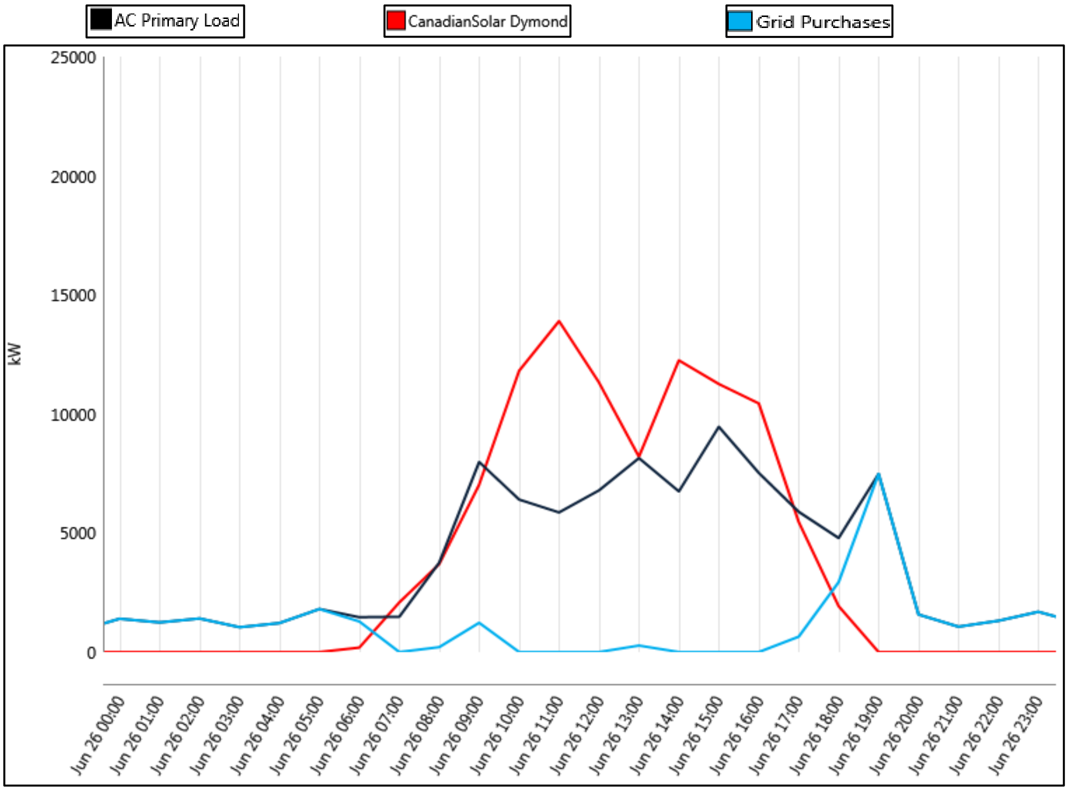


Figure 50: The Performance of the Power Output for Scenario 1, Option 2 in Summer (26th June)

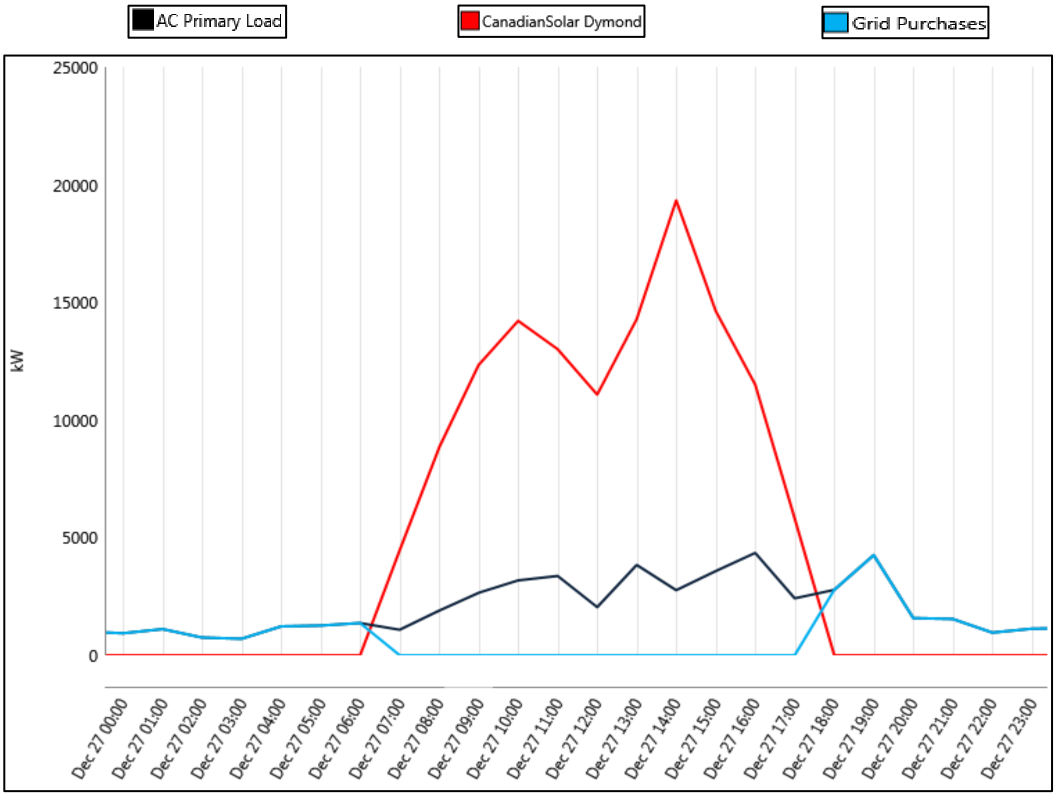


Figure 51: The Performance of the Power Output for Scenario 1, Option 2 in Winter (27th December)

4.1.4 Scenario 1 Evaluation

In this Scenario, both selected options produce power based on a combination of solar PV and the main grid. Both options showed quite similar technical and financial outcomes. Also, neither option wasted any energy, as both are operating based on a grid-connected method which allow any excess power to return to the grid.

In option 1, the PV has a capacity factor of approximately 73%, so the rest of the power was supplied by the grid, which had a capacity factor of almost 26%. Despite the fact that the system scored a high renewable fraction of around 72%, its potential to cover 8 hours of load-shedding was very low as shown in Table 41. During the load-shedding hours the system was only capable of covering 1.5 out of 8 hours of power cut, as shown Figure 48.With regards to winter, where East Soba doesn't face power outages, the 15MW PV component was able to cover 10 out of 24 hours of the daily demand, satisfying the demand from 7am-5pm, without any sort of support from the grid. However, during the night, the 15MW PV didn't have any power to produce due to lack of sun, and therefore the supply came only from the grid, see Figure 49.

In option 2, where a capacity of 25MW for the PV was selected and tested, the system demonstrated a better overall renewable fraction with approximately 83%. The solar PV has resulted in a high capacity factor of 84%, and the grid was only required to generate 15%. In terms of the 8 hours of summer load-shedding, the result in Figure 50 showed that, option 2 has accomplished a supply of approximately 6 hours load-shedding, which is clearly a far better result compared to option 1. In winter, the 25MW PV component achieved 10 hours of comprehensive coverage during the day, from 7am-5pm, however, after 5pm once sunlight diminishes, the grid was able to cover the rest of the night hours, as shown in Figure 51.

In light of carbon emissions, option 1's total annual carbon emissions were evaluated at approximately 6,595 tonnes, with 62% carbon reduction. However, option 2 achieved lower total annual carbon emissions with around 5,574 tonnes, and higher carbon reduction at around 68%. These reduction percentages were calculated after taking into account the 17,414 tonnes of total annual carbon emissions for the base model (see Table 32).

In a comparison between system costs, both options in this scenario have demonstrated a lower COE with $0.077/KWh compares to the base model which has COE of $0.16/KWh. Also, both options have payback periods of 8 years. The differences were most visible regarding the capital cost and NPC, as option 1 was found to have a total capital cost of $25.3M, and NPC of $30.1M, whereas option 2 had a capital cost of $42.1M, and NPC of $50.2M. The variation in these financial elements is logical, because with a higher PV farm capacity, the installation, construction, and operation costs will increase too.

To summarise this Scenario, both options have shown far more feasible results than the base model. However, option 2 with 25MW solar PV and grid, has particularly accomplished higher levels of renewable penetration, reduction of carbon emissions, load-shedding coverage, COE and NPC, while option 1 with 15MW solar PV and grid was superior in only one element which was lower capital cost. Therefore, with overall evaluation, an integrated system of 25MW PV and grid was chosen as more appropriate and feasible option to represent Scenario 1.

4.2 Scenario 2 (AD-Grid)

The aim of this Scenario was to check the feasibility of a system combining Anaerobic Digestion and the grid, without any the PV component. This system has the potential to exploit the town's considerable volume of organic waste and convert it to electricity through the Anaerobic Digestion process, which then can supply the town directly with AC power. The grid will act as a backup for the AD, to either supply the town when there is shortage in AD capacity or import the power from the AD when there is surplus. Figure 52 below expresses a simple schematic of Scenario 2.

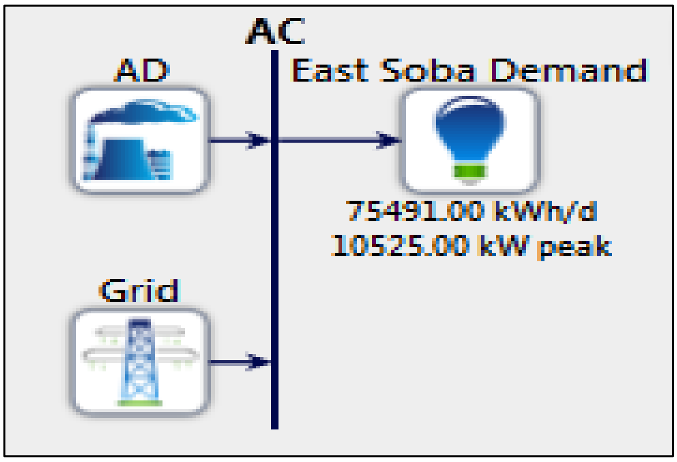


Figure 52: Schematic of Scenario 2

4.2.1 Scenario 2 Technical Configuration Details

Components	Capacity (MW)	Production (GWh/Year)	Capacity Factor (%)	Surplus Sent Back to Grid (GWh/Year)	Renewable Fraction (%)	Load-Shedding Coverage (Hours)	Wasted Energy (%)
AD	544	4.76	17	0	17	0	0
Grid	999,999	22.79	83				

Table 44: Technical Configuration Outcomes of Scenario 2

4.2.2 Scenario 2 Carbon Emissions & Financial Outcomes

Features	544KW AD + Grid
Total Annual CO2 Emissions (Ton/Year)	14,407
Reduction of CO2 Emissions (%)	17
COE ($/KWh)	0.13
Total NPC ($Millions)	1.68
Initial Capital Cost ($Millions)	1.97
O&M Cost ($/Year)	476,544
Payback Period (Years)	10

Table 45: Carbon Emissions & Financial Outcomes of Scenario 2

4.2.3 Scenario 2 Power Performance in Summer & Winter

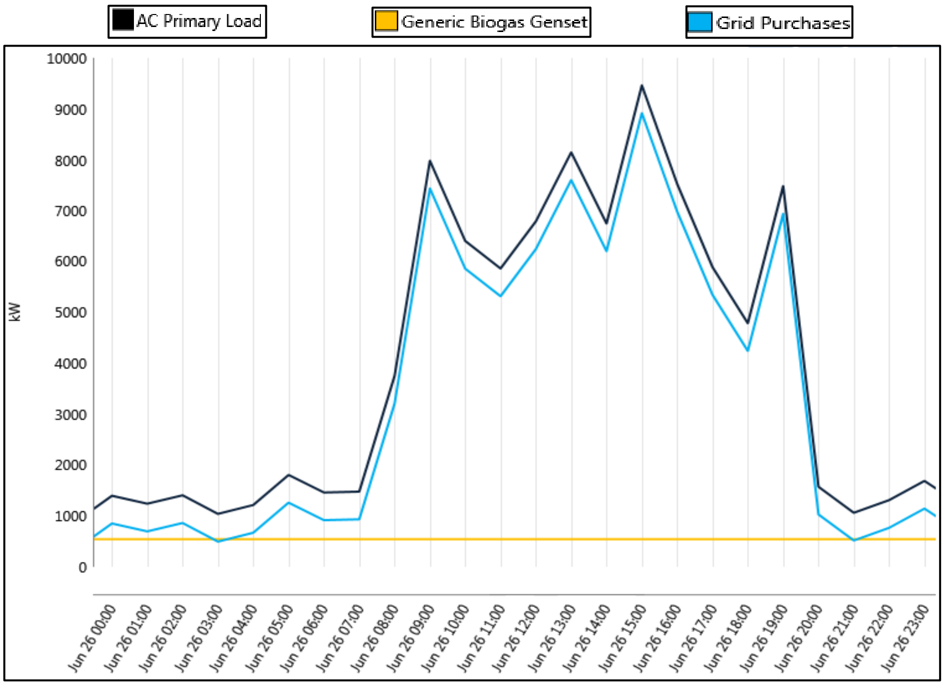


Figure 53: The Performance of the Power Output for Scenario 2 in Summer (26th June)

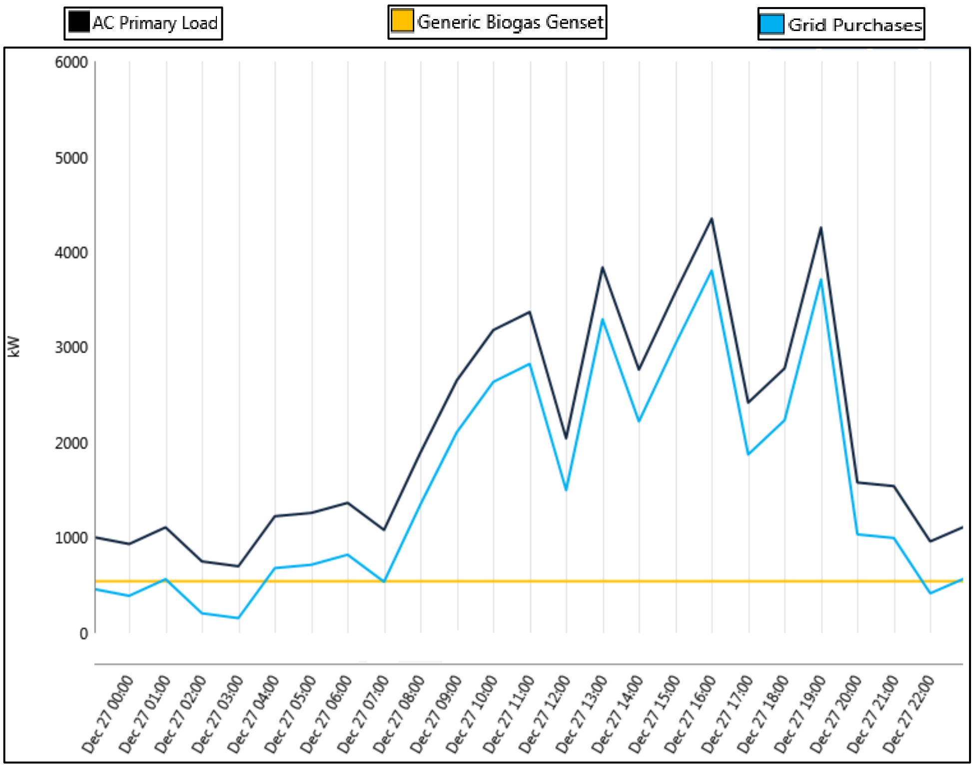


Figure 54: The Performance of the Power Output for Scenario 2 in Winter (27th December)

4.2.4 Scenario 2 Evaluation

In this Scenario, a combination of AD and grid was modelled and tested. The results in Table 44 show that an AD plant with a capacity of 544KW can produce a maximum of annual 4.76GWh, with a capacity factor of only 17%. Nevertheless, the rest of the power had to be supplied from the grid with an annual production of 22.79GWh and a capacity factor of 83%. Applying this scenario, the AD unfortunately cannot cover the whole demand in the town, as the renewable fraction was limited to around 17%.

In the summer, it must be taken into consideration that the grid is down for 8 hours per day, and that the AD plant operates constantly over 24 hours. However, the AD was only able to accomplish approximately less than 10% of the demand during the day, so it would not be able to shorten or stop the power cuts in any significant way. In addition, during the night, the majority of the demand was covered through the grid, and the small remaining percentage was achieved through the AD, Figure 52 explains this point. In winter, despite the fact that the peak demand is almost half that of the summer’s demand, the AD still covered less than 10% of the total demand, thus most of the demand was satisfied through the grid.

With regards to carbon emissions, the hybrid system in this scenario achieved 17% carbon emissions reduction, with estimated annual total carbon emissions of around 14,407 tonnes. This carbon emissions reduction is much lower than Scenario 1, which had achieved 68%. Furthermore, Scenario 2’s system resulted in \$0.13/KWh as the COE, \$1.68M as NPC, \$1.79M as the capital cost, and a payback period of 10 years. The cost of producing electricity through this scenario is still cheaper than the base model.

To conclude this scenario, the combination of AD and the grid has illustrated a poor potential and performance in summer and winter, due to low renewable penetration, and lack of ability to alleviate the daily 8 hours of load-shedding during summer months. Despite the fact that the system had a low capital cost, the COE is still higher than Scenario 1.

4.3 Scenario 3 (PV-AD-Grid)

The aim of this Scenario was to integrate two renewable sources in a grid-connected operational method. The system consisted of Solar PV, AD, grid and converter. The DC power generated by PV was converted to AC power, in order to marry it with the AC power generated by AD and the grid. The total power was then tested to see if it could cover East Soba's demand. When there was surplus power produced from the system, the grid absorbed it efficiently. Figure 55 below displays a schematic of Scenario 3.

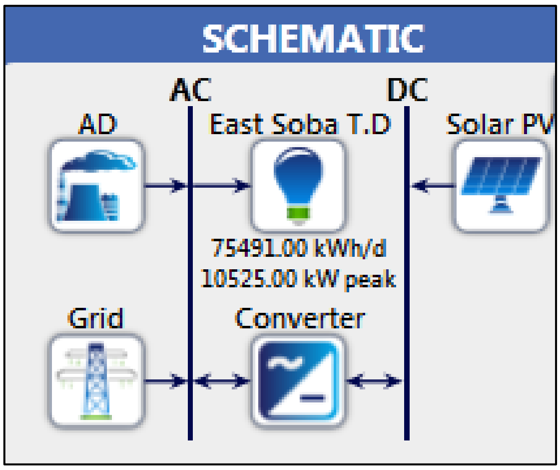


Figure 55: Schematic of Scenario 3

4.3.1 Scenario 3 Technical Configuration Details

HOMER was used to select the optimal sizing capacities for this Scenario. The AD capacity had to be considered at a constant of 544KW, as it relies on the specific amount of organic waste generated in East Soba which is 5,285 tonnes/year. Various PV capacities were checked to discover the optimum performance and the least costly option. Two options of system were concluded, these are: 25MW PV + 544KW AD + grid, and 30MW PV+ 544KW AD+ grid. The technical configuration outcomes of both options are defined below.

Components	Capacity (MW)	Production (GWh/Year)	Capacity Factor (%)	Surplus Sent Back To Grid (GWh/Year)	Renewable Fraction (%)	Load-Shedding Coverage (Hours)	Wasted Energy (%)
PV	25	47.39	83	27.74 (50%)	89	7	0
AD	0.544	3.76	6.58				
Grid	999,999	6.1	10.6				
Converter	25	-	-				

Table 46: Technical Configuration Outcomes of Scenario 3, Option 1

Components	Capacity (MW)	Production (GWh/Year)	Capacity Factor (%)	Surplus Sent Back To Grid (GWh/Year)	Renewable Fraction (%)	Load-Shedding Coverage (Hours)	Wasted Energy (%)
PV	30	56.86	85.7	36.5 (57%)	91	8	zero
AD	0.544	3.76	5.62				
Grid	999,999	5.74	8.66				
Converter	30	-	-				

Table 47: Technical Configuration Outcomes of Scenario 3, Option 2

4.3.2 Scenario 3 Carbon Emissions & Financial Outcomes

Features	25MW PV+ 544KW AD + Grid	30MW PV+ 544KW AD+ Grid
Total Annual CO2 Emissions (Ton/Year)	3,816	3,632
Reduction of CO2 Emissions (%)	78	80
COE ($/KWh)	0.083	0.082
Total NPC ($Millions)	49.8	59.88
Initial Capital Cost (($Millions)	44.2	52.6
O&M Cost ($/Year)	826,544	826,544
Payback Period (Years)	8	8

Table 48: Carbon Emissions and Financial Outcomes of Scenario 3

4.3.3 Scenario 3 Power Performance in Summer & Winter

<u>Option 1: 25MW PV+ 544KW AD+ Grid</u>

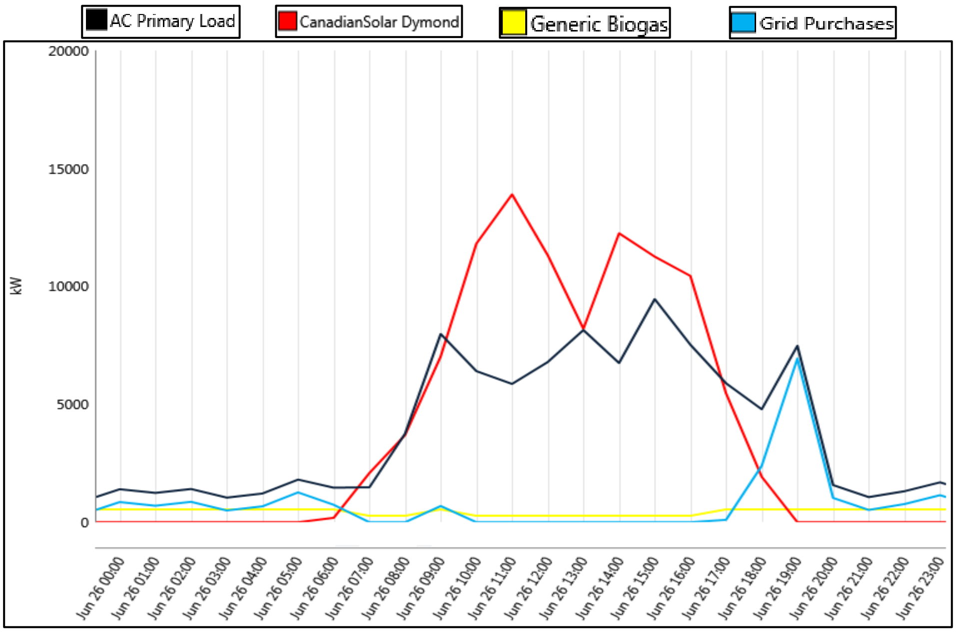


Figure 56: The Performance of the Power Output for Scenario 3, Option 1 in Summer (26th June)

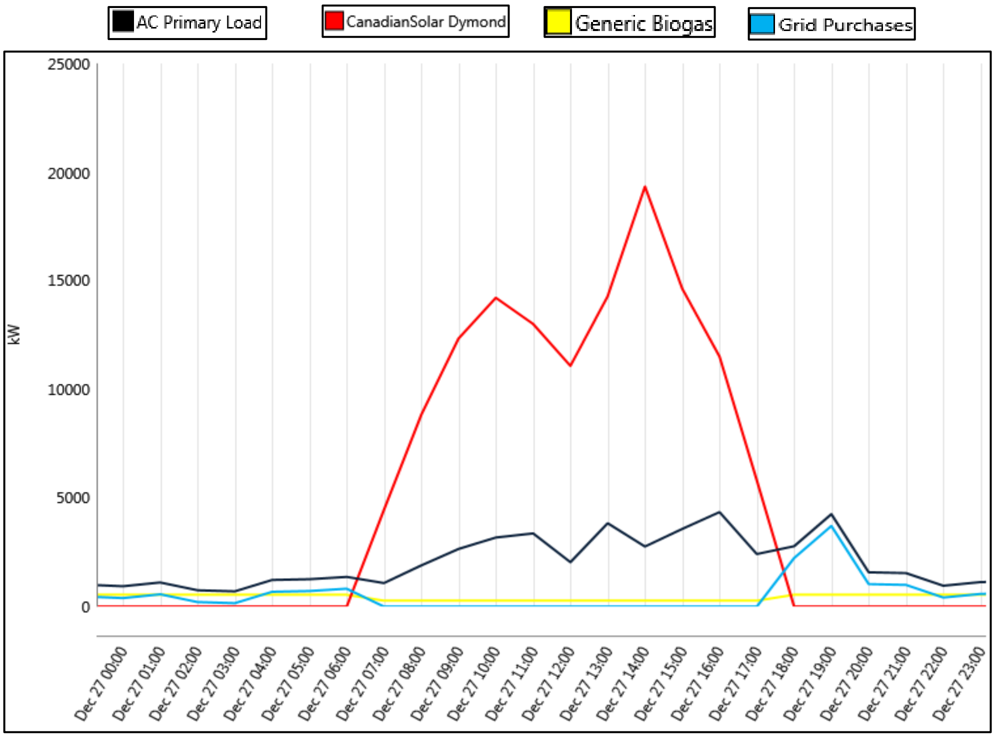


Figure 57: The Performance of the Power Output for Scenario 3, Option 1 in Winter (27th December)

Option 2: 30MW PV+ 544KW AD + Grid

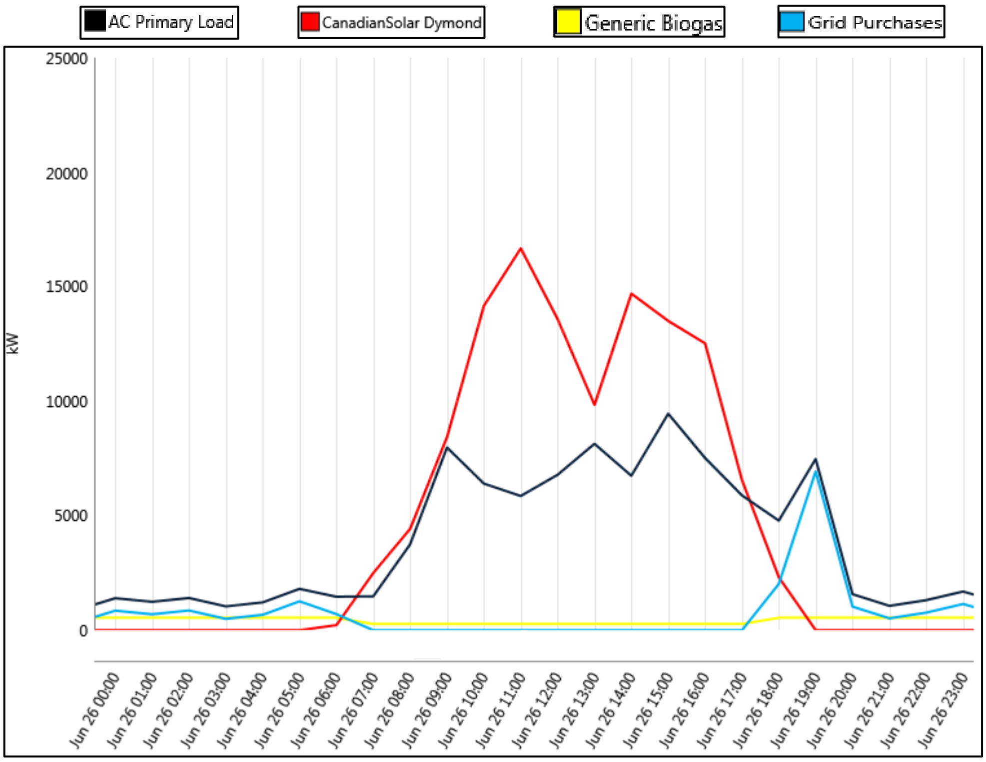


Figure 58: The Performance of the Power Output for Scenario 3, Option 2 in Summer (26th June)

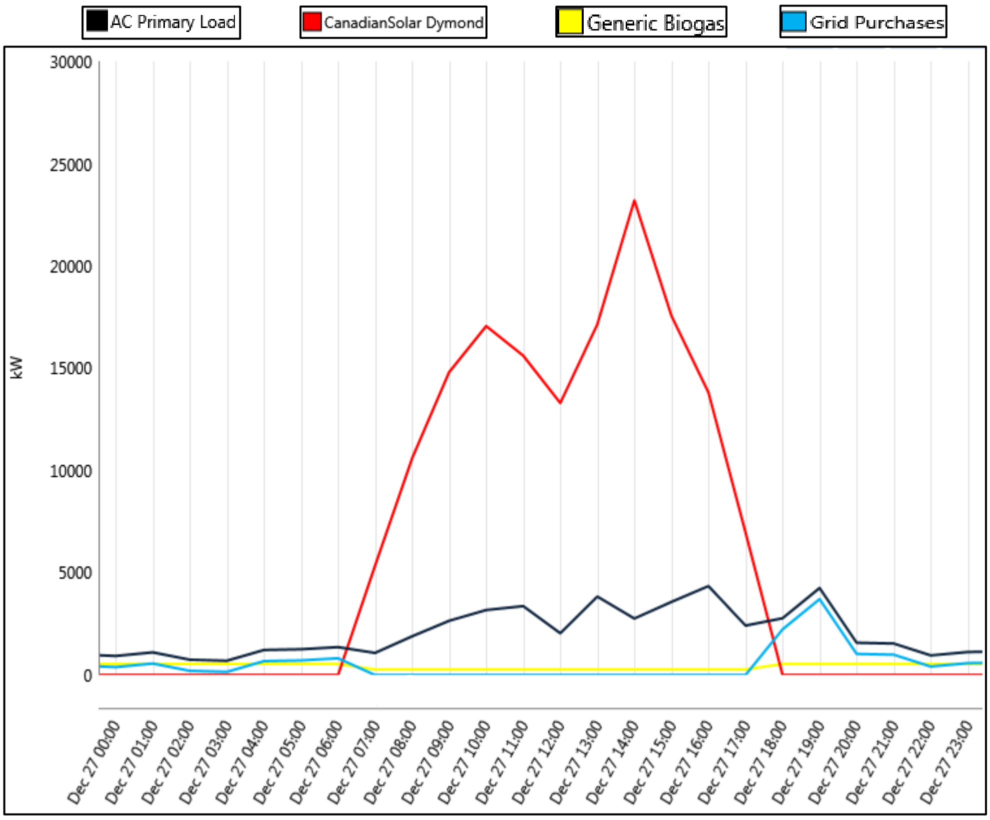


Figure 59: The Performance of the Power Output for Scenario 3, Option 2 in Winter (27th December)

4.3.4 Scenario 3 Evaluation

Both options in this Scenario have demonstrated pretty much similar technical, financial and environmental results. In option 1, the capacity factors of PV, AD, and the grid components, are 83%, 6.5%, and 10.6% respectively, as shown in Table 45. Moreover, this option has a renewable fraction of around 89%, but because the system generates so much surplus, around 50% of the power is sent back to the grid.

In the summer, as displayed in Figure 56, the PV and AD components accomplished almost continuous supply coverage, covering around 7 out of the 8 hours of power cut, from 10am-5pm. Furthermore, during the night, the vast majority of the supply originated from the grid, due to the overall low productivity of the AD plant, and no energy generation from the Solar PV farm.

In the winter, as shown in Figure 57, the grid was only used as a backup for a limited time during the night. Also, during the day in winter, PV and the AD were able to cover a full 10 hours - 7am-5pm - without any support from the grid. Nonetheless, there was a high amount of surplus which was sent back to the grid.

With regards to the carbon emission level, option 1 had a total annual carbon emissions level of around 3,816 tonnes, as shown in Table 48. That is equal to a reduction of 78% in comparison with the carbon emissions of the current existing base energy model (see Table 32). The integrated system in option 1 also demonstrated a reasonable COE of $0.83/KWh, with a total of NPC of $49.8M, and an expected payback period of 8 years; yet its high capital cost of around $44.2M must be considered (see Table 48).

On the other hand, the combination of 30MW solar PV, 544KW AD and grid in option 2 has presented slightly better results overall than option 1. In fact, the majority of the output power was generated from PV, with a capacity factor of 85.7%, followed by the grid with a capacity factor of 8.6%, and then AD with a capacity factor of 5.6%, as presented in Table 47. In addition, option 2 scored a slightly higher renewable fraction, 91%, compared to option 1, but there was a bigger surplus sent back to the grid - 57% of the total power produced. This is due to the fact that the system was sized on a higher PV capacity of 30MW, which is highlighted in Table 47.

Additionally, option 2 had a higher capability to cover the town’s demand in summer and winter than option 1. As clarified in Figure 58, during the summer, a combination of PV and AD was able to cover the 8-hour blackout completely, even if it were to increase to 10 hours, from 7am-5pm. In summer nights, when the peak demand is less than 5000KW, a combination of the AD and the grid components coped effectively with covering the rest of the demand. In winter, and similarly to option 1, the entire demand during the peak hours of the day was covered by the AD and PV components, without any need for grid assistance. However, during winter nights, the grid supplied some power in a combination with AD, considering that PV is inactive, as shown in Figure 59.

Shifting attention to greenhouse gases emissions, option 2 accomplished an 80% reduction of carbon emissions with a total 3,632 tonnes of annual carbon emissions; this improved beyond option 1’s total annual emissions as revealed in Table 48. Option 2 has a COE of $0.082/KWh and a payback period of 8 years. Yet option 2 was calculated to have a capital cost of $52.6M, and an NPC of $59.88M, which are higher than option 1 (see Table 48). Comparatively, the COE of both options in scenario 3 are almost half the price of the COE of the current existing base model (see Table 32).

To conclude the analysis of Scenario 3, although both options have illustrated similar technical performances, less greenhouse gases emissions and competitive financial outcomes, option 2 was more than equipped to cover the demand during load-shedding, meaning that inhabitants of East Soba will have a consistent, full electricity supply during summer days. However, the only drawback of this system is the high capital cost, which would need either foreign investment or governmental support.

4.4 Scenario 4 (PV-AD -Battery)

The purpose of this Scenario is to trial a system working entirely without the unreliable grid, replacing it with an efficient battery storage. This Scenario operates based on a stand-alone system method, where the power produced by the PV panels is used to charge the battery during the day, which can be used later at night when the solar irradiance is unavailable. Diverse options have been modelled through HOMER software to choose the best configuration, and therefore the most appropriate option was: 18.9MW PV, 544KW AD, and 33MWh li-Ion battery and 12.49MW converter. The process of how the system works is presented below in Figure 60.

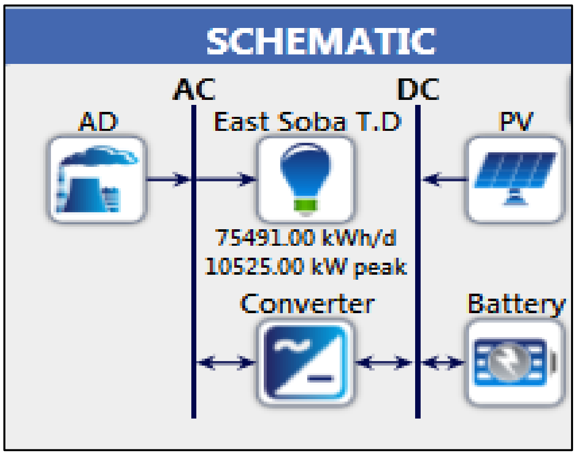


Figure 60: Schematic of Scenario 4

4.4.1 *Scenario 4 Technical Configuration Details*

Components	Capacity (MW)	Production (GWh/Y)	Capacity Factor (%)	Surplus Sent Back To Grid (GWh/Y)	Renewable Fraction (%)	Load-Shedding Coverage (Hours)	Excess Energy (GWh/Y)	Unmet Electric Load (GWh/Y)
PV	18.98	35.98	89.4	No grid connected	100	8	11.5 (28%)	0.5 (2%)
AD	0.544	4.25	10.6					
Li-Ion Batteries	33	-	-					
Converter	12.49	-	-					

Table 49: Technical Configuration Outcomes of Scenario 4

4.4.2 *Scenario 4 Carbon Emissions & Financial Outcomes*

Features	18.9MW PV + 544KW AD + 33MWh Batteries
Total Annual CO2 Emissions (Ton/Year)	zero
Reduction of CO2 Emissions (%)	100
COE ($/KWh)	0.12
Total NPC ($Millions)	20
Initial Capital Cost ($Millions)	37.9
O&M Cost ($Millions /Year)	1.90
Payback Period (Years)	12

Table 50: Carbon Emissions and Financial Outcomes of Scenario 4

4.4.3 *Scenario 4 Power Performance in Summer & Winter*

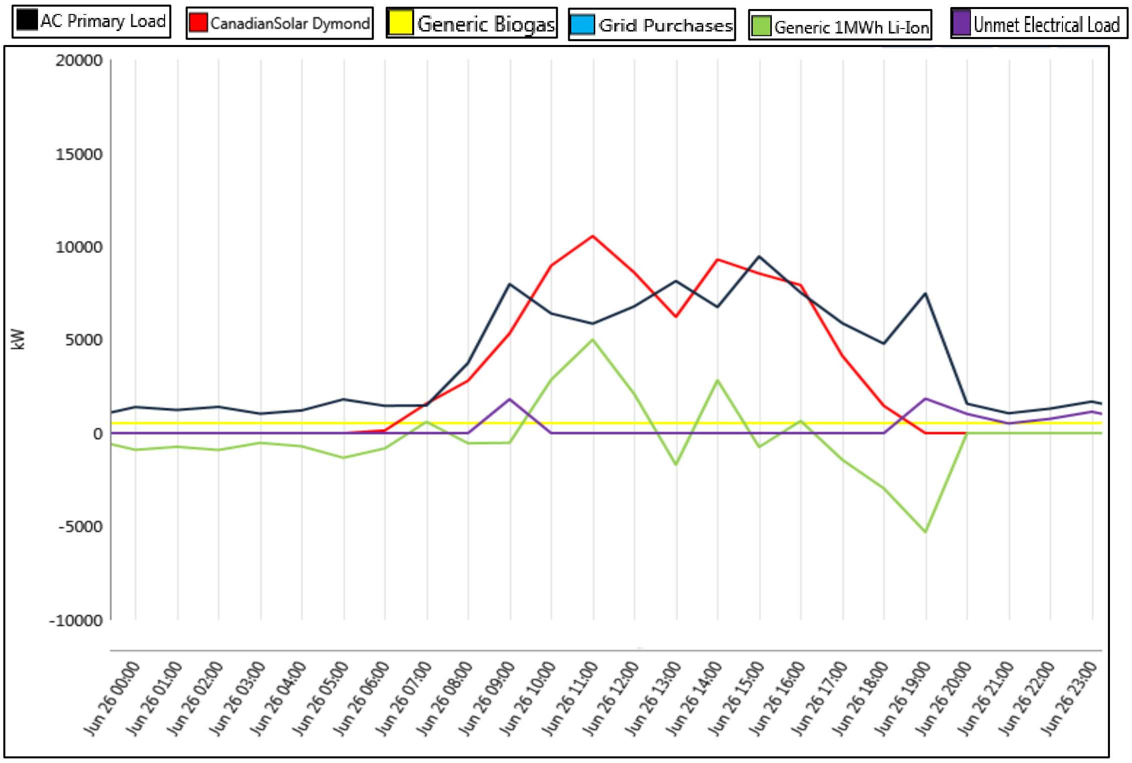


Figure 61: The Performance of the Power Output for Scenario 4, in Summer (26th June)

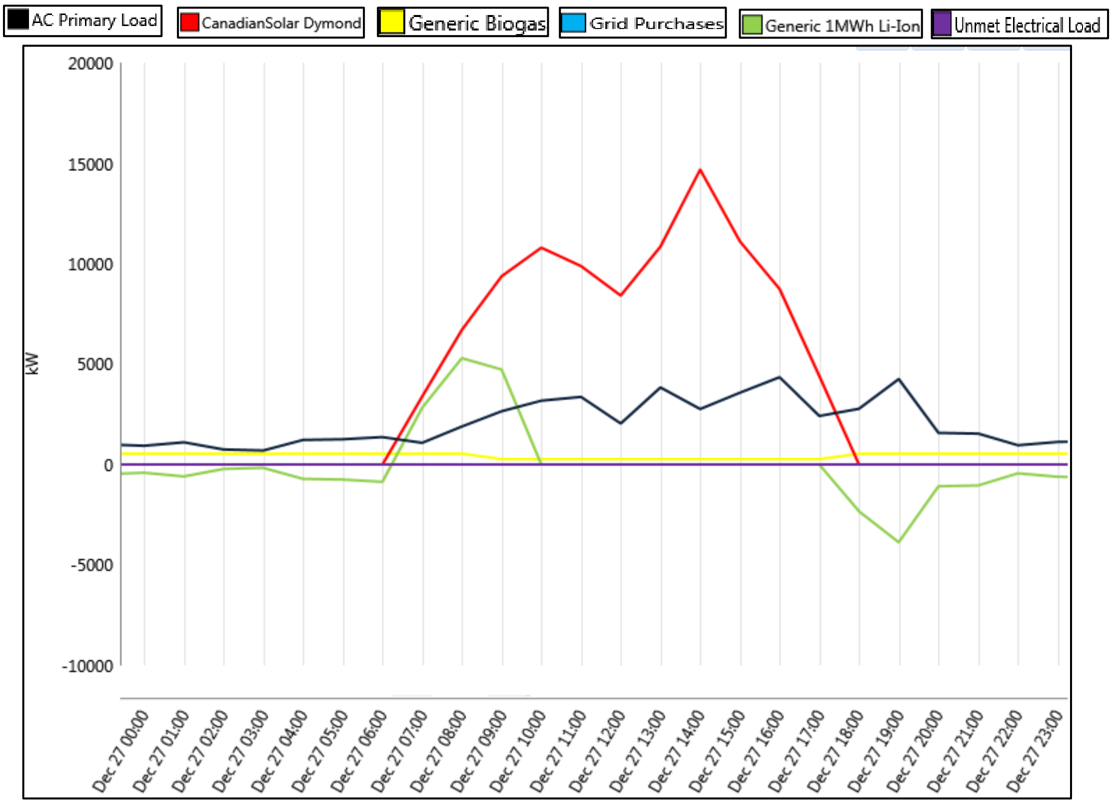


Figure 62: The Performance of the Power Output for Scenario 4, in Winter (27th December)

4.4.4 *Scenario 4 Evaluation*

The results in Table 49, revealed that an off-grid system of 18.9MW PV, 544KW AD, and 33MWh batteries has a renewable fraction of 100%. The overwhelming majority of the power was generated by the PV with a capacity factor of nearly 90%. The AD worked 24/7 with a low consistent output power supply, and a capacity factor of around 10%. However, even though the system had complete renewable penetration, there was some surplus power of around 28%, and some slight unmet electrical load of just under 2% during the day.

Furthermore, the results in Figure 61 shows that during summer months, the system was capably to cover 90% of the total peak demand especially during the load-shedding hours, because of high-power production from the PV. Nonetheless, there was a small amount of unmet electric load, particularly from 8am-10am. During the night, where PV production is zero, the battery started to discharge and managed to cover approximately 80% of the night demand, taking into account that the supply during this time came not only from the battery, but also from the 544KW AD, despite its lesser power generation.

In winter, the system has proven it is able to cover 100% of the demand without any obstacles. During the peak hours of the day, a combination of the PV and AD have fulfilled the demand, while the battery stored any excess power. Then, after 5pm, the battery began to discharge and covered the demand with constant support from the AD plant as well, which resulted in no unmet electric load, as shown in Figure 62.

Scenario 4 also produced almost zero total annual carbon emissions as described in Table 50. That means 100% reduction of carbon emissions compared to the current existing base energy mode (see Table 32). This makes sense because the system has no non-renewable component, or connection to the grid. With regards to cost outcomes, this off-grid system offers $0.12/KWh COE, a payback period of nearly 12 years and $20M of total NPC, as displayed as well in Table 50. It must also be taken into consideration that the system has a capital cost of around $37.9M. Despite this, the scenario does have a cheaper COE than the base model (see Table 32).

Scenario 4’s off-grid integrated system has confirmed an excellent demand coverage performance in both summer and winter with total renewable penetration, and less COE than the current base model. However, there were some minor unmet electric loads in summer, which is unlikely to be a substantial issue.

Each Scenario model has been assessed under the same technical, environmental and financial assessment criteria; therefore, a full comparison must be undertaken in order to narrow down selection for the proposed integrated system in East Soba.

5 SCENARIOS COMPARISON AND DICUSSSION

5.1 Summary & Comparison

Summary	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Components	PV, Grid, Converter	AD, Grid	PV, AD, Grid, Converter	PV, AD, Battery, Converter
Capacities	25MW PV 999,999KW Grid 25MW Converter	544KW AD 999,999KW Grid	30MW PV 544KW AD 999,999KW Grid 30MW Converter	18.9MW PV 544KW AD 33MWh Li-batteries 12.49MW Converter
Assessment Criteria				
Renewable Fraction (%)	83	17	91	100
Load-Shedding coverage (Hours)	6	0	8	8
CO2 reduction (%)	68	17	80	100
COE ($/kWh)	0.077	0.13	0.082	0.12
Capital cost ($)	42.1M	1.97M	52.6M	37.9M
NPC ($)	50.2M	1.68M	59.88M	20M
Payback period (years)	8	10	8	12

Table 51: Scenario 1-4 Summary Results

Table 51 above presents a summary of Scenarios 1-4. It is obvious that all the Scenarios demonstrated a feasible techno-economic and environmental outcome. Scenarios 1-3 operate based on grid-connected methods, while Scenario 4 is the only Scenario which operates entirely off-grid. Following the evaluation criteria, Scenario 2 was the least feasible Scenario, especially in terms of renewable penetration and load-shedding. This is due to the small potential generation capacity of the AD plant, which is totally dependent upon the annual availability of feedstock. However, this limitation could possibly be overcome in the future if there was potential to obtain additional feedstock from areas further away from East Soba.

Scenarios 1 and 3 have shown similar results in various elements such as renewable fraction and payback period. However, Scenario 1 was able to cover almost 75% of the load-shedding hours with 68% carbon emissions reduction, whilst Scenario 3 has 100% coverage of the critical peak load during the power outages, and 80% carbon emission reduction. The key difference between Scenario 1 and 3 is the incorporation of AD into Scenario 3. This added more power stability during the night and reduced the reliance on the grid; particularly as the PV component cannot produce during night due to zero solar irradiance.

It is important to remember that, these 8-hour daily power outages are the main reasons behind inhabitants' frustration in the town of East Soba (see Section 1.4) - supplying reliable power during these times would be a top priority for this project. Therefore, Scenario 3 and 4 are the only Scenarios that have managed to cover 8 out of 8 hours of the demand when the grid is entirely down.

Other factors like capital cost, COE and payback period are crucial in attracting investments and governmental subsidy. In fact, all Scenarios have shown a competitive COE compared to the base model; However, Scenario 3 presented the lowest COE, followed by Scenario 1, Scenario 4 and lastly Scenario 2. Including more components in the system would definitely increase the capital cost and add more complexity in the installation and operation processes; this is why Scenario 3 had the highest capital cost, followed by Scenario 1, then Scenario 4 and finally Scenario 2. As the project lifetime was chosen to be 25 years, it is vital for the investor to know when exactly he starts to make a profit. By reflecting on this, relating to all Scenarios, Scenarios 3 and 1 have the shortest payback period, followed by Scenario 2, and then Scenario 4.

Overall, all the above-mentioned concluded Scenarios are feasible and appropriate to implement. Each Scenario would be better than others in certain times and circumstances. However, taking into account all the applied assessment criteria, Scenario 3 and 4 would be the most suitable integrated energy systems for this project.

5.2 Uncertainty Analysis

Scenarios 1-4 have been examined and it has been concluded that the most appropriate integrated systems would be Scenario 3 and 4. It is now necessary to explore the behaviour of these two scenarios considering the uncertainty of some input parameters, which helps in decision-making, future design and implementation.

Future Load-shedding Time

Scenario 3 and 4 are currently able to cover the load-shedding hours in the town of East soba, which is 30% of the day. However, in the future if the load-shedding increased to more than 50% of the day, then the grid would be classified as extremely unreliable - therefore it would better to run the system entirely based on off-grid method and use batteries as a backup. That means the off-grid Scenario 4 would be more feasible and fit perfectly with those circumstances.

On the other hand, if in the future the government decides to invest more on improving the quality of the grid and increasing its reliability, bringing load-shedding to a much less critical 10% of the day for example, then it would be far better and technically more effective to implement grid-connected Scenario 3.

Future Electricity Selling Price

Currently, the price of electricity in Sudan is estimated to be \$0.16/KWh. Scenario 3 and 4 resulted in \$0.082 /KWh, and \$0.12/KWh of COE respectively which both are cheaper than the base model. However, in the future there is no guarantee that the current price of 0.16\$/KWh will continue. So, if the current price rose in the future for any political or economic reasons, then both Scenarios would still be profitable. On the other hand, if the current price declined to a certain level, for example below \$0.12/KWh, then Scenario 3 would be the only profitable and cost-effective scenario. For a broad cost understanding, Figure 63 below presents sensitivity analysis of the selling price against the total NPC and payback period

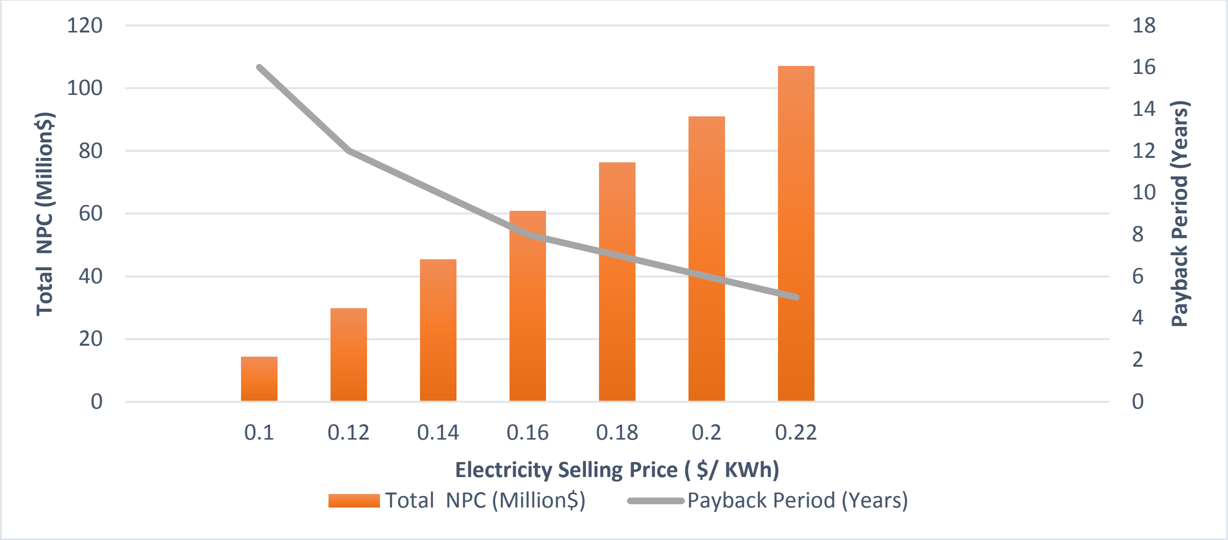


Figure 63: Sensitivity Analysis of the Electricity Selling Price against NPC and Payback Period

6 STUDY LIMITATIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Study limitations

Although the project proposed a comprehensive feasible strategy based on an integrated renewable energy system, to provide reliable and sustainable power to the town of East Soba in Sudan, there were some limitations due to project timeframe constraints. There was limited input data in HOMER software in modelling the AD component part. Also, there were some difficulties in HOMER relating to modelling the grid when there is a power outage; without this issue more accurate outcomes could have been reached.

Moreover, it would have been more beneficial to include a logistics analysis for solar PV and AD. This logistics analysis could include suggested sites and the space required for the system. In terms of AD, identification of collection points for the waste, and giving more details on the mechanism of collection and transportation for the waste and digestate to/from the AD plant, would have expanded this feasibility project further. Furthermore, due to lack of information on some types of organic waste in the town, such as sewage sludge and its treatment, some forms of waste have not been included in the feedstock analysis of this project, which could have enabled more precise results from the AD section.

As the proposed hybrid system generates a high amount of surplus, some analysis about the current financial electricity incentives policy in Sudan such as Feed in Tariff (FIT), could have been relevant; this would have helped in calculating the future profit of selling the surplus and understanding the legal and business procedures required. Unfortunately, there wasn’t enough available information about any renewable energy adoption projects in Sudan, let alone a specific financial incentive.

6.2 Recommendations & Future Work

For further improvements of the project analysis and the outcomes, here are some future recommendations, which should be taken into consideration. These future works can be classified into five different fields: location of the system, feedstock expansion strategy, demand reduction technologies, grid capacity, and incentives and contracts.

- **Location of the Integrated System**

Suggesting a suitable location for both the PV farm and the AD plant would be a useful subsequent step. This location should have an adequate space for the PV panels, wires and converter devices. Also, it is highly recommended, for the AD plant in particular, to be located far away from the town by approximately 5-10KM, that is due to health and safety considerations - predominantly the strong smell and noise which are by-products of the waste digestion.

Likewise, it would be valuable to perform an environmental impact assessment related to PV and AD, with their suggested locations. This initial assessment would help in mitigating the social, economic, health and safety risks associate with system installation and operation during the implementation of project.

- **Feedstock Expansion Strategy**

Including other organic waste from other nearby towns, villages and farms would be a strong future strategy for expanding the feedstock of the AD plant, and therefore elevating the generation capacity of the AD plant. This future strategy could be carried out through a partnership or coordination between the local authorities and the investors of the plant. Furthermore, this would also result in improving the waste management infrastructure of the town.

- **Demand Reduction Technologies**

It was identified through this project that the overwhelming majority of the residential energy demand was caused by air-conditioners, followed by some other inefficient appliances, such as lights and fridges. Therefore, a possible approach would be to implement some demand reduction measures; for instance, more environmentally conscious residential building designs, or perhaps replacing those appliances with more sustainable and efficient ones, such as LED lights. These reduction measures would decrease the total annual electricity consumption in the town, and hence, less hybrid system capacity would be required.

- **Grid Capacity**

As previously discovered, the proposed integrated system will result in a high power surplus, which will be sent to the grid. Therefore, further investigation of the national grid’s capabilities to cope with this power input would be required for a practical application of any grid-connected renewable system.

- **Incentives and Contracts**

Presently, there are no financial incentives or contracts for renewable electricity generation in Sudan. It would be beneficial in the future to have governmental contracts such as a Feed In Tariff (FIT), which would allow larger renewable generation capacities to be implemented, and also guarantee a constant profit for investors. This feasibility study has indicated that a higher generation capacity of the PV-AD-grid system would be more profitable, hence would attract more prospective foreign investments.

7 CONCLUSION

To conclude this research journey, every attempt has been made to solve the unreliable energy supply issues of East Soba, Sudan. This was approached by analysing the total estimated annual electricity consumption, through detailed residential, public services and commercial premises investigation, as well as the performance of the current energy grid. Solar irradiance and biomass were considered to be readily available local renewable resources – hydropower and wind were evaluated and found to be unfeasible energy options for this study. Both demand and supply were modelled using HOMER and AD Excel spreadsheet calculator, and multiple integrated system options, based on Anaerobic Digestion and Solar Photovoltaic, were thoroughly tested and checked before reaching four main contending Scenarios.

All four Scenarios were found to be viable to some extent and each are suitable for implementation within specific circumstances. However, Scenario 3 of PV-AD-Grid, and Scenario 4 of PV-AD-Battery, were proven to have the most appropriate hybrid combinations for this project. The list below explains some of the main findings.

- A Solar PV farm would be the highest renewable generating component of each system, due to the high and prolonged solar irradiance in Sudan almost all year round.
- An Anaerobic Digestion plant alone would not be able to cover the peak demand of the town, unless it is combined with solar PV, due to its small capacity and limited amount of feedstock.
- Scenario 3's integrated system of PV-AD, operating on a grid-connected method, would cover 100% of the power blackout times, with a general renewable fraction over 90%
- Replacing the unreliable grid with 33MWh Li-ion batteries and operating the system entirely on off-grid method, as in Scenario 4, would still satisfy almost 100% coverage during the load-shedding, and full renewable fraction, however there some minor unmet electric load would be expected during summer.
- Both options of PV-AD-Grid, and PV-AD-battery have demonstrated a cheaper COE than the current existing grid-only system.
- The capital cost might seem very high, however a reliance on foreign investment and governmental subsidy would be mandatory for any new energy project anyway.

Overall, this research study concludes that an integrated renewable system of Solar Photovoltaic and Anaerobic Digestion, operating either connected to the grid, or completely off-grid but with Battery storage, would be most appropriate and feasible for this project.

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