Addis Ababa University
Addis Ababa Institute of Technology
Center for Renewable Energy

Techno-economic Feasibility of Biogas Utilization for Grid Connected Biogas and Solar PV System: Case for Kaliti Waste Water Treatment Plant

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February 2023

Addis Ababa, Ethiopia

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A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES, AT ADDIS ABABA INSTITUTE OF TECHNOLOGY, CENTER FOR RENEWABLE ENERGY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN RENEWABLE ENERGY TECHNOLOGY

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Approval of MSc. Thesis

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DECLARATION

This is to declare that thesis work entitled *"Techno-economic Feasibility of Biogas Utilization for Grid Connected Biogas and Solar PV System; Case for Kaliti Waste Water Treatment Plant"* has not been presented for a degree in any of universities and it is my own work. I have acknowledged the materials used in this thesis and referenced appropriately.

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First, I praise and thank humbly to the creator of all, my Lord God, he who holds my hands, opens my eyes and leads my mind to work well before, now and to the future. I also humbly thank mother of the Lord, Holy Virgin Marry & Lord's saints being my strength in all challenging moments.

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ACRONYMS

AAWSA	Addis Ababa Water & Sewerage Authority
AC	Alternating Current
AD	Anaerobic Digestion
AM	Anti-Meridian
CV	Calorific Value
CO_2	Carbon di Oxide
CO	Carbon Mono Oxide
CC	Cycle Charging
DC	Direct Current
ETB	Ethiopian Birr
GHI	Global Horizontal Irradiance
GHGs	Green House Gases
HOMER	Hybrid Optimization of Multiple Energy Resources
H_2S	Hydrogen Sulphide
InC	Initial Capital
Kg	Kilo grams
kWh/kW	Kilo watt hour/ Kilo Watt
KWWTP	Kality Waste Water Treatment Plant
LCOE/COE	Levelized Cost of Energy/Cost of Energy
LPG	Liquefied Petroleum Gas
LF	Load Following

LHV	Lower Heating Value
MAPE	Mean Absolute Percentage Error
CH_4	Methane
NMA	National Meteorology Agency
NPC	Net Present Cost
NO_X	Nitrogen Oxides
NM^3	Nominal Cubic Meter
NTP	Normal Temperature and Pressure
O&M	Operation & Maintenance
OC	Operating Cost
$PM_{10}/PM_{2.5}$	Particulate Matter
PPM	Parts Per Million
PM	Past Meridian
PV	Photovoltaic
RF	Renewable Fraction
SO_2	Sulfur di Oxide
SCADA	Supervisory Control and Data Acquisition
USD ($)	United States Dollar
USA	United States of America
UASB	Up-flow Anaerobic Sludge Blanket
WWTP	Waste Water Treatment Plant

ABSTRACT

Wastewater treatment plants consume large amount of energy, which in turn will lead to incurring higher operating cost. On the contrary, they have a significant amount of energy potential through treatment processes especially biogas produced from anaerobic treatment phases. Utilizing this energy potential will help to supply power for the plant from its as well as to reduce operating costs.

This study is conducted in Kaliti wastewater treatment plant that is receiving septic & latrine wastes via trucks and truncated sewage pipes. During the process of treatment, one of the products is biogas, which is not being converted to useful application. In this study, assessment of demand & resources for the plant is done & the peak primary load is about 111 kW and the daily primary energy demand of about 1278 kWh/day. Maximum & minimum monthly average hourly solar Ground Horizontal Irradiance (GHI) of 5.47 $kWh/m^2/day$ & 3.71 $kWh/m^2/day$ respectively and it has a daily average biogas production of 3903 Nm^3/day. Modeling and Optimization of energy systems is done by Hybrid Optimization of Multiple Energy Resources (HOMER) software using biogas resource, solar resource, diesel gen-set and main grid by categorizing off-grid and grid connected systems.

From all the systems investigated and compared, off-grid systems are found by having highest Net Present Cost & Cost of Energy. Grid-PV scheme with Net Present Cost of 1.81M＄& Cost of Energy of 0.329＄/kWh and Grid-biogas scheme with Net Present Cost of 1.8M & Cost of Energy of 0.403＄/kWh are the 1st and the 2nd ranked. And Grid-biogas scheme is found optimal system due to its smaller initial capital and no excess electricity.

CHAPTER ONE - INTRODUCTION

1.1Background

Water is precious resource in the world and it should be utilized efficiently. worldwide freshwater use has grown by a factor of 6 (six) over the past 100 years and increased at a rate of roughly 1% per year since the 1980s and much of this growth can be attributed to a combination of population growth, economic development and shifting consumption patterns (U. N. 2021). It is estimated that four billion people live in areas that suffer from severe physical water scarcity for at least one month per year (Mekonnen and Hoekstra 2016) and about 1.6 billion people face 'economic' water scarcity, that is even though water may be physically available, there is lack of the necessary infrastructure to access that water (Molden 2013). Above two billion people, face lack of safe drinking water access and above four billion people face lack of safe sanitation access (WWAP 2018). If waste water resulting from different human activities are released untreated to water and non-water bodies, they are potentially polluting the quality of water and affect the health of living matter (U. N. 2021). Waste Water Treatment Plants (WWTPs) have series of processes or different stages that are cascaded to provide treated water from either municipal or industrial or commercial wastes by reducing or removing pollutants from polluted water (Bodík and Kubaská 2013).

Water resources are being depleted through time (U. N. 2021). And therefore, in response to efficient resource utilization and environmental protection, WWTPs have various contributions such as providing recycled/treated water for which will be used for different applications, making a clean & safe environment which in turn is to protect human life & other living matter and providing an opportunity for generating energy from waste.

Conventional WWTPs have mainly three stages as primary, secondary and tertiary. primary treatment includes wastewater collection and pumping, screening, grit removal & sedimentation in primary sedimentation tanks this step (primary) is mainly for the removal of suspended solids, secondary treatment is for organic pollution removal and tertiary treatment is to remove nitrogen & phosphorus (Bodík and Kubaská 2013).Since there are energy requiring processes undergoing and electromechanical equipment & machineries used, WWTPs are energy intensive processes (Barroso Soares 2017). On the other hand, sewage can be a source of different types of energy, one of it is biogas production from the anaerobic digestion of sludge which will be converted in to useful forms or transported to natural gas networks (Callegari and Hlav 2020; Frijns, Hofman, and Nederlof 2013). Biogas's chemical composition depends on the feedstock and operational conditions in which the Anaerobic Digestion (AD) undergoes A raw biogas is composed of 40–75% methane (CH_4), 15–60% carbon dioxide (CO_2) and trace levels of nitrogen (0-2%), oxygen (0-1%), water (5-10%), hydrogen sulfide (0.005-2%), siloxanes (0-0.02%), ammonia (<1%), carbon monoxide (< 0.6 %) and various Volatile Organic Compounds (VOC < 0.6%) (IEA Bioenergy 2000; Makisha and Semenova 2018; Ryckebosch, Drouillon, and Vervaeren 2011; Wan et al. 2020) .

In this thesis work techno-economic evaluation of energy system model mainly based on least Net Present Cost and levelized cost of energy is conducted using HOMER modeling and optimization tool.

1.2 Statement of the Problem

Utilization of energy resources in an inefficient manner will lead to energy wastage, additional cost and increase rate of depletion of energy resources. Biogas is produced in Up-flow Anaerobic Sludge Blanket (UASB) reactors in wastewater treatment plants and this gas will be used for different applications by using conversion mechanisms. In Kaliti wastewater treatment plant the maximum daily biogas production capacity is estimated to 13,000 Nm^3/day and this resource could be used for heating and power applications.

However, this biogas is flared before it is emitted to the atmosphere, it is not being used for any applications that in turn will decrease the operating cost for energy utilization and will bring additional options for source of energy to the plant. Currently, the plant uses electricity from the grid and standby diesel generator set when grid is not available. Even if techno-economic feasibility studies of grid connected and off grid energy systems are conducted for residential or any other community loads, similar study specifically for Kaliti Wastewater Treatment Plant to improve utilization energy resources and potential of the plant is still in need. So, in this thesis work renewable energy resource assessment (identifying produced biogas & solar energy resource), energy system modeling & optimization is conducted based on the energy demand & utilization of the plant. In addition, the effect of frequency of existing grid power outages per year & variation of mean repair time, effect of considering deferrable loads rather than having all primary loads on the system performance is analyzed.

1.3 Objectives

1.3.1 Main Objectives

The main objective of this research is to conduct modeling and optimization of a grid connected energy system for Kaliti Waste Water Treatment Plant.

1.3.2 Specific Objectives

The specific objectives are:

1. Conducting assessment of load and prepare load profile of the plant;
2. Identification of constituents of biogas produced in Up-flow Anaerobic Sludge Blanket (UASB) reactor;
3. Modeling and optimization of energy system (Solar-Biogas fueled generator with battery backup system) for the treatment plant;
4. Conducting economic feasibility of the proposed system and evaluating the emission reduction.

1.4Scope of Thesis

In this research, assessment & analysis of energy resources and modeling & optimization of energy systems to show optimized energy sources configuration for Kaliti wastewater treatment plant is conducted. It does not cover/include installation & prototype preparation of the proposed energy model. In addition, it does not include characterization of influent (wastes) & effluents (treated water and sludge) and produced biogas & reasoning out of why the proportion of composition of biogas vary with time.

1.5Organization of Thesis Report

This thesis work report contains six main parts classified in chapters and appendixes. The first chapter is introductory part of the report. Chapter 2 covers literature review on related works such as relation between energy & WWTPs, modeling & optimization of energy systems. Chapter 3 presents brief introduction on the working processes and stages of KWWTP and presents the materials & methods used to achieve the objectives of this thesis work that is to assess the resources & loads of the plant and to do modeling & optimization of energy systems. Chapter 4 discusses the results of loads assessment and resources assessment. Chapter 5 provides the results of energy modeling & optimization for the treatment plant selection of optimal system based on technical & economical parameters. Chapter 6 contains conclusions on the thesis work and recommendations for future related works. Appendixes part contains details of data that was being used.

CHAPTER TWO - LITERATURE REVIEW

2.1 Waste Water Treatment Plants (WWTP)

2.1.1 Characteristics of wastewater

Wastewater may come from residential or domestic activities, agricultural activities, and industrial processes. Municipal wastewater will have physical, chemical and biological characteristics. Physical characteristics of domestic sewage mainly include temperature, odor, color, turbidity. Main chemical characteristics include Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Total Nitrogen, Total Phosphorous, PH and Alkalinity, chlorides, oils and grease, total solids. Biological characteristics include bacteria, fungi, algae, protozoa, helminths (parasitic worms and/ or their eggs) and viruses (von Sperling 2007).

Contaminants may be biological, physical, chemical, or radiological substance that has an adverse effect on water, soil or air. When contaminating substances enter water bodies such as river, sea, lake, ground water, it will cause pollution that in turn has health risks and environmental impact. Composition of municipal wastewater can vary considerably which indicates the variety of contaminants released from several domestic, industrial, commercial and institutional sources. Wastewater from domestic sources is usually relatively free of hazardous substances, but there are growing concerns about emerging pollutants including commonly used medications that, even at low concentrations, may have long-term impacts. Whereas wastewater from industries is more toxic and hazardous than domestic wastes (UNESCO 2017).

2.1.2 Operation of WWTPs

Working of WWTPs bases different steps to remove contaminants found in wastewater or sewage and these steps are mainly primary treatment, secondary treatment and tertiary treatment. The treatment system starts with receiving the collected waste/raw sewage via sewage pipes. The first stage in the treatment system is primary treatment. In this stage, sewage that enters to the system is directed to the preliminary treatment which comprises of screen to remove large objects like rags, parts of plants, and similar objects that will block and /or damage the next treatment phases. Next to screening, it is directed to a grit chamber to remove grit, sand and relatively smaller sized stones by allowing them to settle down to the bottom. Even after screening and grit removed wastewater contains dissolved organic & inorganic constituents along with suspended solids which can be slow down and settle to the bottom by implementing sedimentation or gravity settling, chemical coagulation, or filtration. Objects caught using screening and grit removal need to be collected periodically and taken to appropriate waste incineration or landfill disposal (E. P. A. United States 1998; USA 2004). The next stage is the secondary treatment and the waste that pass through aforementioned processes flows to this stage.

In the secondary treatment, biological treatments are implemented to remove organic matter. These processes can remove about 90 % of organic matter. Secondary treatment will be achieved through either attached growth process (fixed film process) or suspended growth processes (activated sludge process) to remove organic matter found in wastewater that leaves sedimentation tank in primary treatment. *In attached growth processes*, the microbial growth occurs on the surface of stone/rock or plastic media. Wastewater being treated passes over the media along with air to provide oxygen. In this process trickling filters, bio-towers, and rotating biological contactors. Attached growth processes are effective at removing biodegradable organic material from the wastewater. A trickling filter that is also referred bio filter is a bed of media may be rocks or plastic in which the wastewater passes through. Large numbers of microorganisms attach and grow on this media then they consume or absorb organic matter from the wastewater that is to be treated. Bacteria, algae, fungi and other microorganisms attach/ grow and multiply, forming a microbial growth or slime layer (biomass) on the media. During this treatment process, the bacteria use oxygen from the air and consume most of the organic matter in the wastewater as food. When the wastewater flows down through the media, oxygen-demanding substances are consumed by microorganisms and the water leaving the media is much cleaner (USA 2004).

Suspended growth process/ activated sludge process, also designed to remove biodegradable organic material and organic nitrogen-containing material by converting ammonia nitrogen to nitrate unless additional treatment is provided. In these processes, the microbial growth is suspended in an aerated water mixture where the air is pumped in, or the water is agitated sufficiently to allow oxygen transfer. Centrifugal blowers through the bottom of aeration tank provide oxygen. Suspended growth process units include variations of activated sludge, oxidation ditches and sequencing batch reactors. The process speeds up the work of aerobic bacteria and other microorganisms that break down the organic matter in the sewage by providing a rich aerobic environment where the microorganisms suspended in the wastewater can work more efficiently. In the aeration tank, wastewater is vigorously mixed with air and microorganisms acclimated to the wastewater in a suspension for several hours. This allows the bacteria and other microorganisms to break down the organic matter in the wastewater. The microorganisms grow in number and the excess biomass is removed by settling before the effluent is discharged or treated further. Now activated with millions of additional aerobic bacteria, some of the biomass can be used again by returning it to an aeration tank for mixing with incoming wastewater. Sufficient supply of oxygen is necessary for effective functioning of activated sludge process. From the aeration tank, the treated wastewater flows to a sedimentation tank (secondary clarifier), where the excess biomass is removed. Some of settled sludge from secondary clarifier is returned back to the aeration tank for continuously supply microorganisms, the remaining sludge from the secondary clarifier & the sludge from primary clarifiers are either pumped to anaerobic reactors for biogas production or fed to be incinerated and the final remaining is transported to land field. Treated water is then disinfected before it leaves or discharged out from the treatment (Asadi, Verma, and Yang 2016; USA 2004).

Tertiary or advanced treatment system is applied to ensure the quality of treated water by removing nitrogen, heavy metals phosphorous bacteria, viruses, and biodegradable organic matter that are not removed with previous stages (Strauss 1986). Decision to select the level in which wastewater treatment processes may be based on the type of waste or source of waste (industrial, domestic), to what quality level is needed to be treated.

2.2 Energy needed for WWTPs and energy produced from WWTP processes

2.2.1 Energy needed for WWTPs

Energy required for WWTPs depends on the influent and effluent quality, size of the treatment plant, worked time or age of the plant, type of technology, type of treatment processes and equipment used (Gu, Li, Li, Luo, Wang, Robinson, et al. 2017; Gu, Li, Li, Luo, Wang, Wang, et al. 2017; Longo et al. 2016).

(Longo et al. 2016) showed proportion of the level of energy consumption in different countries in the percentage share of energy consumption of WWTPs as in Italy & Germany 1% of countries' total consumption, in Spain as 2-3% of total electric energy consumption, in United States a rough estimation of 4% of electricity demand is used for potabilization & distribution of water and also for collection & treatment of wastewater.

The energy requirement varies in each phase of WWTPs. For instance, it is relatively lower in primary treatment phase. Processes in primary treatment which include wastewater collection and pumping, filtration, screening, grit removal and sedimentation in primary sedimentation tanks have different energy demand (Bodík and Kubaská 2013; Matos et al. 2014). Energy consumption for wastewater collection and pumping varies from 0.02 to 0.1 kWh/m^3 in Canada, from 0.045 to 0.14 kWh/m^3 in Hungary, energy for primary treatment in Australia is from 0.01 to 0.37 kWh/m^3 and in USA raw sewage collection & pumping consume an average of 0.04 kWh/m^3. In New Zealand, energy consumption for wastewater pumping ranges from 0.04 to 0.19 kWh/m^3 (Bodík and Kubaská 2013; Matos et al. 2014).

In secondary treatment, the aeration process consumes highest energy and it consumes 50-60% of all electricity consumption in most of medium and large WWTPs with conventional activated sludge treatment systems. The sludge treatment is also emphasized as high energy demanding process in WWTPs consumption of 15–25% of energy, consumption by secondary sedimentation including recirculation pumps reaches about 15% (Gu, Li, Li, Luo, Wang, Wang, et al. 2017). Secondary treatment with Oxidation Ditch (OD) has higher energy demand as compared with that of conventional activated sludge system due to the longer Hydraulic Retention Time (HRT) and greater power consumption for higher specific oxygen demand, ranging from 0.5 – 1.0 kWh/m^3 in Australia, about 0.302 kWh/m^3 in China, 0.43 – 2.07 kWh/m^3 in Japan (Gu, Li, Li, Luo, Wang, Wang, et al. 2017). Tertiary or advanced wastewater treatment stage consumes relatively higher amount of energy due to the nutrient removal processes. Processes in advanced wastewater treatment are highly energy intensive with energy demand ranging from 0.39 to 3.74 kWh/m^3 in Japan whereas conventional municipal WWTPs in USA typically consume 0.43 kWh/m^3& in Taiwan is 0.41 kWh/m^3, in New Zealand is 0.49 kWh/m^3, and in Hungary is from 0.45 to 0.75 kWh/m^3 (Gu, Li, Li, Luo, Wang, Wang, et al. 2017).

2.2.2 Energy produced from WWTP processes

Despite WWTPs consume higher amount of energy resources, those systems are estimated to contain about 10 times the energy that is demanded for the treatment (Barroso Soares 2017).

Biogas produced in anaerobic treatment processes is one of form of energy (Gu, Li, Li, Luo, Wang, Robinson, et al. 2017) from waste. The produced biogas can be used for the production of heat, mechanical and electrical energy by a means of utilizing the biogas either a combustion in heating boilers producing heat for the heating or combustion in gas engines coupled with the generators producing mechanical energy powering pumps. Alternatively, combustion in gas engines or gas turbines coupled with power generators for producing electricity which will power devices in a WWTP. The energy contained in sewage sludge will be recovered either using application of biogas produced in the anaerobic treatment or through combusting it in thermal installations (Adam Masłon, Joanna Czarnota, Grzegorz Łagód, Aleksandra Szaja 2020). Biogas at wastewater treatment facilities of Moscow is directed to produce steam in boilers(Makisha and Semenova 2018).

2.3 Biogas as a fuel

Optimized anaerobic digestion occurs in two temperature ranges, mesophilic from 32 to 35°C, and thermophilic from 50 to 57°C, thus digester heating might be necessary in some climates. In these temperature ranges, anaerobic digestion produces biogas containing 40 to 75% methane, with a balance of primarily carbon dioxide, water vapor and small amounts of siloxanes and hydrogen sulfide, which must be removed before the biogas can be used as a fuel for electricity generation to prevent damage to the generation equipment (Stillwell 2010).

The main component of biogas from the calorific point of view is methane. The rest components are not involved in combustion process, and rather absorb energy from combustion of CH_4 as they leave the process at higher temperature than the temperature they had before the process (N.H.S.Ray, M.K.Mohanty 2013). The study further discusses that in case for using biogas in internal combustion engines, the presence of high CO_2 reduces the power output that in turn has negative impact by being uneconomical to use it as transportation fuel and the H_2S can cause corrosion on engine parts. Purification is needed to alleviate such a problem. (Adam Masłon, Joanna Czarnota, Grzegorz Łagód, Aleksandra Szaja 2020) showed characterization of quality of biogas and determining the other constituents using gas chromatograph, the calorific value using Junker's Calorimeter.

(Akpojaro, Ofualagba, and Akpojaro 2019) discussed that to generate electrical power output, a low-pressure gas carburetor was incorporated into the Internal Combustion (IC) spark ignition engine coupled with synchronous generator used to enable the combustion of biogas in the combustion chamber in order to trigger the engine to provide a torque to rotate the synchronous generator. Alternatively, with some modification on spark ignition engine as spark ignition engines are originally designed to operate on an air-fuel mixture with spark ignition. The modification process involves the addition of methane (biogas) - air mixer to the engine and used a low-pressure gas carburetor to run the IC engine on biogas by controlling the engine through varying the mixture supply. The reason for using the low-pressure gas carburetor in this design was to ensure safety due to its functionality and interface the biogas generation and purification system. The study showed during biogas to electricity conversion 65% of the energy is lost. (Akpojaro, Ofualagba, and Akpojaro 2019) also assessed the working duration using biogas and petrol comparatively as 1kg of biogas will run for 71 minutes with a load capacity of 1400W and 1 liter of petrol will run for 42 minutes with the same load capacity. From the consumption analysis of these two fuels, biogas obtained the longer lasting time with respect to the same load input and burnt cleaner releasing even lesser heat than petrol.

In the study from (Surata et al. 2014), the effect of mixing of biogas with liquefied petroleum gas (LPG) on the engine speed with a mixing ratio up to 80% biogas to 20% LPG using gasoline engine is investigated with variations of biogas composition in the mixture of biogas-LPG from namely 80%, 85%, 90%, 95% and 100%. Biogas used is after desulfurizing it. This study shows experimental result of this mixing as when LPG is added to about 5% (95% biogas) in to the mixture, the engine speed was found about 1600 rpm and engine speed is still not increased significantly with addition of 10% LPG that the speed was about 1750 rpm. The significant increase in engine speed was found with addition 15% LPG that yielded about 2600 rpm of engine speed and it reaches its maximum value about 3600 rpm by adding about 20% LPG that is the speed when using gasoline fuel. (Senthilkumar et al. 2016) Conduct experimental investigation to determine the performance of dual fuel mode CI engine using biogas and diesel as a fuel.

Investigation on effect of preheated biogas-air mixture in a biogas-diesel dual fuel compression ignition engine's performing and emission was presented in (Prabhu et al. 2021) using different intake temperatures of biogas-air mix and load conditions.

2.4 Hybrid energy modeling and optimization aspects for WWTP

Since availability of renewable energy sources depend on climate conditions, it influences the energy production. Turning to hybrid making and optimization of renewable energy resources with other renewable or non-renewable resources and with or without grid connected is a reliable solution than conventional grid system. And the main challenge in such combined systems is to compute the optimal size and configuration of components to meet the demanded electricity with minimum cost (Baneshi and Hadianfard 2016; Shahzad et al. 2017).

Study by (Baneshi and Hadianfard 2016) modeled stand-alone as well as grid connected hybrid diesel/PV/wind/battery energy system for non-residential loads in southern Iran climate conditions using HOMER software. From its results presented, the renewable fraction of 0 – 43.9% are achieved with PV, wind turbine and battery sizes of 0 – 1000 kW, 0 – 600 kW, and 1300 kWh, respectively and incorporating batteries to the off-grid system reduces the excess electricity and increases the renewable fraction in expense of increasing capital cost. In case of grid connected systems the one with PV, inverter, and wind turbine sizes of 400, 320, and 300 kW, respectively, shows the cost of electricity of about 0.084 $/kWh. The optimal grid connected configuration based on minimum cost of electricity has 1000 kW PV, 800 kW inverter, and 300 kW wind turbine capacities.

(Saeed, Fawzy, and El-saadawi 2018) Presented modeling and simulation of a power system fueled by biogas using MATLAB/Simulink which fully simulates a biogas fueled power plant and it is composed of three models for biogas reactor, a micro turbine generation system and storage system in which three of them can be executed separately or collectively in order to simulate the biogas power plant. (Diana Robescu et al. 2015) Conducted analysis of technical feasibility to install PV and co-generation engines using biogas to produce electricity for WWTP in Constanta city - Romania to reduce annual cost of electricity for the plant. The WWTP treats 60% of domestic and industrial wastewater collected by the combined sewer system of the city. The study presents the result of optimization model for WWTP operation to reduce annual operation cost through minimizing the costs of purchasing electrical energy along a year by using at maximum the PV and the thermal engine fed with biogas. The model for this WWTP was implemented & tested for each 24-hour operation, within four different seasons (in which both consumption and availability of energy may vary during these seasons) using the software environment GAMS/MATLAB. The obtained result is presented as annual electricity cost reduction by 181638 Euro for 20-25 years lifetime and the plant can inject power to the grid during high production of Photovoltaic in summer season.

(Martins 2019) evaluated techno-economic performance of floating PV technology for wastewater treatment plant found in California and Windsor by comparing it to ground mounted PV technology. MATLAB is used to model energy system so as to investigate based on lifetime, capacity factor and cell temperature for both of the technologies. The study also provides economic investigation of both energy systems & identified Net Present Value of floating PV technology is smaller than that of ground mounted PV technology & LCOE is greater in floating PV technology than ground mounted PV. After this comparative assessment, the more cost-effective system identified by this study was floating type PV.

Techno-economic analysis on Grid-PV-Biomass gasifier hybrid energy system for supplying energy for wastewater treatment plant treating about 388,800 m^3/month located in Sao Paulo, Brazil (Buller et al. 2022) is conducted using HOMER modeling. The study compared the performance of existing Grid-PV energy system with a system that incorporates biomass gasifier, biomass gasifier standalone system, Grid only system, Grid-Biomass gasifier & PV-Biomass gasifier and identified the Grid-PV-Biomass gasifier (24-hour biogas combustion) is optimal because of its reduced COE & a surplus energy production which can be sold back to the grid.

CHAPTER THREE - METHODOLOGY

Methods to achieve the stated objectives of this research are described in this chapter. For this research work, the actual plant data records were taken, summarized and profiles are prepared. Data for power consumption, daily biogas production potential and daily inlet wastewater amount also found from records in the treatment plant, quarter reports and from the SCADA (Supervisory Control and Data Acquisition) backup. For biogas composition data, biogas measurement data records are taken. In addition to measurement records in the treatment plant, biogas measurement has been conducted by using portable biogas analyzer with model MCA100 BIO-P for biogas composition measurement. Then these data are summarized, analyzed and load profiles & resource profiles are prepared using MS Excel. Modeling and optimization of the energy systems is conducted using Hybrid Optimization of Multiple Energy Resources (HOMER) software tool, to optimize a system with lowest Net Present Cost (NPC) & Cost of Energy (COE) and to identify technically feasible system.

3.1 Treatment plant Location and Description

Kaliti Waste Water Treatment Plant (KWWTP) is under Addis Ababa Water and Sewerage Authority (AAWSA) and it is wastewater treatment plant located in Addis Ababa city Akaki Kaliti sub city. This treatment plant is intended to treat domestic wastes coming via trunk pipes from Addis Ababa city and septic & latrine wastes collected by trucks. The plant has 1) preliminary treatment which incorporates. screening, grease and grit removal, 2) secondary treatment which incorporates Up flow Anaerobic Sludge Blanket (UASB) reactor, trickling filters, secondary clarifier 3) disinfection unit in which chlorination and de-chlorination processes are done 4) pretreatment of latrine sludge and dewatering of all sludge using sludge drying beds. Finally, the treated water is discharged in to a river.

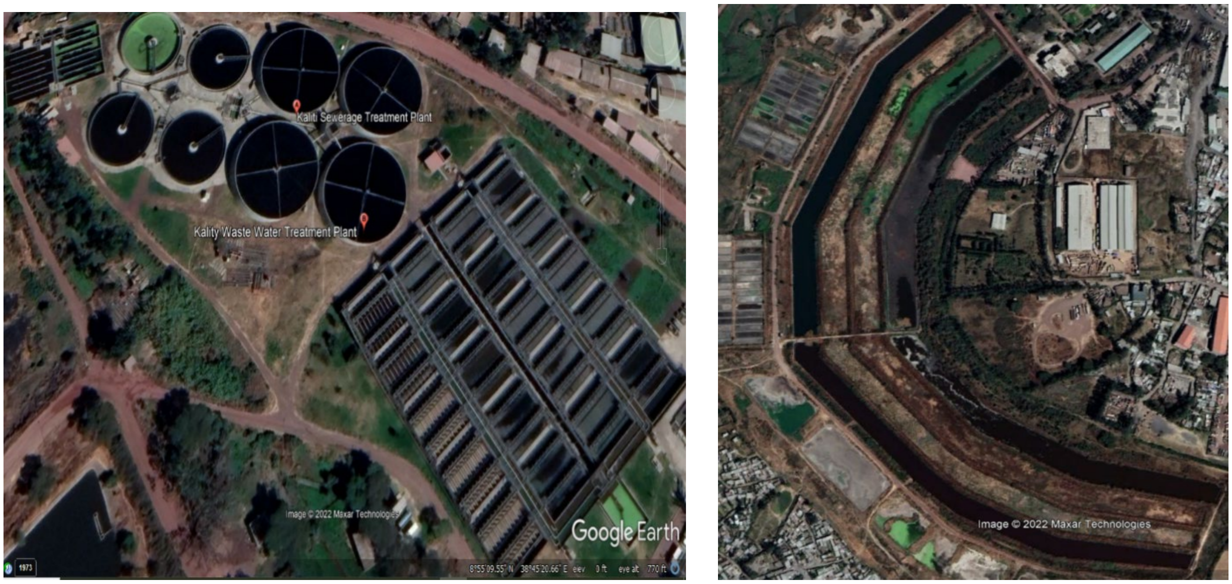


Figure 3. 1: Kaliti Waste Water Treatment Plant (KWWTP)

First, course screens remove rags, sticks and larger sized objects form the entering waste. Next to screens, aerated grit and grease removal from waste takes place. Settled grit is collected by travelling bridge scraper to a collection hopper and evacuated with a vortex v pump to the grit classifier and a surface scraper transfers fat & grease to a storage pit. Next to grit removal, the sewage is led to UASB reactors in which anaerobic digestion of sludge takes place and biogas is produced during this process. The gas produced is collected, sent to a gas flare equipment that is installed to burn the gas produced. After the UASB treatment sludge is withdrawn using sludge withdrawal pipes to sludge storage tank and the liquid effluent is led to trickling filters which incorporates rotary distributor, reinforced concrete walls and base, plastic UV resistant coated filter media, filter block, underdrainage system, and a forced ventilation system. Here aerobic microorganisms that are attached and grow on the surface provided by trickling filter media consume organic matter in the wastewater. Water leaving trickling filter enters to a secondary clarifier with return sludge pumping station for further settlement& separation of sludge available and it settles then finally the water undergone through disinfection (chlorination & de-chlorination) and discharged out of the treatment plant.

The designed maximum influent flow is 100,000 m^3/day and the energy demand by the plant is met from the Grid and standby diesel generator. Treatment plant is equipped with a laboratory and the treatment system operation is controlled by SCADA system.

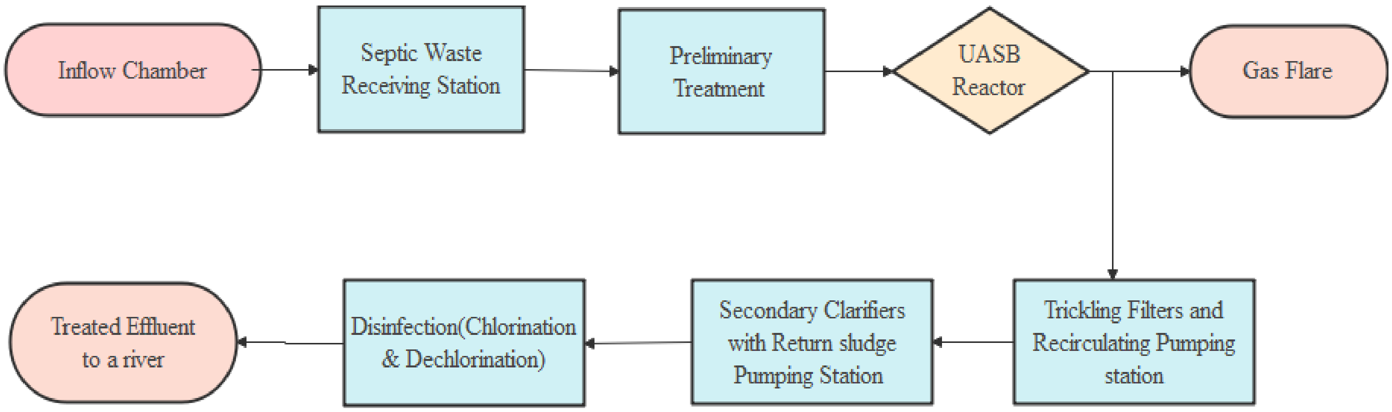


Figure 3. 2: Working Process Stages of Kaliti Waste Water Treatment Plant (KWWTP)

3.2 Methods and Materials

3.2.1 Load Assessment Methods

Treatment plant loads are taken from the overall power consumption data of the plant. The consumption data that is found from SCADA backup & quarter reports of the plant is daily average power consumption data items for 12 months and hourly power consumption data for June & for few days in November, December, and March. Despite 8760 series of consumption data is needed for HOMER software, the available quantity of hourly data is about 1730 data items (19.45%). So, hourly data for the rest of the months is estimated by computing hourly variation factor (averaging the available records on each respective hour on each day and divide it with the overall average of these hourly data) and multiplying this hourly variation factor with a daily average records of respective days. The hourly estimation is validated by using the available data for the whole month of June.

In addition, there are 2(two) recorded data items on the days of 10th of July and 8th of August for daily consumption data which are two or more times lower than records before & after these records (Appendix A). There is also 1(one) data on 13th of September for daily consumption record which seems unrealistic (159.11 kWh) as compared with the other entries in the list and this may be due to recording failure or system in maintenance. Since all those records with lower values and missing data will lead to error in the optimization result, the data is filled by taking those all lack in data as missing data and do linear interpolation using previous and next corresponding values.

Loads are categorized as primary that are in first priority and deferrable loads by assuming more deferrable loads are considered during lower power consumption times and vice versa in order to take in to account that some deferrable loads will become mandatory in some tight or full load working times so as not to affect the system's operation. Assumed list of deferrable loads (Appendix 1C) are taken in three categories as low (parts of listed loads) in higher energy consumption times, medium in medium energy consumption times, and large in lower energy consumption times. These deferrable loads are assumed for load management in the treatment plant in order to reduce the electricity consumption without affecting the treatment plant's operation which will be done by utilizing wastewater storage or lagoon for keeping the incoming waste during peak electricity consumption times (E. P. R. I. United States 2013).

The daily incoming wastewater amount data for 4 months in four seasons is taken from SCADA backup data. Then daily energy used per daily inlet wastewater is analyzed for these months. There was 1(one) missing data on 13th of September and 1(one) data on 20th of June exceeds above the plant's maximum daily treatment capacity for daily wastewater inlet amount & these are filled using linear interpolation using previous and next corresponding values. After such preparations of data monthly, daily & hourly load profiles are prepared & analyzed using MS Excel.

3.2.2 Resource Assessment Methods

3.2.2.1 Biogas resource

Data for daily biogas production potential and data for biogas composition measurement is found from previous measurement records, quarter reports and from the SCADA backup. In addition to previous measurement records, gas measurement has been conducted by using portable biogas analyzer modelled MCA100 BIO-P for biogas composition measurement.

Daily biogas production data on 12th, 14th and 15th September are too low as compared with neighboring days' records and also data for 13th & 25th September are not available or it is zero (Appendix B) which maybe recording failure or system under maintenance or low biogas production capacity. These values are treated as missing and replaced by estimation using moving average technique with 2 intervals. Data for daily biogas production potential and composition of biogas for one year that is 365 data items that will be used for optimization is taken on a daily basis. Here the biogas production potential data is available in Nm^3/day and for HOMER simulation, it is converted to its equivalent tones per day by assuming its density as 1.15 kg/m^3 at normal temperature and pressure (Mitiku Teferra and Wubu 2019). Then these data are summarized, analyzed and daily & monthly biogas resource profile is prepared using MS Excel.

3.2.2.2 Solar Global Horizontal Irradiance

Measurement records for solar Global Horizontal Irradiance (GHI) by the National Meteorology Agency (NMA) for the year 2015 (ranges from January 2015 to December 2015), is used. The record is with a range of 15 minutes and this data is converted to hourly data by averaging the records within the 15 minutes range in the respective hours. Then the daily & seasonal variation of solar resource profile is prepared using MS Excel.

3.2.2.3 Grid

The Grid tariff rates approved by the Council of Ministers Ethiopia on September 2018 for four consecutive years is used. Even if grid is main source of electricity for the plant, it has outages. Data for frequency of this power outage is taken from annual records of standby diesel generator operation and the mean grid repair time is taken from the duration of this generator by supplying electricity for the plant.

3.2.3 Hybrid Energy System components

Components used for the hybrid energy systems this thesis are Biogas generator, Photovoltaic solar panels, Diesel generator, System converter, storage batteries and grid resource for grid connected systems.

3.2.3.1 Biogas generator

The input or fuel source that will be available in KWWTP is from anaerobic treatment process /UASB reactor that produces a significant amount of biogas, although currently it is flared. The produced biogas in the treatment plant mainly consists of 60-75% methane. Getting this energy resource primarily has little or no cost because it is produced or harnessed during other main purpose that is waste treatment. However, when it comes to its utilization it will need gas storage tank and also the gas may need further cleaning and upgrading to increase its purity by removing the unnecessary gas components and these will bring capital & operational cost. For this particular study, the produced biogas is analyzed for electricity production by selecting biogas generator. The power output P_G (t) and energy generated E_G (t) at hour t from the biogas generator can be estimated as follows (Al-Najjar et al. 2022; Anand, Rizwan, and Bath 2019);

$$\boldsymbol{P_G\,(t) = \frac{Q_g \times F_g \times \eta_g}{860 \times H_g}} \qquad \text{Eq. 3. 1}$$

$$\boldsymbol{E_G\,(t) = P_G(t) \times \Delta t} \qquad \text{Eq. 3. 2}$$

Where; Q_g - available biogas per day (m^3/day),

F_g - biogas calorific value (kcal/m^3),

η_g – overall conversion efficiency from biogas to electricity production (28%).

H_g - operating hours of biogas generator per day.

860 – Conversion for kcal to kWh (1 kWh = 860kcal)

$E_G\,(t)$ - energy generated by biogas generator system at hour t

3.2.3.2 Diesel generator

Power option for the treatment plant for the existing plant operation is from the main grid and standby diesel generator. For this study diesel generator is also included in the optimization that will be a backup power source in case of grid outages and lack sun power & little or no biogas production. The fuel consumption by the diesel generator is expressed as (Das, Hasan, and Rashid 2021; Rashid et al. 2021; Sanni et al. 2021);

$$\boldsymbol{F_c = F_1 \times R_d + F_2 \times P_d} \qquad \text{Eq. 3. 3}$$

Where; F_1 - is the intercept coefficient of the fuel curve,

R_d - is the diesel generator's rated capacity,

F_2 - is the slope of the fuel curve,

P_d - is the generator's electrical output at any instant

Then the efficiency of the diesel generator (η_d) can be obtained using (Eq. 3.4) (Das, Hasan, and Rashid 2021; Rashid et al. 2021)

$$\eta_{d} = \frac{P_d \times 3600}{\rho \times F_c \times LHV} \quad \text{Eq. 3. 4}$$

Where; ρ - is diesel fuel density (assumed 820 kg/m^3),

LHV - is lower heating value of diesel fuel (assumed 43,200 KJ/Kg),

3.2.3.3 Photovoltaic (PV) panels

Since manufacturers give the capacity of the specified PV panel is at STC (standard testing conditions, where T = 25°C and Irradiation = 1000W/m^2), the output may vary when these parameters get changed. The power output delivered by the photovoltaic (PV) panel P_{out} is expressed as (Beza, Wu, and Kuo 2021; Das, Hasan, and Rashid 2021; https://www.homerenergy.com/products/pro/docs/latest/index.html (accessed online on July 14, 2022) n.d.);

$$P_{out} = P_{rated} \times D_{factor} \times \left(\frac{G_T}{G_{T,STC}}\right) \times \left[1 + \alpha_p (T_c - T_{c,STC})\right] \quad \text{Eq. 3. 5}$$

Where; P_{rated} = rated PV capacity at STC, D_{factor} = PV derating factor,

G_T = the solar radiation incident on the PV array in kW/m^2

$G_{T,\,STC}$ = incident solar radiation at STC (1000W/m^2 or 1 kW/m^2)

α_p= the temperature coefficient of solar power in %/°C

T_c = the PV cell temperature in °C

$T_{c,STC}$ = the PV cell temperature at STC in °C, 25°C

The PV cell temperature T_c will be expressed as (https://www.homerenergy.com/products/pro/docs/latest/index.html (accessed online on July 14, 2022) n.d.);

$$\boldsymbol{T_c = T_a + G_T \times \left(\frac{\tau\alpha}{U_L}\right) \times \left(1 - \left(\frac{\eta_{pv}}{\tau\alpha}\right)\right)} \quad \text{Eq. 3. 6}$$

Where; τ = the solar transmittance of any cover over the PV in %

α = the solar absorptance of the PV in %

T_a = the ambient temperature in °C

$U_{L,}$ = the coefficient of heat transfer to the surroundings in kW/m^2°C

η_{pv} = efficiency of PV

G_T = the solar radiation incident on the PV array in kW/m^2

It is difficult to directly measure the $\tau\alpha/U_L$ value, so it is determined from the manufacturers' nominal operating cell temperature (NOCT), defined as the cell temperature which results at an incident radiation of 0.8 kW/m^2, an ambient temperature of 20°C, and no-load operation (meaning $\eta_c = 0$). By substituting these values into Eq. 3.6, T_c becomes;

$$\boldsymbol{T_c = T_a + (T_{c,NOCT} - T_{a,NOCT}) \times \left(\frac{G_T}{G_{T,NOCT}}\right) \times \left(1 - \left(\frac{\eta_{pv}}{\tau\alpha}\right)\right)} \quad \text{Eq. 3. 7}$$

$$T_c = T_a + (T_{c,NOCT} - 20) \times \left(\frac{G_T}{0.8}\right) \times \left(1 - \left(\frac{\eta_{pv}}{\tau\alpha}\right)\right)$$

Where; $T_{a,NOCT}$ = the ambient temperature at which the NOCT is defined (20°C)

$T_{c,NOCT}$ = Nominal Operating Cell Temperature in °C

$G_{T,\,NOCT}$ = the solar radiation at NOCT (0.8 kW/m^2)

Estimate of 0.9 for $\tau\alpha$ can be used without serious error since the term $\eta_{pv}/(\tau\alpha)$ is small compared to unity (Duffie and A. 2013).

3.2.3.4 System Converter

A bi-directional system converter that incorporates a rectifier application (to convert Alternating Current (AC) to Direct Current (DC) when extra AC (from Grid, biogas & diesel generators) is needed to be stored in the batteries and an inverter application (to convert DC to AC) to utilize stored energy in a battery. The output from the inverter can be found as follows by Eq. 3.8 (Aderemi et al. 2018; Sanni et al. 2021)

$$\boldsymbol{P_{out\ inv}} = \boldsymbol{P_{in\ dc}} \times \eta_{\boldsymbol{inv}} \qquad \text{Eq. 3. 8a}$$

$$\boldsymbol{P_{out\ rec}} = \boldsymbol{P_{in\ ac}} \times \eta_{\boldsymbol{rec}} \qquad \text{Eq. 3. 9b}$$

Where; $P_{out\ inv}$ – AC output power from the inverter, P_{indc}–DC input power to the inverter,

η_{inv} – efficiency of inverter, $P_{out\ rec}$ –*DC* output power from the rectifier,

$P_{in\ ac}$ - *AC* input power to the rectifier, η_{rec} – efficiency of rectifier

3.2.3.5 Battery

The battery system serves as a storage for energy when there is excess energy production than needed by the system loads and act as a supply for energy when there is shortage of energy. The Depth of Discharge (DOD), battery capacity & efficiency and battery system voltage mainly affect sizing of battery. The battery system energy storage capacity P_{batt} (Watt-hour) can be expressed as (Al-Najjar et al. 2022; Salisu et al. 2019);

$$\boldsymbol{P_{batt}} = \frac{\boldsymbol{P_{load}} \times \boldsymbol{T}}{\boldsymbol{DOD} \times \eta_{\boldsymbol{batt}} \times \eta_{\boldsymbol{inv}}} \qquad \text{Eq. 3. 10}$$

Where; P_{load} - daily demand electrical AC load, T – days of autonomy (the backup time)

DOD – depth of discharge, η_{batt} – battery efficiency

η_{inv} – AC load conversion efficiency.

Furthermore, when hourly generated power is more than load demand, the excess energy will be stored in the battery (charging state) and when the load demand is more than the generated power, then the shortage of energy will be taken from the battery (discharging state). For the charging state and discharging state the battery capacity can be found using (Eq. 3.10) & (Eq. 3.11) respectively as follows (Anand, Rizwan, and Bath 2019);

$$\boldsymbol{E_b(t) = (1-\gamma) \times E_b(t-1) + \eta_{ch} \times E_{gexc}\,(t)} \qquad \text{Eq. 3. 11}$$

Where; γ – is the self-discharging rate of battery at hour t, η_{ch} - charging efficiency

$E_b(t)$ – is the amount of energy stored in the battery in kWh,

$E_{gexc}(t)$ – is the excess energy generated (kWh) after meeting the load demand

$$\boldsymbol{E_b\,(t) = (1-\gamma) \times E_b(t-1) - \frac{E_{def}}{\eta_{inv} \times \eta_{dis}}} \qquad \text{Eq. 3. 12}$$

Where; η_{dis} - discharging efficiency, η_{inv} = inverter efficiency

$E_{def}(t)$ – is the amount of unmet demand (shortage energy) in kWh,

$E_d(t)$ = load demand

CHAPTER FOUR – LOAD AND RESOURCE ASSESSMENT

In this chapter, results of load assessment & available energy resources' profiles of the plant are discussed. As it is described in Chapter 3 data for loads is taken from consumption records. Biogas resource data it is taken from records of biogas flared in each day. The solar resource & temperature data are taken from National Meteorology Agency (NMA) records for one year is used.

4.1 Load Assessment

The Load profile of the plant is analyzed in monthly, daily and hourly basis. Variations of load, peak, minimum power consumption operation times are identified. The consumption data are overall treatment plant load including the main treatment system loads and auxiliary plant loads such as office, laboratory, and store, other inside the treatment plant loads.

4.1.1 Monthly load profiles

Monthly plant's energy consumption for the year 2021-22 (from July 2021 to June 2022) shows that the plant has a relatively maximum consumption of about 46660 kWh and minimum consumption of about 35990 kWh in March 2022 and July 2021 respectively, Figure 4.1. The total annual consumption from July 2021 to June 2022 is about 509,325 kWh based on records in the treatment plant.

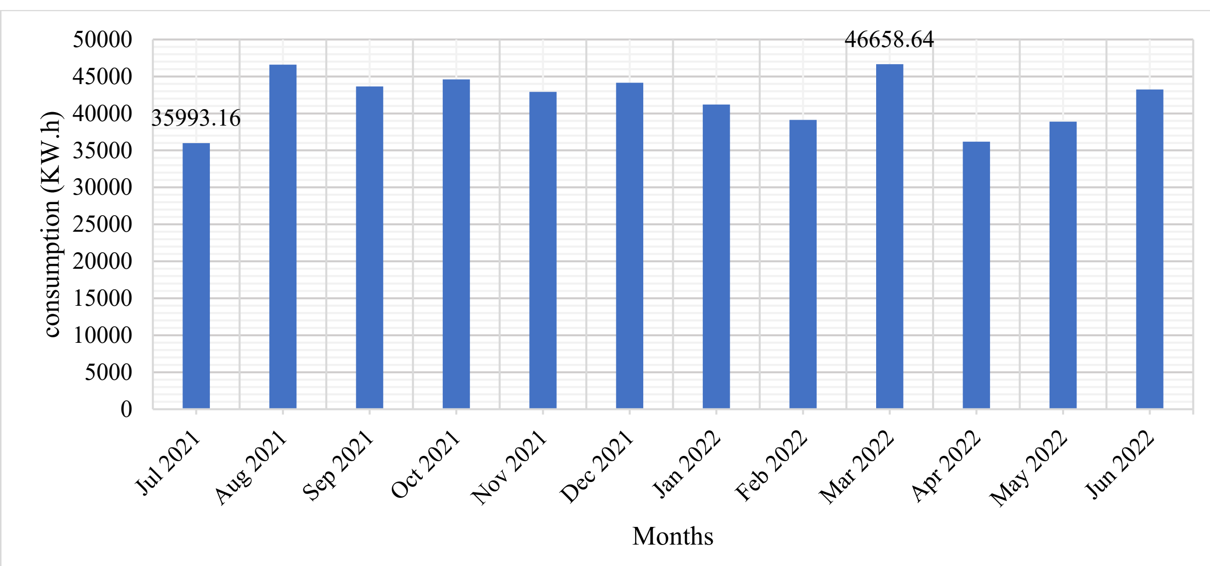


Figure 4. 1: Monthly Consumption

4.1.2 Daily load profiles

The daily variation of loads during 12 months of the year are depicted in Figure 4.2. It describes that there is relatively higher consumption during ninth of Aug & 5th of October. The next higher consumption among 12 months was recorded in days found in June that will be due to the availability of storm water because of the rainy season, the more waste is coming to be treated so do for the energy consumption. Days in months from November up to May have patterns close to each other. The overall consumption pattern profiles show that plant's consumption is varying based on the incoming waste amount and type of waste.

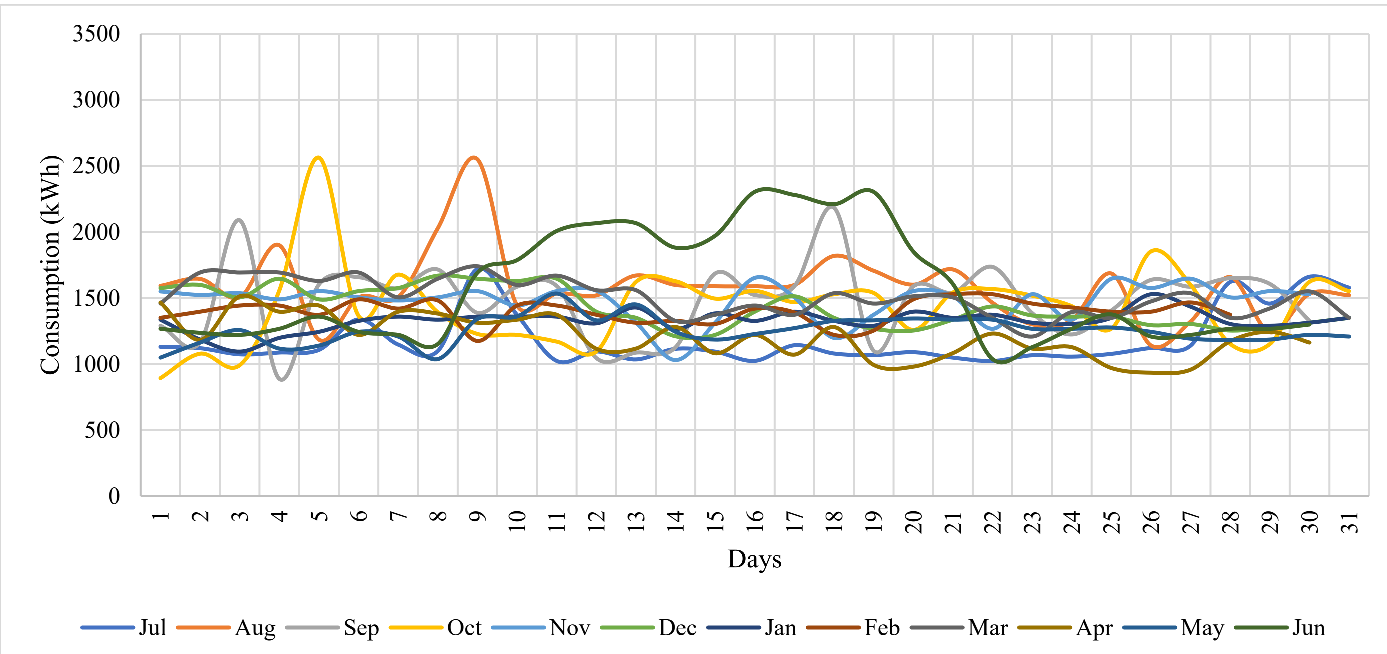


Figure 4. 2: Monthly Consumption Profile

4.1.3 Hourly load profiles

In most of the days, the peak consumption hours or time ranges duration from 00:00 – 09:00 & from 18:00 – 23:00 and relatively drops from 10:00 – 17:00. However, there are exceptional consumption patterns. For instance, on *June 15 &19* higher consumption from 00:00 – 23:00 except 07-08 & 15:00-17:00, on *June 11* increases or higher consumption from 01:00 – 23:00, on June 14 decrease from 00:00-18:00 and increase from 19:00-23:00, on *November 17* increases from 00:00 - 07:00 and drops from 08:00 – 23:00. On *November 19* continues with a small change from 00:00 – 07:00 & increases from 07:00-08:00 and stays with small increase from 08:00 – 23:00.

Hourly consumption pattern of days of the year that is for 8760 hours' consumption pattern is described in Figure 4.3 as follows.

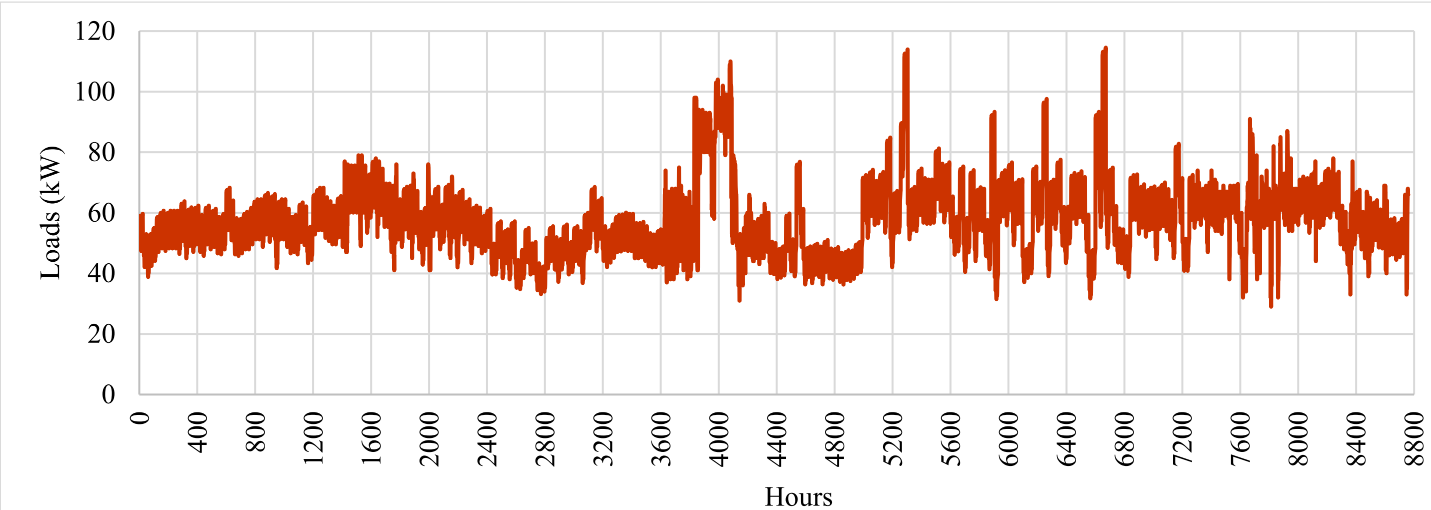


Figure 4. 3: Hourly Consumption Profile of The Year

4.1.4 Consumption and inlet waste water

The daily consumption per inlet wastewater to be treated (kWh/m^3) on four months November, January, March and June that fall on four different seasons is analyzed and described in Figure 4.4. In most of the days this pattern shows the consumption in the treatment plant varies with the amount and content of wastewater entering to the system. There are days with energy consumption is relatively small while the amount of wastewater increases & vice versa. For instance, during 21st, 22nd of November, 2nd, 10th, 14th, 28th of January, 5th, 7th, 10th, 14th, 23rd of March & in the beginning of June consumption drops but inlet increases. Whereas on 11th, 16th, 23rd of November, 6th, 15th, 26th of January, in the beginning, 8th, 9th, 16th, 30th of March, 9th, 12th, 16th, 28th of June consumption is higher but the inlet wastewater drops which will be due to loads like recirculating pumps in the trickling filters come in to operation during hours of low flow conditions and also will be due to the existence of type or level of pollutants in the wastewater.

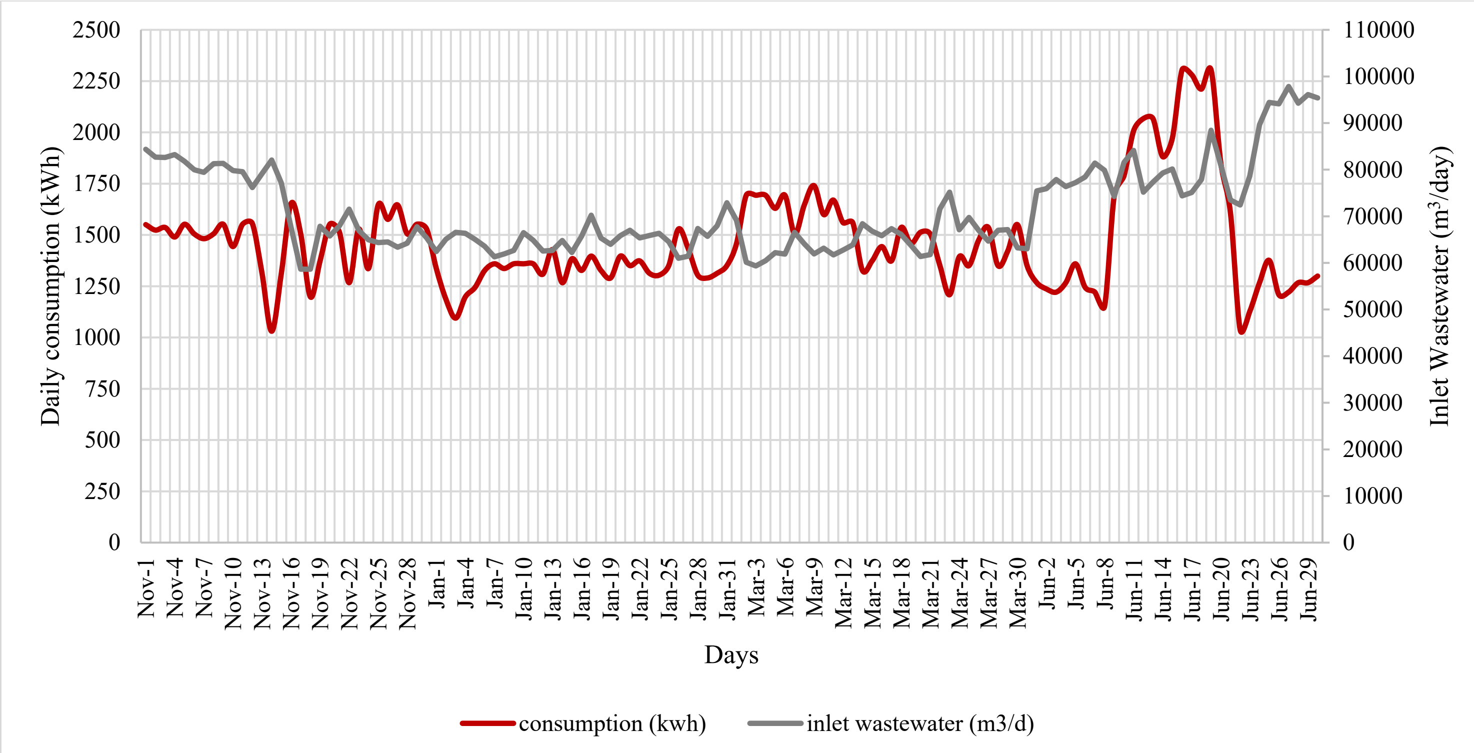


Figure 4. 4: Consumption versus Inlet Wastewater

4.1.5 Validation for load Estimation

The hourly load data for all 30 days in June is taken from records and compared with the estimated load data for this month as shown in Figure 4.5. This was done using the Mean Absolute Percentage Error (MAPE), estimation error (MAPE) was less than 10% (it is 9.85%) which is an accurate estimation (Montaño Moreno et al. 2013). Hourly loads for the rest of months of the year which were not available in records of the plant is also estimated.

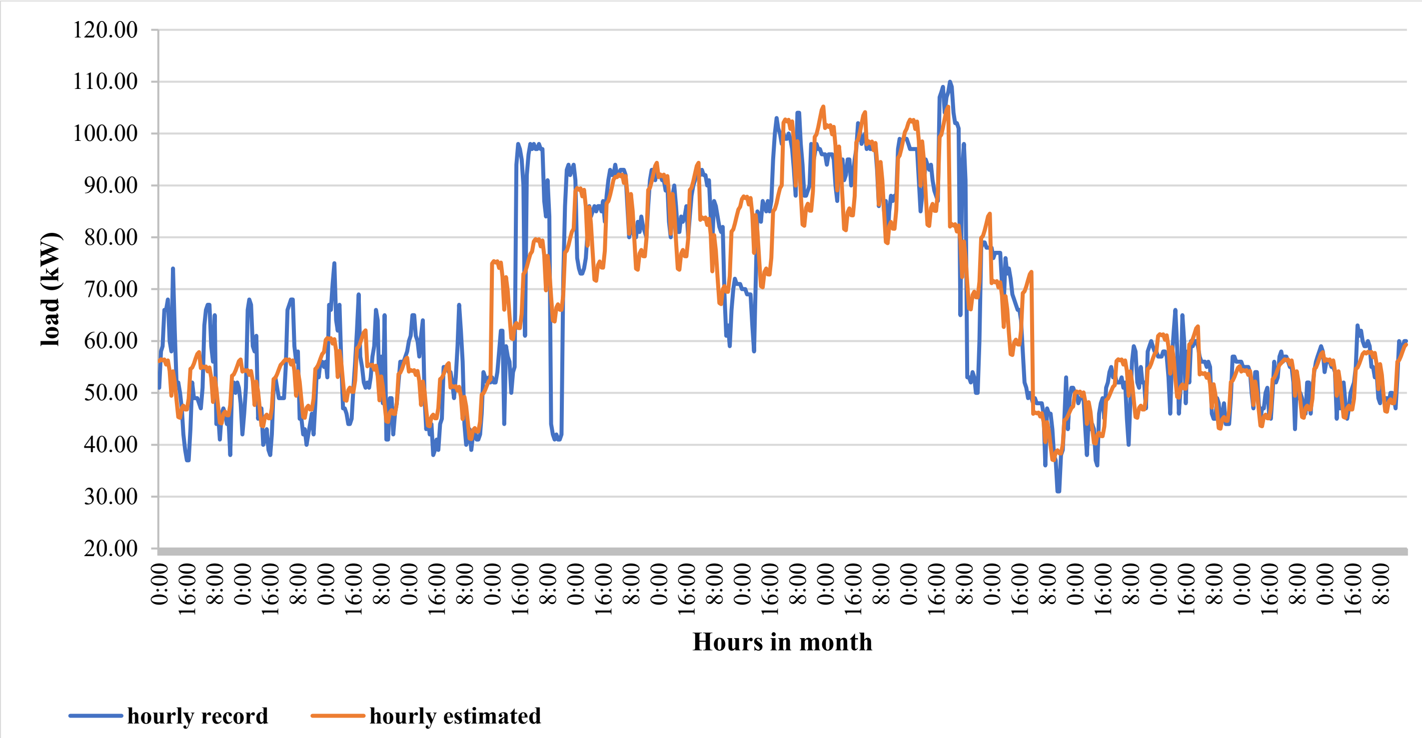


Figure 4. 5: June Hourly Consumption Records & Estimation

4.2 Biogas Resource Assessment

Currently the plant is consuming energy from the grid primarily and the standby diesel generator in case of grid power outages. Here the biogas resource in the treatment plant and the solar energy resource for the area is assessed.

4.2.1 Biogas production

The maximum daily capacity of biogas production in KWWTP is 13,000 Nominal cubic meter (Nm^3) that is a considerable potential. The biogas production capacity on year 2021-2022 is provided on a monthly and daily basis.

4.2.1.1 Monthly Biogas production

From measurement records there was highest biogas production is during May 2022. The nature of variation in biogas production depends on the status of coming waste and this differs among months or among seasons. For instance, in the months of summer season the production of biogas drops and this will be because of the influent waste is diluted due to rainstorm (Suresh et al. 1996). Then the production increases starting from October, Figure 4.6. Whereas May has a relatively higher biogas production and this will be since this month was dry and presence of variety of domestic wastes.

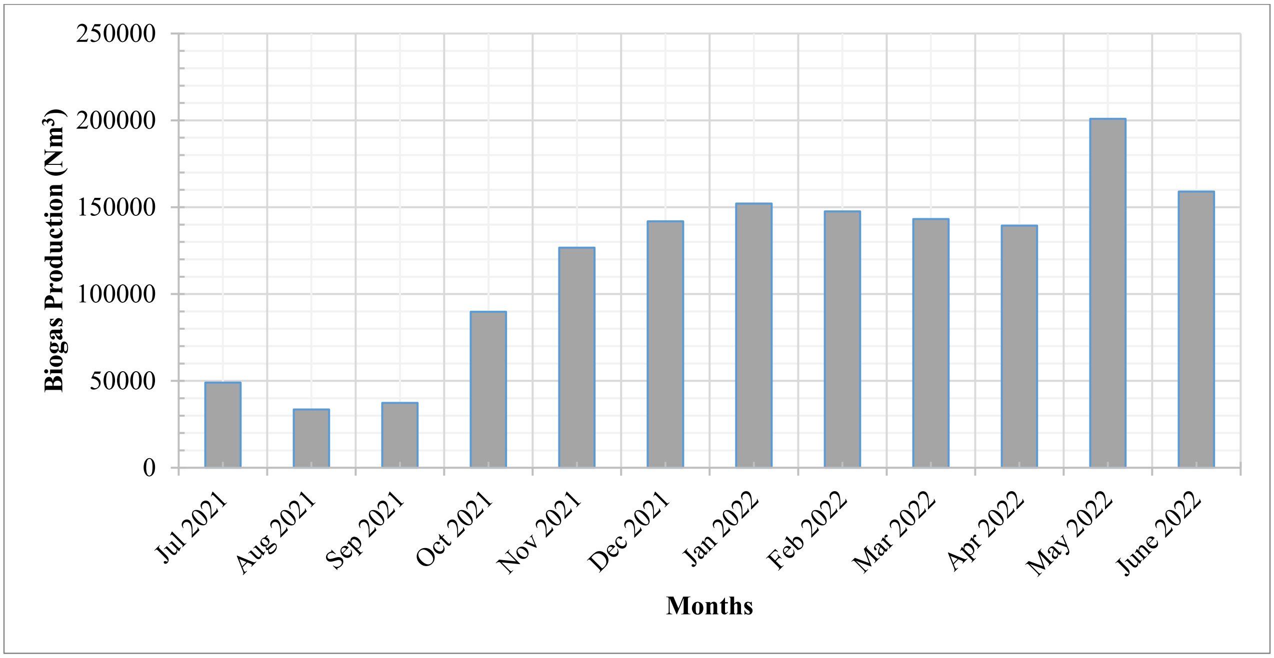


Figure 4. 6: Biogas Production Monthly Profile

4.2.1.2 Daily biogas production

It is possible to see that the plant has a maximum production of biogas with a value of 8016 Nm^3/day during the end of May 2022 and a lower or no biogas production record during 13th & 25th day of September. As it is depicted in Figure 4.7, in the months from December to June, biogas production becomes higher and from July to October, it becomes with a lower production. Biogas production in the plant has a non-uniform pattern in months of the year, it goes up in one incident and down in the other incident. Days in the months from December to June, biogas production becomes higher and from July to October it becomes with a lower. About half of the days in May have higher biogas production.

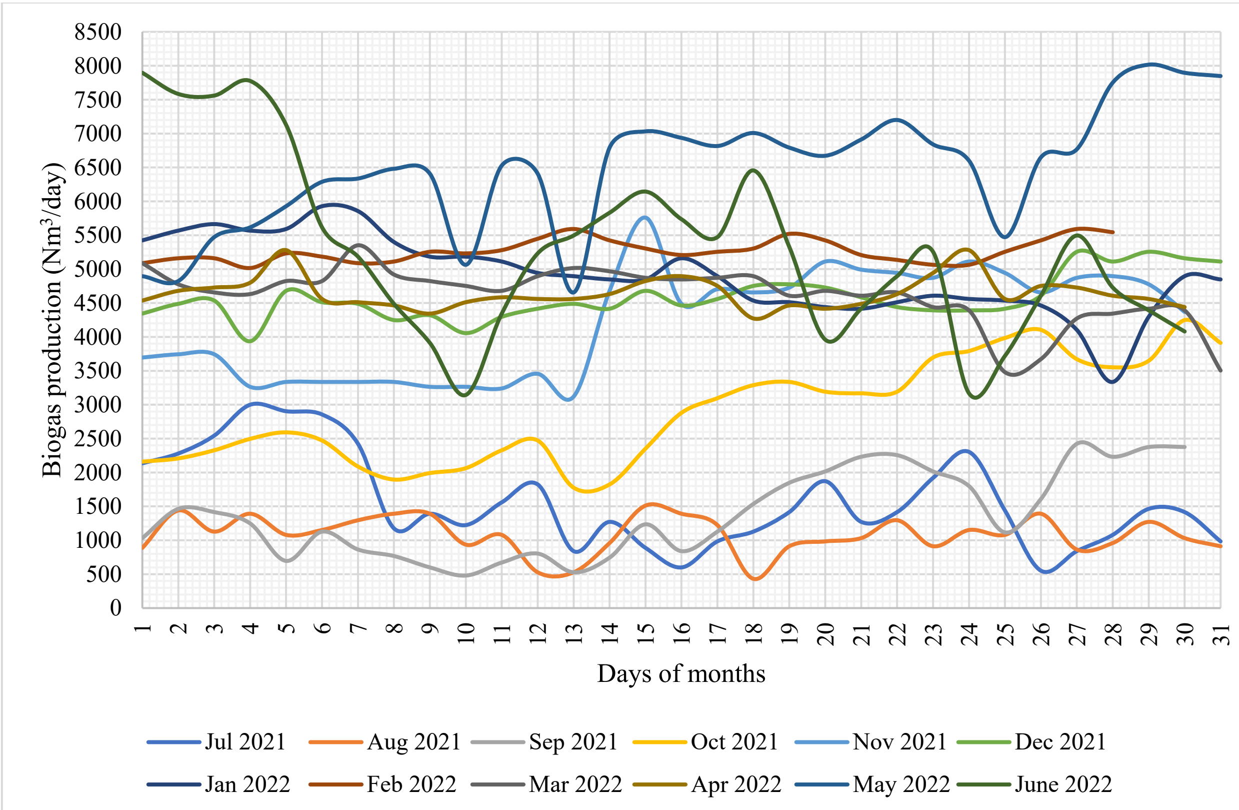
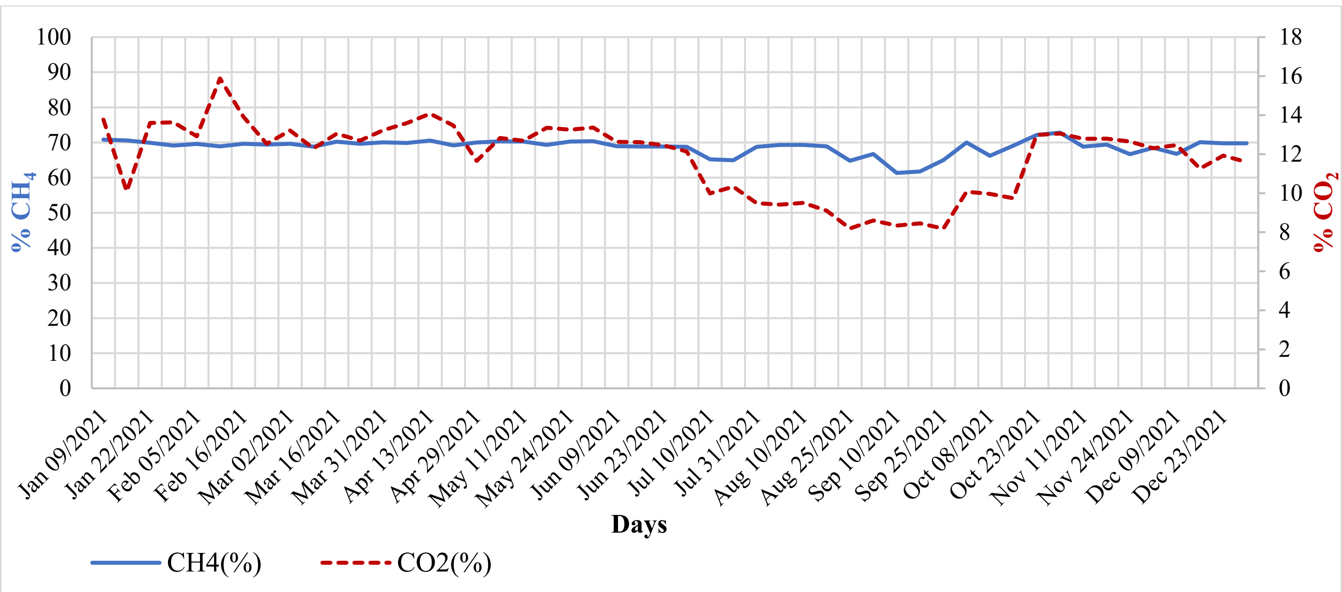


Figure 4. 7: Biogas Daily Profile

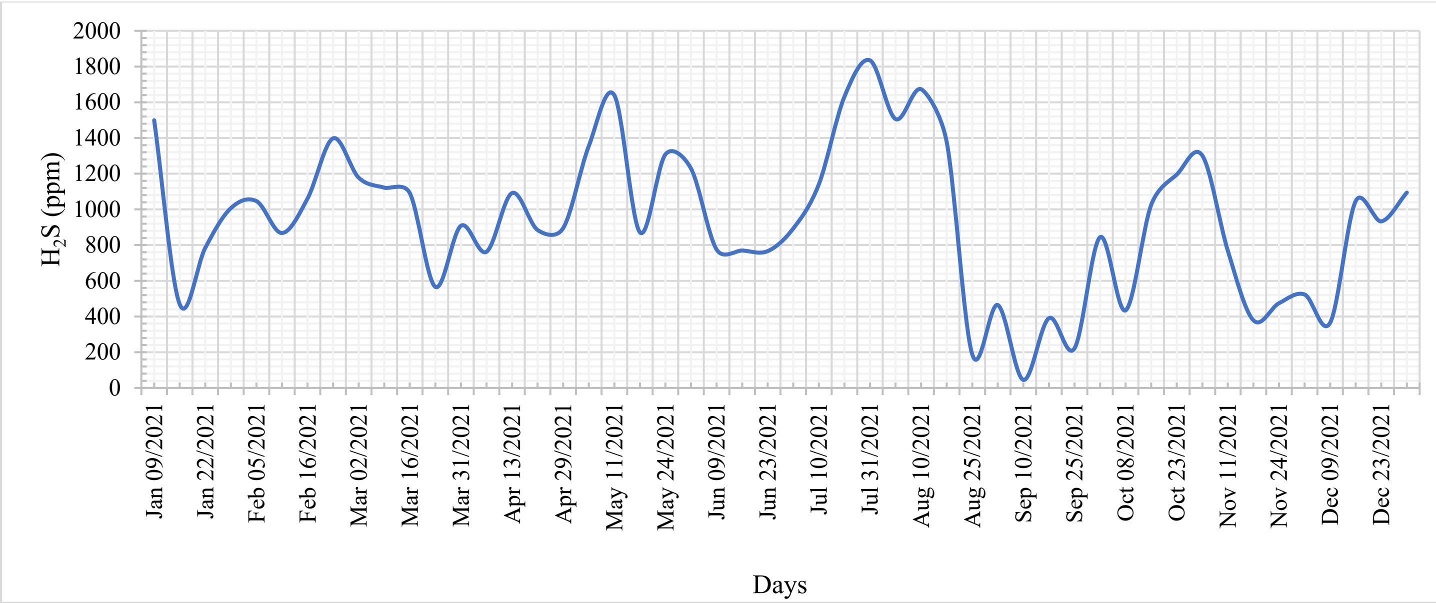
4.2.2 Biogas composition

Biogas composition other than Methane which are CO_2 (carbon di oxide), H_2S (Hydrogen Sulfide), traces of Oxygen, Nitrogen, Carbon Monoxide, Hydrogen are categorized as impurities. From these, H_2S in the gas will affect the metal parts of internal combustion engines & tubing, CO_2 will cause engine power output reduction or reduce have impact on engine's performance (Chen et al. 2015; Mustafi, Raine, and Bansal 2006). As far as the methane content of the biogas increases, it does so for the calorific value of that gas. Therefore, variation of methane content has significant effect on the calorific value of gas (Chen et al. 2015). Based on the record of measurement data of main components of biogas produced by the year 2021 (January 2021 – December 2021) shows that the average value of methane content of the produced biogas ranges from 61.32-72.8%. It gets its maximum of and minimum level during months October (26th Oct) and September (10th Sep) respectively and CO_2 & H_2S contents range is 8.18 – 15.88% & 44.93 - 1834.6 ppm respectively as shown in Figure 4.8 a & b. Both CO_2 and H_2S get relatively maximum values at the same month of the year that is August.

Since the energy contained in the biogas mainly depends on the methane content, as the purity level or methane content decreases so do the calorific value of produced gas. The presence of H_2S exposes energy conversion equipment and accessories such as pipelines, compressors, IC engines etc. to corrosion due to its toxicity that in turn leads to decrease in the lifetime of the engine & increase in maintenance cost and this gas affects humans' health from loss of consciousness to death depending on its amount. CO_2 that is the non-combustible part of biogas, lowers the engine's power output. The impurities found in biogas should be removed or reduced to the maximum allowable amount (Beza, Wu, and Kuo 2021; Huertas, Giraldo, and Izquierdo 2020; Lay Makara, Lor Lytour 2021).



a)



b)

Figure 4. 8: *a)* Biogas composition CH_4 & CO_2 Proportion in Percent *b)* Biogas Composition H_2S Proportion in PPM

The allowable level of H_2S found in the produced biogas to use it in combustion engines for electricity generation should be less than 200ppm and for the plant's gas produced, purification to remove impurities is needed to get a more calorific value that is dependent on the methane portion of the gas. Pure methane has calorific value of 35.8 MJ/Nm^3 (Lay Makara, Lor Lytour 2021). Conducting biogas composition measurement in KWWTP for 5 days, the impact of available methane amount on the calorific value of the produced biogas is described in Table 4.1. UASB (Up-flow Anaerobic Sludge Blanket) reactor in the treatment plant is grouped in to 4 & each of which contains 5 reactor cells labeled as 1A-1E, 2A-2E, 3A-3E, 4A-4E and the first 3 groups, that is 15 of the reactor cells were fully in operation by the time when biogas measurements conducted for this research. This gas measurement is conducted reactor cells labeled 1A-1E, 2A-2E & 3A-3E and result shows the proportion of methane, CO_2, H_2S and other trace compounds.

Table 4. 1: measured calorific values of a biogas with different CH_4 content

Reactor	March 17, 2022		March 25, 2022		June 22, 2022		June 28, 2022		July 30, 2022	
	CH_4 (%)	CV (MJ/Nm^3)	CH_4 (%)	CV (MJ/Nm^3)	CH_4 (%)	CV (MJ/Nm^3)	CH_4 (%)	CV (MJ/Nm^3)	CH_4 (%)	CV (MJ/Nm^3)
1A	72.49	23	69.8	22	68.03	22	63.91	21	61.05	19
1B	70.55	23	68.07	22	67.04	21	62.57	20	62.93	20
1C	71.29	23	68.53	22	68.24	22	62.56	20	63.29	20
1D	71.35	23	69.37	22	68.06	22	63.12	21	62.63	20
1E	70.91	23	65	21	66.97	21	60.19	19	61.88	18
2A	69.76	22	67.39	22	67	21	62.85	20	60.99	20
2B	70.32	22	68.17	22	66.81	21	61.92	20	57.81	18
2C	69.94	22	65.41	21	67.51	22	61.72	20	57.59	18
2D	69.38	22	66.55	21	67.83	22	61.97	20	59.73	20
2E	71.25	23	68.05	22	66.97	21	60.68	19	59.33	19
3A	71.7	23	69.19	22	68.89	22	64	21	60.6	20
3B	70.04	23	68.43	22	67.03	21	63.05	20	61.1	20
3C	70.8	23	66.49	21	58.53	19	58.44	18	59.58	19
3D	67.61	22	64.72	21	67.25	21	60.44	20	60.5	19
3E	66.93	21	66.7	21	65.99	21	60.39	19	61.78	20

Recorded biogas calorific value measurement during the year 2021 (Appendix 3C) and the measurement conducted for this thesis work show that methane content and calorific value of the biogas directly related. The average calorific values of biogas measurement for 5 days is compared with that from available records of biogas measurement during the year 2021 and yields a mean absolute percentage error of 2% that is an acceptable difference. Despite the proportion of oxygen in a raw biogas is 0 – 1% (Ryckebosch, Drouillon, and Vervaeren 2011), gas measurements and previous records in the plant show that there is 5 – 29 % oxygen existing in the produced biogas and this can lead to flammable mixtures being formed with the methane in the biogas and this content therefore needs to be carefully controlled (Petersson 2013).

4.3 Solar Energy Resource assessment

4.3.1 Average Monthly variation of solar resource

According to measurement record from National Meteorology Agency (NMA) for Addis Ababa for one year, the annual average solar radiation varies with seasons. The maximum solar radiation was 5.47 kWh/m^2/day that is in February the next three values are 5.12, 5.02 and 4.99 kWh/m^2/day in October, April and March respectively. The minimum solar radiation data across this year is 3.44 kWh/m^2/day that is in one of the rainy months, June in summer that has cloudy weather and rainfall in most of the days.

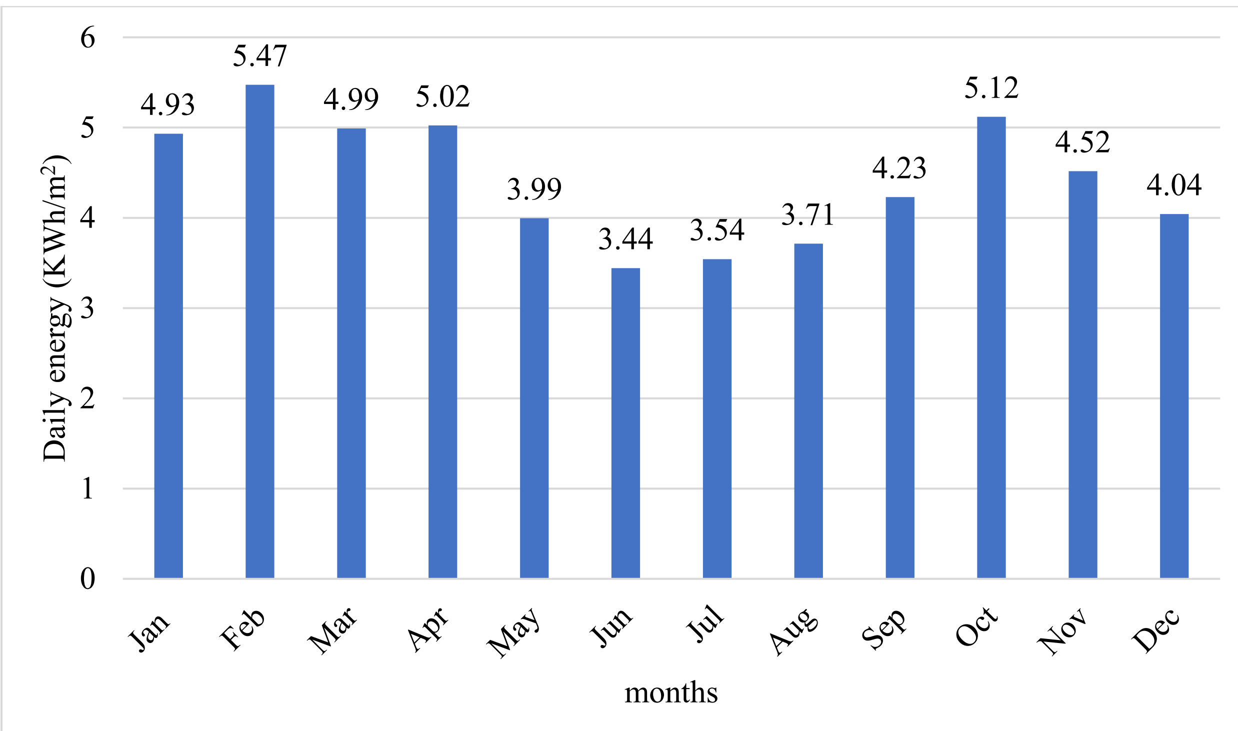


Figure 4. 9: Monthly Average Daily Solar GHI

4.3.2 Daily variation of solar resource

The daily variation of solar energy is observed as the effective sunshine hours range from 09:00 AM to 04:00 PM of the day. For instance, at 12:00 PM & 01:00 PM of February the values are 778.29 W/m^2 and 783.95 W/m^2 respectively. The potential of solar energy in the area varies daily during the day & night and seasonally with a lower potential in summer season that has cloudy and rainy times (as shown in Figure 4.9 & Figure 4.10).

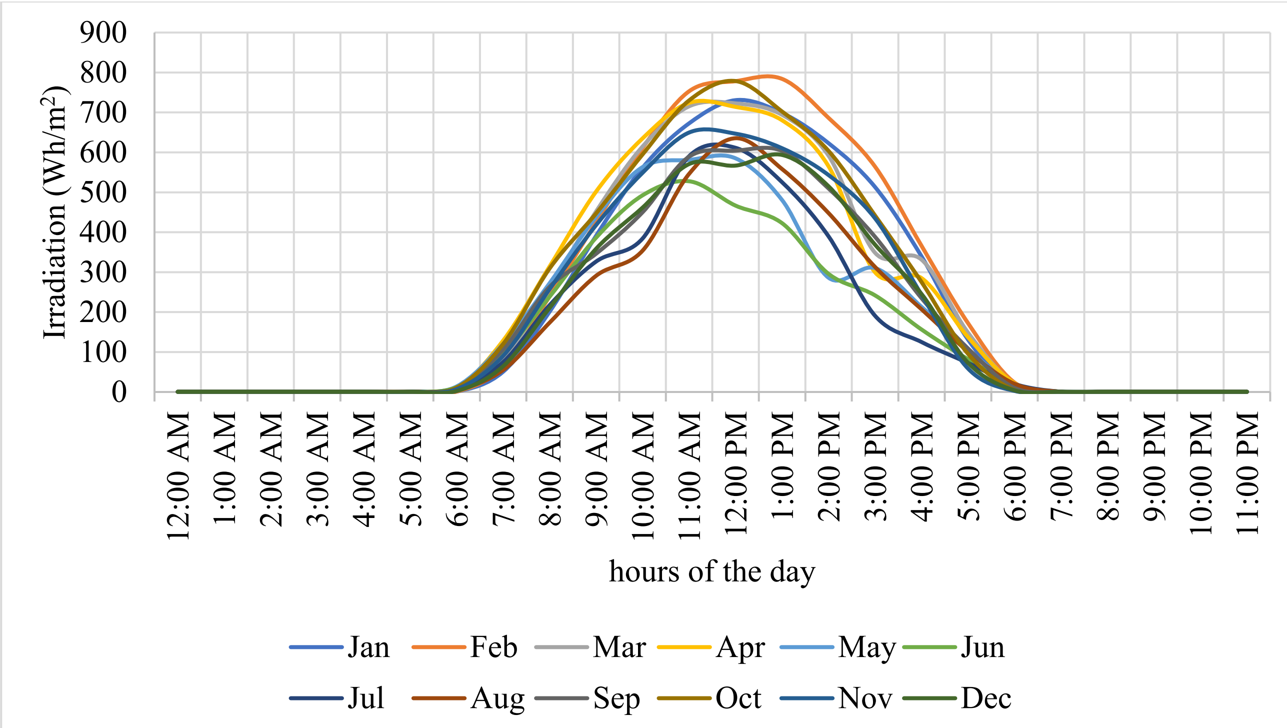


Figure 4. 10: Monthly Average Hourly Solar GHI

Both solar energy potential and biogas production potential are lower in summer seasons, so during these times grid power will meet the unmet load due to scarcity of energy production. in addition to this PV panels cannot generate electricity in night times which in turn means battery storage is needed or the grid with or without the biogas generator will meet the demand during this time.

CHAPTER FIVE – ENERGY SYSTEM MODELING AND OPTIMIZATION

This chapter focuses on the technical, economic and environmental feasibility results of hybrid energy systems with & without consisting grid for KWWTP using HOMER optimization. Costs & specification of selected components, detail parameters set for simulation and simulation results are discussed. Finally, different options of energy systems using the same load type are analyzed and comparison & selection of system configurations based on cost parameters and emission effects are discussed.

5.1 Costs and specification of selected system components

The energy system for this case study consists of biogas and diesel generators, battery for storage, bi-directional converter (which incorporates inverter for DC to AC conversion and rectifier for AC to DC conversion), solar PV panel and grid. The detailed specifications and related cost of selected components are described in Appendix 6.

5.2 Energy System modeling and setting configuration parameters

Loads **–** loads are classified as primary & deferrable, the monthly average values of deferrable loads taken are shown in Table 5.1. The daily primary loads data is described with hourly manner in kilo Watts and the daily energy demand is 1278.24 kWh & a peak load of 110.94 kW for primary loads while for the deferrable loads is 80 kW peak load and 111.75 kWh average daily demand.

Biogas resource - The daily biogas production amount data in Nm^3/d is imported from records & the available daily biogas resource/production in its tones/day equivalent is converted for this modeling and its annual average is 4.4 tones/day.

Biogas Gen-set **-** Generic biogas gen-set is selected for optimization and biomass resource price is almost no cost to produce the biogas, because the primary task is to treat the liquid wastes. In addition, since the process undergoing is biochemical process (not thermochemical process) there is no gasification ratio. However, for simulation purpose it is taken as one (1) because the biogas resource taken is the produced gas. LHV of biogas produced is 22 MJ/Nm^3 = 19.13 MJ/kg @ *NTP* (from previous records of the plant and current measurement using portable gas analyzer). The minimum load ratio, minimum runtime and lifetime is taken as 50%, 10 minutes and 20,000 hours respectively. It is assumed that emissions on exhaust from biogas combustion using ICE by taking maximum values from (Dobslaw et al. 2019) as 2622.3mg/m^3 (2.28 g/Kg) for CO and 2785.3mg/m^3 (2.42 g/Kg) for NO_x.

Table 5. 1: Estimated Deferrable Loads

Months	Average Load (kWh/day)
January	78.6
February	78.6
March	39.9
April	175.6
May	175.6
June	39.9
July	175.6
August	39.9
September	39.9
October	39.9
November	39.9
December	39.9

Carbon contained in CO_2 = 12 / (12+32) = 0.27 & in CH_4 = 12 / (12+4) = 0.75 and Sulfur from H_2S = 32 / (32+2) = 0.94 (Brander 2012). Taking maximum values for proportions components in the produced biogas of CH_4 and CO_2 as 72.80% & 15.88% respectively to get carbon content and H_2S as 1834.60 ppm (1834.6/1,000,000 = 0.001835 = 0.1835%) to get sulfur content in the biogas. Carbon from CO_2 (15.88% x 12/44 = 4.09%) and CH_4 (72.8% x 12/16 = 54.6%) is added up 58.69% and Sulfur from H_2S = 0.1835% x 32/34 = 0.173%.

Diesel Gen-set - Auto Size Gen-set is selected for optimization with minimum load ratio, minimum runtime and lifetime is taken as 50%, 10 minutes *(considering at least warming time during startup & cooldown time for shutdown)* and 20,000 hours respectively. Sensitivity for fuel is considered as 1USD and1.5USD.

Grid – Based on the approved electricity tariff by the Council of Ministers Ethiopia on September 2018 for four consecutive years, the previous grid off-peak and on-peak rates are not employed for industry customers rather flat rate is designed, reactive power payment for the reactive power consumption less than 90% and demand rates are set. According to this, for the year 2021 the grid purchase rate per kWh is taken as 1.193birr/kWh = 0.02237 USD per kWh and the demand charge is 147.54birr/kw = 2.77 USD/kw times each peak demand (kW) in each month for medium voltage industrial consumers. The Grid emission factors for Ethiopian grid case is assumed as negligible or zero (Selvakkumaran and Silveira 2019) since power generation is almost from renewable energy resources. *(Conversion for ETB to USD is based on Currency exchange rate on 12th Aug 2022, 1USD = 53.3251ETB)*

The random power outages from a grid are taken from the previous operation records of the treatment plant as 252 times with mean repair time of 3.11 hours (Appendix 5) and variability in repair time (*The standard deviation of a grid failure duration, expressed as a percentage of the mean, with percentages more than 100% are allowed* (Homer Energy 2016)) is 136.63%.

PV panels - Generic flat plate PV is selected for optimization and its lifetime is taken as 20 & 25 years and that for derating factor 80% & 75% the temperature and solar GHI data is taken from National Meteorological Service Agency data. Default panel slope and default panel azimuth for HOMER is used.

Battery & system converter - Generic 1 kWh lead acid battery with 10-years lifetime & 800 kWh and generic system converter with lifetime 10 years & efficiency of 95% is used for optimization.

Constraints – the annual capacity shortage is set to 0% and the operating reserve is taken as 20% as percentage of the load in current time step.

Emission **–** For optimization purpose, the rates for emission penalty is taken from carbon tax rate of South Africa US$ 9.15 per ton of CO_2e as of April 2021 (United Nations 2021). And this value is converted for other GHGs by the relationship of global warming potential of CH_4 is 25 times more than CO_2 and that for NO_2 is about 298 times more than CO_2 in the 100 years' time horizon (Brander 2012).

Values for limits on emission are taken from World Health Organization (WHO) air quality guideline levels as CO = 4mg/m^3 in 24hr averaging time, $PM_{2.5}$ = 5μg/m^3 in annual averaging time, PM_{10} = 15μg/m^3 in 24hr averaging time, SO_2 = 40μg/m^3 in 24hr averaging time, NO_2= 10μg/m^3 in annual averaging time (World Health Organization 2021). So, assuming plant's annual biogas production of 1,420,512 Nm^3 the annual limits of emission from CO = 4 x 10^{-6} x 1420512 = 5.682 kg/year, from $PM_{2.5}$ = 5 x 10^{-9} x 1420512 = 0.0071kg/year, from SO_2 = 40 x 10^{-9} x 1420512 = 0.05682 kg/year from NO_2 = 10 x 10^{-9} x 1420512 = 0.0142 kg/year through combusting biogas in IC engine.

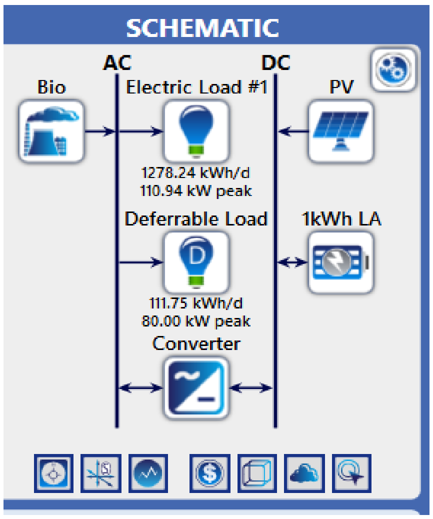
Economics **–** a project lifetime of 25 years, a nominal discount rate of 14.25% average value and expected inflation rate of 3.5% which is taken from non-food inflation in Ethiopia on 2nd quarter of 2021/22 (NBE 2022).

5.3 Modeling & Optimization results

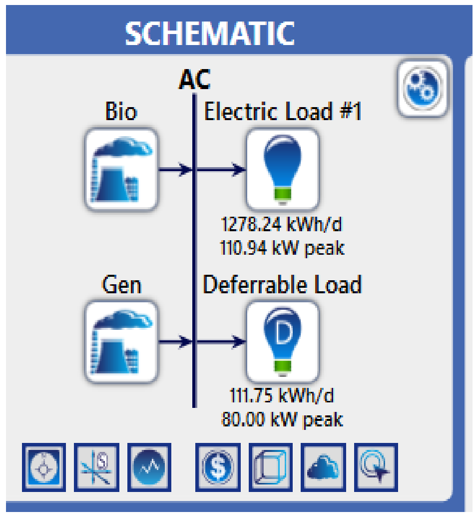
Optimization results show using diesel gen-set standalone as well as integrating it with other sources is not found viable unless limits on emission are eliminated. The configurations analyzed are total of eleven (11) cases with five (5) grid connected & six (6) off-grid energy system types analyzed to assess both alternatives and their performances are investigated based on economic parameters and other technical parameters. During simulation there are energy systems which will not have a result provided by HOMER due to its emission limit factors assigned. So it is necessary to ignore this emission limit & observe the system's performance. Ignoring the emission limits is to mean that assuming there is no emission limits for the simulation purpose only, it not to mean that the emission amount released from the respective energy system is not identified or quantitatively described.

5.3.1 Off-Grid systems

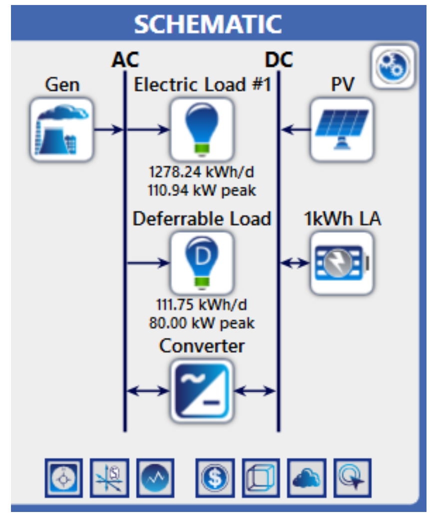
Energy system options under this category are PV-Biogas, Biogas-Diesel, PV-Diesel, Biogas standalone, and PV standalone as shown in Figure 5.1. The performances of these energy systems are examined based on cost parameters such as NPC, LCOE, operating cost & initial capital and technical parameters mainly with excess electricity, unmet load, capacity shortage, equipment used, power generation share.



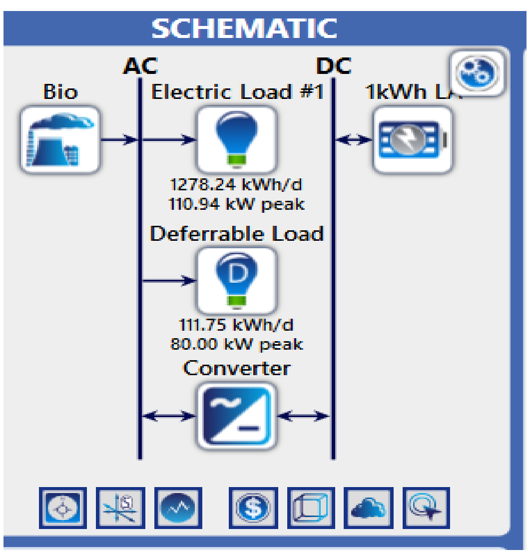
PV-Biogas



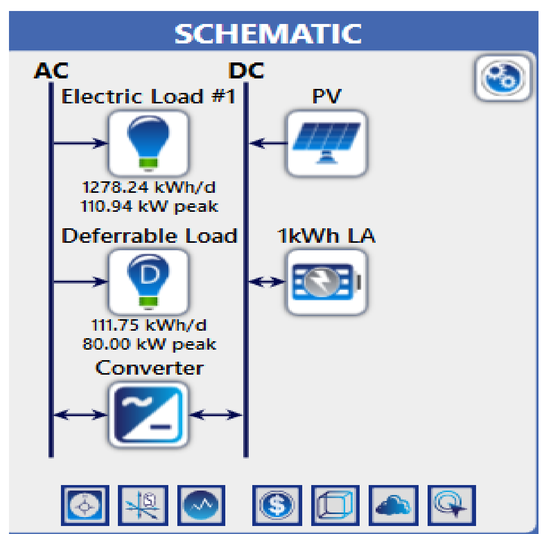
Biogas-Diesel



PV-Diesel



Biogas standalone



PV standalone

Figure 5. 1: Schematic for Off-Grid Energy System Configurations

5.3.1.1 PV-Biogas-Battery

This scheme is analyzed using PV panels with 25-years lifetime & 80% derating factor and biogas gen-set. When battery is not included in this system there is no result if NO_x limits is not ignored. And even if emission limit is ignored and Maximum Power Point Tracking (MPPT) is used for PV, the system has Net Present Cost (NPC) of 13.3M USD, Cost of Energy (COE) of 2.97 USD, biogas gen-set produces 337,571 kWh/year, PV generates 654,537 kWh/year. Moreover, excess electricity of 47.8%, in which there is a small change in excess electricity & biogas gen-set power generation share both for Load Following (LF) and Cycle Charging (CC) dispatches for this system type.

Whereas considering NOx limits, using battery & MPPT the system provides NPC of 3.66M USD and 41.7% excess electricity. In this case biogas gen-set produces 2,620 kWh/year and PV generates 1,033,811 kWh/year in which it has larger proportion & this will increase the initial capital of the system. In this case, it is observed that the excess electricity is too much that it is about close to the annual consumption of the system. The LCOE becomes 0.819USD/kWh as shown in Table 5.2. Components of the system are described in Table 5.3. This result is for LF dispatch but it becomes greater NPC & COE and smaller excess electricity & production by both PV & biogas gen-set in CC dispatch.

5.3.1.2 Biogas-Diesel

When limits on NOx emissions considered, no result is found for this configuration. By ignoring this limit and using biogas gen-set as a main source of power and diesel gen-set for backup, the power generation share of diesel gen-set & biogas gen-set and other technical & economic performance of this system is analyzed as shown in Table 5.2 & 5.3 (using a cost of diesel fuel as 1 USD/Liter) for CC dispatch. LF for this case provides greater NPC & LCOE than CC.

When this system incorporates battery and system converter it has NPC & COE 8.66M USD & 1.94$/kWh respectively which is less than that of a system without battery and converter. This is because of increased operational hours of biogas and diesel gen-sets due to the absence of any storage mechanism & this leads to an increased operation and maintenance costs which accounts 90-95% of the total system costs. Power production share of diesel gen-set is lower than that of Biogas gen-set in case of system without battery (Table 5.2) & higher power production share than biogas gen-set in case of system with battery. Due to this emission of pollutants from the system with battery gets more than doubled from the system without battery.

5.3.1.3 PV-Diesel-Battery

PV is taken as a main source and diesel gen-set is used as a backup here. However, this system has no viable result when battery is not included. When battery is included in the system, diesel gen-set has almost no power production share both when this configuration is set to consider emission limits and when emission limits are ignored or increased. Optimization result shows it is almost similar with that of PV standalone (Table 5.2), it has exaggerated excess electricity for CC dispatch and has slight increment in NPC & COE for LF dispatch.

When battery is omitted from this system, simulation has no result unless emission limits are ignored or increased. By doing so, the result shows that diesel gen-set shares power generation (41.8%) and due to this excess electricity reduced by 3.5%, CO_2 emission becomes 299,353kg/year and the O & M costs of diesel gen-set exceeds which in turn increases NPC & COE of 12.9M USD & 2.88USD/kWh respectively.

Table 5. 2: Technical and Economic Performances of Analyzed Off-Grid Systems

S/N	System type	Production by Diesel gen-set *(kWh/ year)*	Production by PV *(kWh/ year)*	Production by Biogas gen-set *(kWh/ year)*	Excess electricity *(kWh/ year)*	Unmet electric load *(kWh/ year)*	Capacity shortage *(kWh/ year)*	RF (%)	Economic Parameters			
									InC *($)*	OC *($/year)*	NPC *($)*	LCOE *($/kWh)*
1	**PV-Biogas-Battery**	---	1,033,811	2,620	432,085 (41.7%)	0	0	100	2.46M	136,006	3.66M	0.819
2	**Biogas-Diesel (***with all emission limits ignored***)**	180,290	---	327,092	0	0	0	64.5	23,153	1.3M	11.5M	2.57
3	**PV-Diesel-Battery**	0	1,107,216	---	502,664 (45.4%)	0	0	100	2.89M	126,742	4M	0.895
4	**Biogas Standalone** – ***A)*** *with battery backup,* **B)** *without battery backup*											
	A	---	---	583,505	0	0	0	100	564,513	1.27M	11.8M	2.63
	B	---	---	563,355	55,992 (9.94%)	0	169	100	30,000	2.2M	19.4M	4.35
5	**PV Standalone**	---	1,139,437	---	535,085 (47%)	342	469	100	2.7M	128,043	3.82M	0.856

Table 5. 3: System Components of Analyzed Off-Grid Systems

S/N	System type	System component type and size					
		PV *(kW)*	**Biogas gen-set *(kW)***	**Diesel gen-set *(kW)***	**Battery *(strings)***	**System converter *(kW)***	**RF *(%)***
1	**PV-Biogas-Battery**	954	125	---	2,788	138	100
2	**Biogas-Diesel (*with all emission limits ignored*)**	---	80	59	---	---	64.5
3	**PV-Diesel-Battery**	1,109	---	140	3,536	138	100
4	**Biogas Standalone**						
	with battery backup	---	125	---	1,505	104	100
	without battery backup	---	125	---	---	---	100
5	**PV Standalone**	1,033	---	---	3,233	141	100

5.3.1.4 Biogas Standalone

In this scheme, biogas gen-set is the main source and battery backup is used. This system has no result unless NOx emission limit is either ignored or increased. By ignoring/increasing NOx emission limit the system will perform with and without battery backup differently with excess electricity, unmet load and capacity shortage and significant change in NPC & COE as shown in Table 5.2 for CC dispatch.

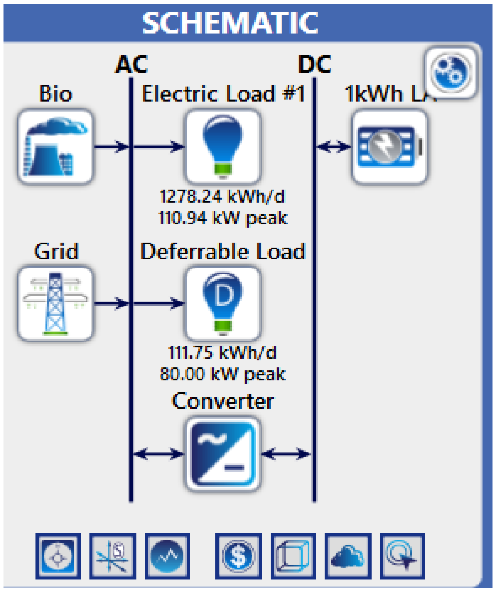
Biogas gen-set without battery has higher cost than that of biogas gen-set with battery due to the reason that when biogas gens-set does not incorporate any backup or storage, it is expected to serve continuously throughout all the operation times which will lead to higher O & M cost and repeated replacement cost due to longer operation hours. But when storage is incorporated the system is served from biogas and storage turn by turn which will help the system to have a smaller O & M and replacement costs. Biogas gen-set without battery performs similar in both LF & CC dispatches but when battery is incorporated, the system provides higher NPC & COE and lesser power generation in LF than in CC dispatch.

5.3.1.5 PV Standalone

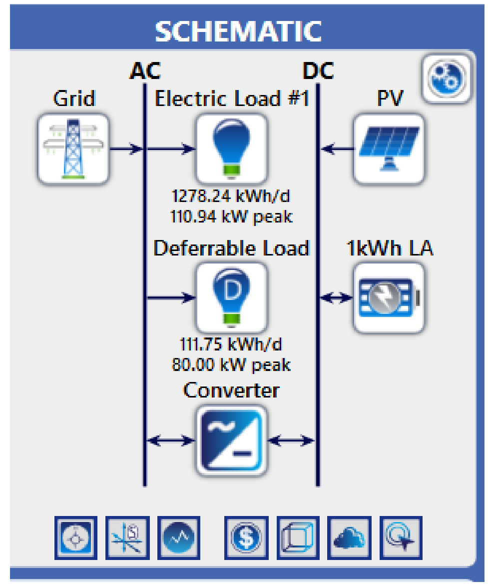
Here PV only with battery, system converter and MPPT is analyzed and the renewable fraction is 100%. In this system there is exaggerated amount of excess electricity produced about 490 MWh/year and this is the highest among all analyzed systems which is close to plant's consumption annually. Technical and Economic parameters for this system are described in Tables 5.2 & 5.3 with CC dispatch. This scheme is found with NPC & LCOE among the analyzed systems as 3.82M USD and 0.856 USD/kWh respectively.

5.3.2 Grid connected energy systems

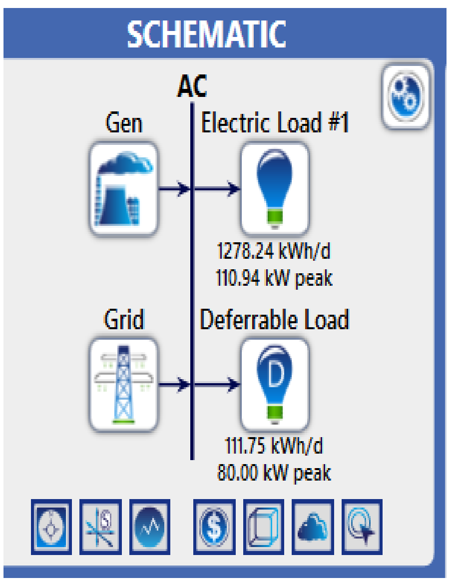
Performances of grid-connected systems with options of Grid-Biogas, Grid-PV, Grid-Diesel and Grid system (Figure 5.2) are investigated based on cost parameters and technical parameters. Results of these energy systems are as described in Table 5.4 & 5.5. The Grid-Diesel system is analyzed to assess performance of the existing energy system.



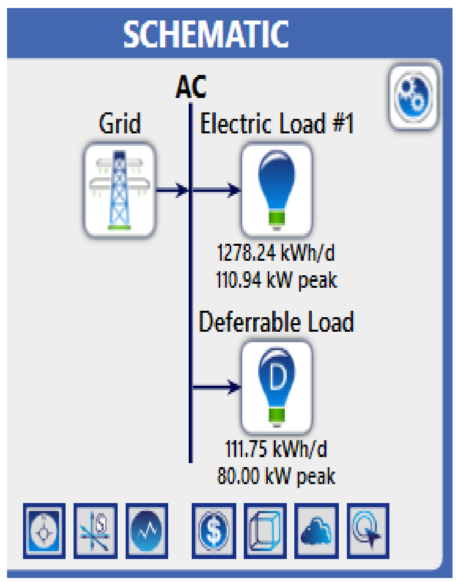
Grid/Biogas



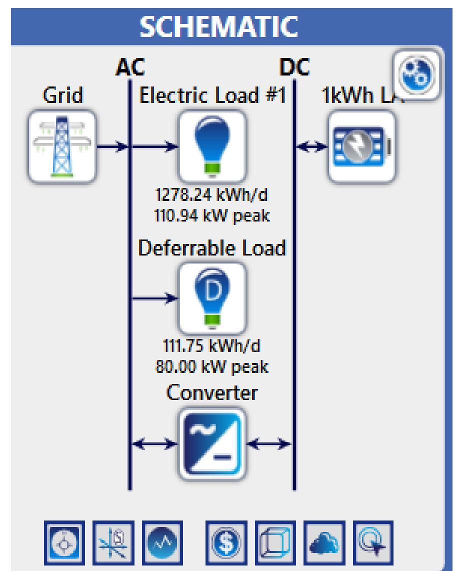
Grid/PV



Grid-Diesel



Grid System with no outages



Grid System with Outages

Figure 5. 2: Schematic for Grid-Connected Energy System Configurations

5.3.2.1 Grid-Biogas-Battery

This scheme considers to integrate the main grid with tariff of 0.02237USD per kwh and biogas gen-set. Components for this system are described in Table 5.5 are used. This system simulation has no result unless limits on NOx emission is eliminated or ignored and by ignoring this limit, the scheme gives a result for the actually existing frequency of power outage with its respective repair time that is 252 power outages per year with 3.11 mean repair time. When battery is incorporated in this system, the system has reduced size of the biogas gen-set which provides lower O & M costs, NPC & COE (Table 5.4) with CC dispatch. Operating cost of the system is high due to O & M cots for biogas gen-set, replacement cost for storage battery and biogas gen-set. Grid-Biogas scheme without battery has NPC of 2.02M USD & LCOE of 0.453 USD/kWh respectively for CC dispatch by ignoring limits to Nitrogen Oxides' emission.

5.3.2.2 Grid-PV-Battery

PV integrated with the Grid is another option studied in this case. This Grid-PV scheme is not found viable without system converter & battery. Grid is analyzed by considering its unavailability or power outages 200 & 252 times a year with mean repair time of 2hour & 3.11 hours. PV with 25-year life time & 80% derating factor generates 355,447 kWh/year for 200 times by 2hours, 431,199 kWh/year for 252 times by 2hours, 447,798 kWh/year for 252 times by 3.11hours with CC dispatch. Results for this case are described in Table 5.4 and 5.5.

Table 5. 4: Technical and Economic Performances of Analyzed Grid Connected Systems

S/N	System type	Grid Purchase *(kWh/ year)*	Production by PV *(kWh/ year)*	Production by diesel gen-set *(kWh/ year)*	Production by Biogas gen-set *(kWh/ year)*	Excess electricity *(kWh/ year)*	Unmet electric load *(kWh/ year)*	Capacity shortage *(kWh/ year)*	RF** *(%)*	Economic Parameters			
										InC *($)*	OC *($/year)*	NPC *($)*	LCOE *($/kWh)*
1	**Grid-Biogas-Battery (***with NO_x emission limits ignored***) – *A)*** *with 200 annual outages & 2hour repair time,* ***B)*** *with 252 annual outages & 2hour repair time,* ***C)*** *with 252 annual outages & 3.11-hour repair time*												
	A	465,463	---	---	40,597	0.04	391	483	8.02	63,005	100,063	944,949	0.212
	B	452,626	---	---	53,542	0	300	461	10.6	47,796	124,422	1.14M	0.257
	C	420,586	---	---	85,452	0	406	406	16.9	109,068	191,657	1.8M	0.403
2	**Grid-PV-Battery – *D)*** *with 200 annual outages & 2hour repair time,* ***E)*** *with 252 annual outages & 2hour repair time,* ***F)*** *with 252 annual outages & 3.11-hour repair time*												
	D	280,016	355,447	---	---	15,374 (2.42%)	380	505	53.2	932,073	49,737	1.37M	0.26
	E	270,606	431,199	---	---	80,918 (11.5%)	315	490	54.7	1M	50,076	1.44M	0.274
	F	254,177	447,798	---	---	49,157 (7%)	358	498	59.2	1.22M	65,994	1.81M	0.329

S/N	System type	Grid Purchase *(kWh/ year)*	Production by PV *(kWh/ year)*	Production by diesel gen-set *(kWh/ year)*	Production by Biogas gen-set *(kWh/ year)*	Excess electricity *(kWh/ year)*	Unmet electric load *(kWh/ year)*	Capacity shortage *(kWh/ year)*	RF** *(%)*	Economic Parameters			
										InC *($)*	OC *($/year)*	NPC *($)*	LCOE *($/kWh)*
3	**Grid-Diesel G*)*** *with 200 annual outages & 2hour repair time, H) with 252 annual outages & 2hour repair time, I**)** with 252 annual outages & 3.11-hour repair time with emission limits ignored*												
	G	464,983	---	41,475	---	2.83	0	0	0	9,380	150,991	1.34M	0.3
	H	455,426	---	51,039	---	2.83	0	0	0	9,380	182,076	1.61M	0.362
	I	430,266	---	76,169	---	2.86	0	0	0	9,380	264,518	2.34M	0.524
4	**Grid System – *J)*** *Grid without outages,* ***K)*** *Grid with outages 40 times a year & 1hour repair time*												
	J	506,478	---		---	0	0	0	0	0	16,515	145,559	0.0326
	K	503,228	---		---	0	357	471	0.6	1.76M	166,632	3.23M	0.724

** take into consideration that HOMER takes grid power as non-renewable resource

Table 5. 5: System Components of Analyzed Grid Connected Systems

S/N	System type	System component type and size					
		PV ***(kW)***	**Biogas gen-set** ***(kW)***	**Diesel gen-set** ***(kW)***	**Battery** ***(strings)***	**System converter** ***(kW)***	**RF**** ***(%)***
1	**Grid-Biogas-Battery (*with NOx emission limits ignored*)**						
	with 200 annual outages & 2hour repair time	---	70	---	118	13.5	8.02
	with 252 annual outages & 2hour repair time	---	75	---	71	10.6	10.6
	with 252 annual outages & 3.11-hour repair time	---	80	---	217	31	16.9
2	**Grid-PV-Battery**						
	with 200 annual outages & 2hour repair time	307	---	---	1,151	130	53.2
	with 252 annual outages & 2hour repair time	356	---	---	1,155	112	54.7
	with 252 annual outages & 3.11-hour repair time	375	---	---	1,730	140	59.2
3	**Grid-Diesel (*with emission limits ignored*)**						
	with 200 annual outages & 2hour repair	---	---	140	---	---	0

S/N	System type	System component type and size					
		PV ***(kW)***	**Biogas gen-set** ***(kW)***	**Diesel gen-set** ***(kW)***	**Battery** ***(strings)***	**System converte r** ***(kW)***	**RF**** ***(%)***
	time						
	with 252 annual outages &2hour repair time	**---**	**---**	140	**---**	**---**	0
	with 252 annual outages & 3.11-hour repair time	**---**	**---**	140	**---**	**---**	0
4	**Grid System**						
	without outages	**---**	**---**	---	**---**	**---**	0
	with annual outages 40 times & 1hour repair time	**---**	**---**	---	5,655	78.3	0.6

** take into consideration that HOMER takes grid power as non-renewable resource

5.3.2.3 Grid -diesel

This scheme has no result for the existing situation of power outage frequency with its respective mean repair time (252 annual power outages with 3.11 mean repair time) unless emission limits are ignored. With emission limits ignored, a fuel cost of 1USD & 252 annual power outages with 3.11 mean repair time the system provides COE & NPC of 0.524 USD & 2.34M USD respectively as shown in Table 5.4 with LF dispatch which is lower than in CC dispatch. The main cost in this scheme is diesel fuel cost, O&M cost for diesel gen-set and grid energy cost.

5.3.2.4 Grid System

Grid by assuming no grid power outages & with power outages considered is studied in this system for comparison as described in Table 5.4. For the first one since there is no power outage, no need to have a system converter and battery. Whereas for grid with power outages considered, system converter and battery are needed and in addition the frequency of grid outage should not exceed 40 times per year with a mean repair time of not more than 1 hour. Other than this, grid system with outages considered has no result for the actually existing power outage with respective repair time unless the allowed capacity shortage is increased (even a grid with outage frequency more than 50 or 60 will have result by increasing limit of capacity shortage, but this in turn will increase unmet electricity and capacity shortage). It will have a feasible result if other energy options such as diesel generator by eliminating limits on emission or other renewable energy source incorporated. The investment or cost for grid system with outages is mainly for the initial capital, O & M, replacement of battery and system converter, cost of energy & demand charge for the Grid. The cost for grid system without outages considered is only for energy cost and demand charges.

5.4 Emission Analysis

Emissions are identified only from both off-grid and grid connected energy generation & conversion systems not from other operational parts in the treatment plant. Limits on emission from a system operation are considered as it is described above (in section 5.2 of this chapter). Biogas standalone without battery & with battery backup has the highest negative CO_2 emission of (-4.43) kg/year & (-4.39) kg/year but both have higher positive Nitrogen Oxides emission (Table 5.6). Having a negative CO_2 emission from these energy systems means that this system generates a lot of low-emissions electricity through a biogas gen-set or this energy system can remove more CO_2 from the atmosphere (Homer Energy 2016; Minx et al. 2018).

Next is grid-biogas scheme with grid outages frequency of 252 times a year & mean repair time of 3.11 hours has CO_2 emission of (-0.643) kg/year which is the third highest negative emission from all systems considered (both off-grid and grid connected). On the contrary when power outages from the grid increases, biogas gen-set power production share increases which increase the CO and NOx emissions to the environment due to the biogas combustion here. The same is true for Grid-diesel scheme, as the grid outages increase so do the diesel generator production share that will increase emissions. Emission from Biogas-Diesel system is found the most polluting system in all emission types discussed among all the systems analyzed, it is because both diesel and biogas gen-sets have emissions and systems incorporating diesel gen-set have CO_2. Grid-diesel system provides the highest CO_2, CO, PM, SO_2, NO_x emission is grid-biogas scheme as shown in Table 5.6.

Table 5. 6: System Emission Comparison

S/N	System type	CO_2 *(kg/year)*	CO *(kg/year)*	PM *(kg/year)*	SO_2 *(kg/year)*	NO_x *(kg/year)*	RF** *(%)*
Off-Grid							
1	**PV-Biogas-Battery**	-0.0202	0.0128	0	0	0.0136	100
2	**Biogas-Diesel**	142,833	902	5.46	350	847	64.5
3	**PV-Diesel-Battery**	0	0	0	0	0	100
4	**Biogas Standalone**						
	with battery backup	-4.39	2.8	0	0	2.97	100
	without battery backup	-4.43	2.82	0	0	2.99	100
5	**PV Standalone**	0	0	0	0	0	100
Grid connected							
1	**Grid-Biogas-Battery**						
	with 200 annual outages with 2hour repair time	-0.305	0.194	0	0	0.206	8.02
	with 252 annual outages with 2hour repair time	-0.403	0.256	0	0	0.272	10.6
	with 252 annual outages with 3.11-hour repair time	-0.643	0.409	0	0	0.434	18.8

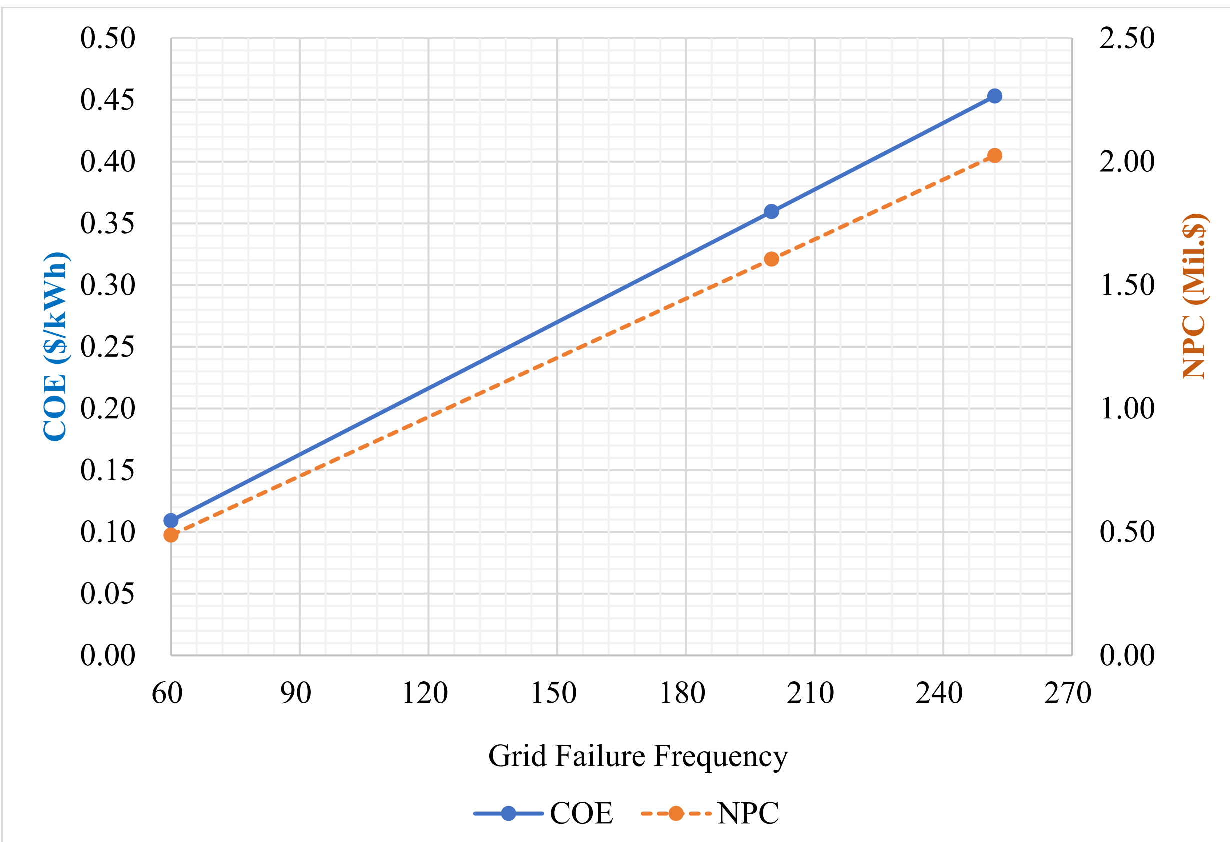
S/N	System type	CO_2 (kg/year)	CO (kg/year)	PM (kg/year)	SO_2 (kg/year)	NO_x (kg/year)	RF** (%)
2	**Grid-PV-Battery**						
	with 200 annual outages with 2hour repair time	0	0	0	0	0	0
	with 252 annual outages with 2hour repair time	0	0	0	0	0	0
	with 252 annual outages with 3.11-hour repair time	0	0	0	0	0	0
3	**Grid-Diesel**						
	with 200 annual outages with 2hour repair time	33,342	210	1.27	81.6	197	0
	with 252 annual outages with 2hour repair time	41,034	259	1.57	100	243	0
	with 252 annual outages with 3.11-hour repair time	61,284	386	2.34	150	363	0
4	**Grid System**						
	without outages	0	0	0	0	0	0
	with outages 40 times a year & 1hour repair time	0	0	0	0	0	0

** take into consideration that HOMER takes grid power as non-renewable energy

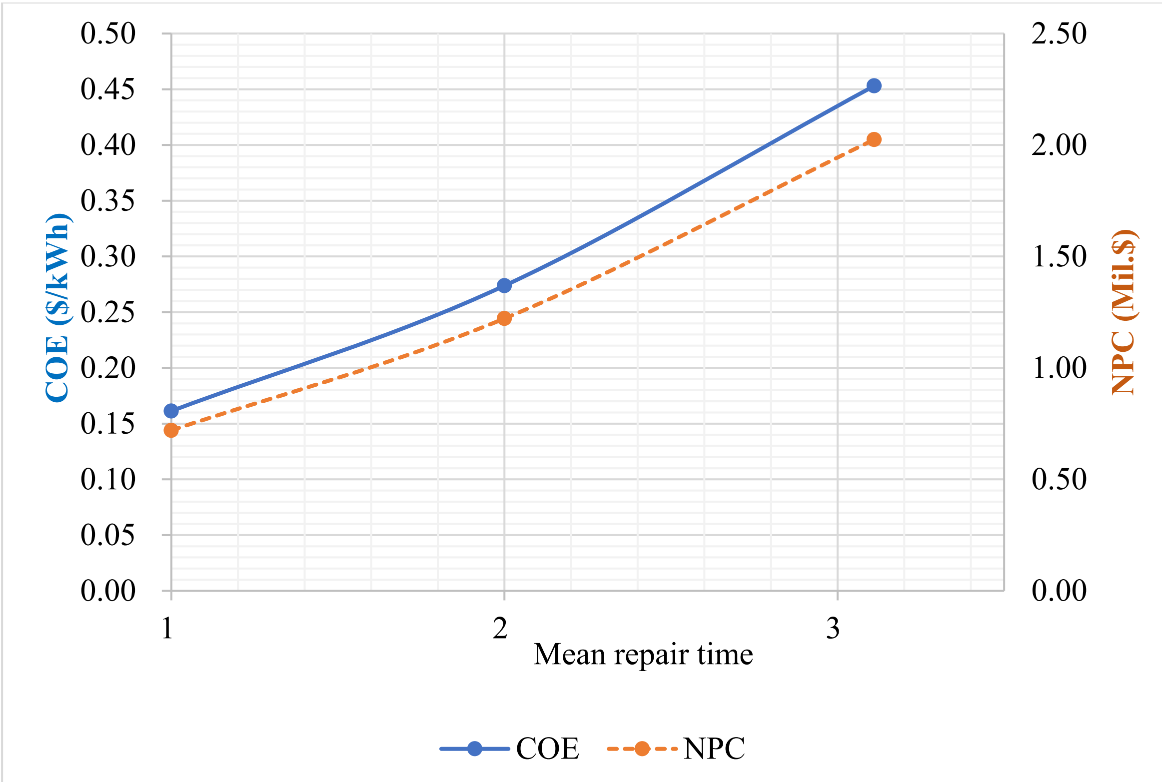
5.5 Effect of change in parameters and loads on system performance

5.5.1 Grid Power Outage Frequency and mean repair time

When grid outage frequency keeps varying (60, 200, 252 outages per year are taken) and other sensitivity parameters kept unchanged as PV derating factor of 80%, 25 years of PV lifetime, mean grid repair time of 3.11 hours, both NPC & COE keep varying. Keeping grid failure mean repair time varying (mean repair time of 1 hour, 2 hours & 3.11 hours are taken) and other parameters kept fixed as outage frequency of 252 per annum, both NPC & COE show increment (Figure 5.3, for grid-biogas case). As far as the grid outage frequency & mean repair time duration increases, there is an increase in the overall cost of the system because it needs alternative energy supply to cover the loads during such outages.



a)



b)

Figure 5. 3: Effect of *a)* Grid Outage Frequency and *b)* Mean Repair Time on NPC & COE

5.5.2 Deferrable loads

As it is described in chapter 3 & chapter 4 loads are categorized as primary and deferrable. The effect of using all loads as primary loads and classifying loads as primary & deferrable loads on system performance is analyzed. When all loads are taken as primary the LCOE and excess electricity increases as compared with the system that consist loads that are categorized as primary and deferrable.

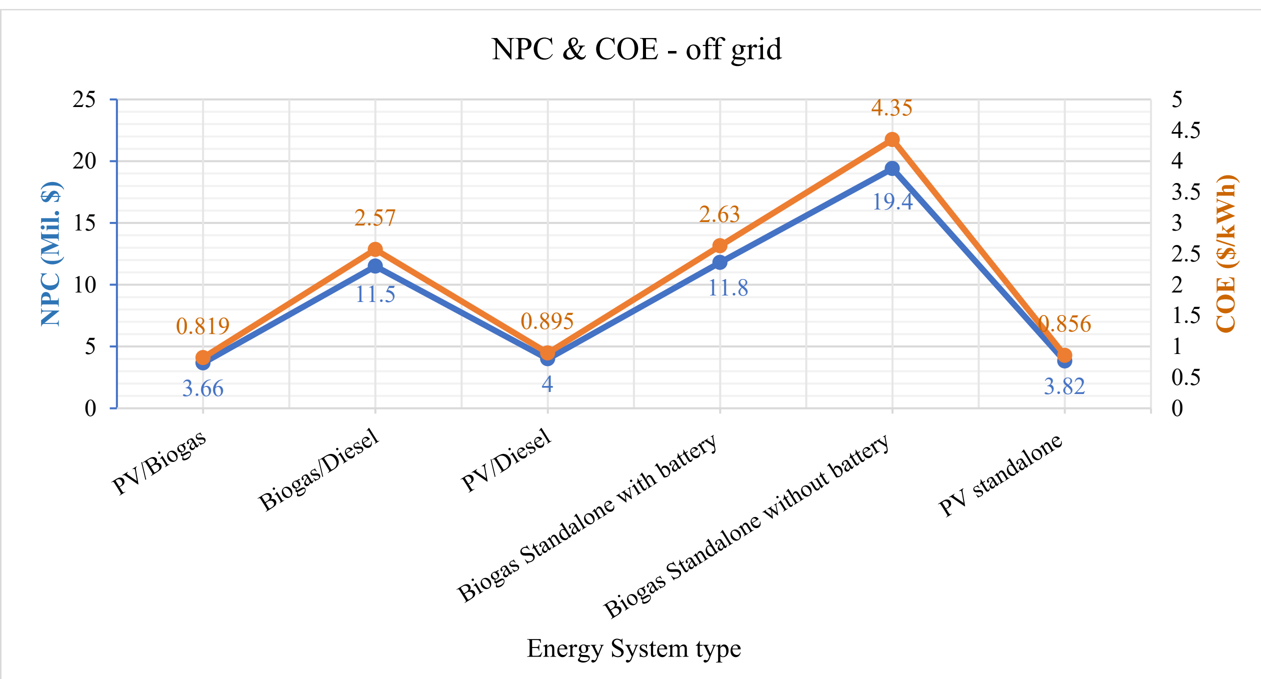
5.5.3 Seasonal effect on share of energy resources

As it is discussed in chapter 4 (resource assessment) the solar energy resource is low in rainy/cloudy seasons of the year and during night times. So, during these variations the power production share by each of the sources is analyzed by taking the hybrid PV-Biogas system with and without battery in order to observe the effect of seasonal and daily variation of the resource on share of power production.

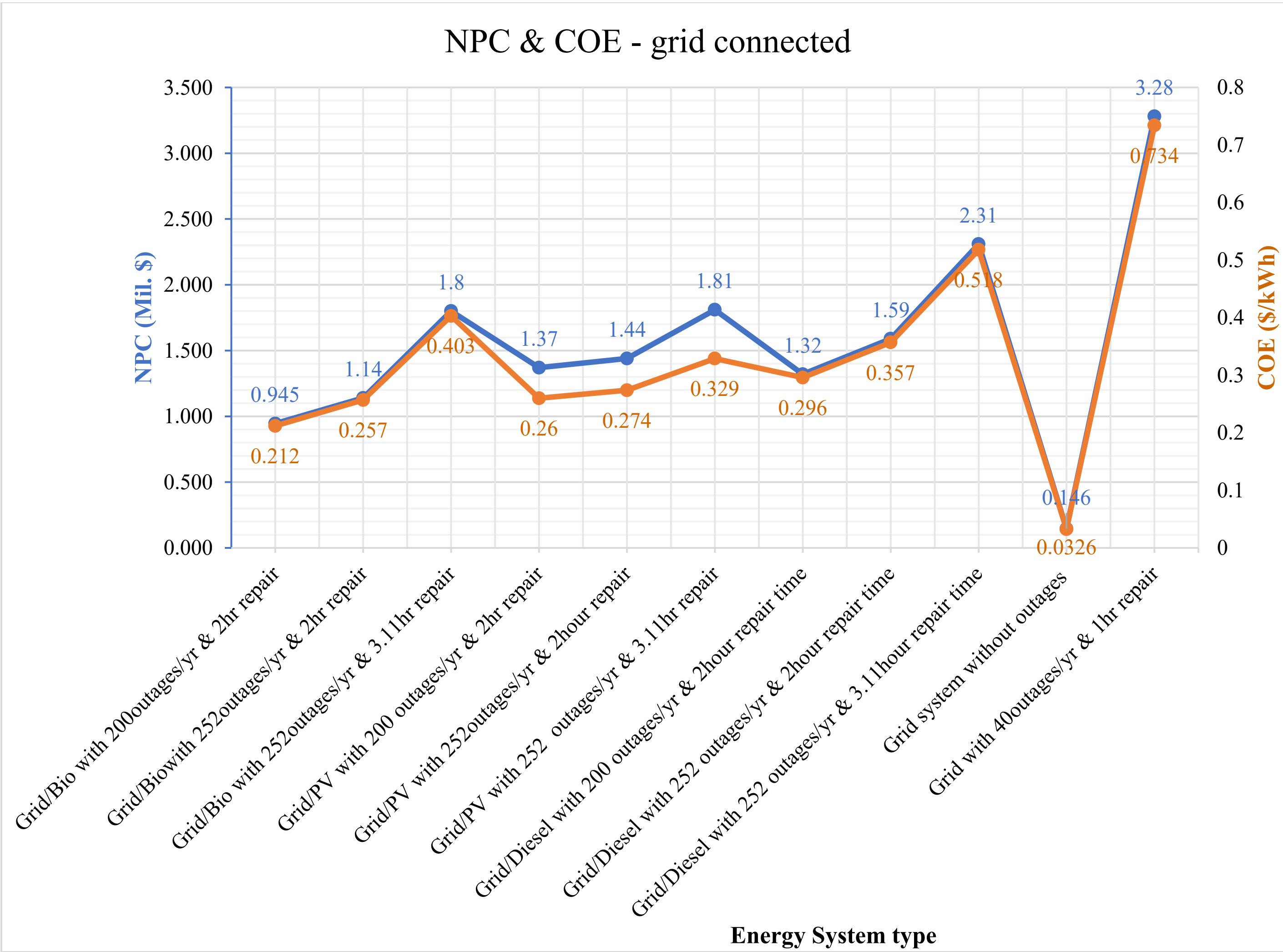
For the case of battery-incorporated system, the largest power share is by PV during the day & by PV charged battery during nights. Biogas gen-set fills the gap when battery is not charged with enough power especially during some of summer nights to supply the loads. When battery is not included in the systems, PV supplies the daytime loads whereas biogas gen-set supplies nighttime loads throughout the year & daytime loads in the summer in which PV is incapable to supply the loads.

5.6 Comparison and Selection of Optimal System

Based on the NPC, grid system without outage considered comes to the front line by its lowest cost but this is unrealistic when it comes to practice because the main grid actually experiences power outages of about 252 times per year with at least a mean repair time of 3.11 hours. Grid system with outages considered is also impractical because optimization result shows it is not viable more than 40 power outages/year with 1hour mean repair time and this is far from the existing annual power outages with mean repair time. In addition, this Grid system with outages considered has 7th highest (among 5 grid connected & 6 off-grid energy system types analyzed) NPC & COE, Figure 5.4.



a)



b)

Figure 5. 4: NPC & COE for (a) Off-grid and (b) Grid connected energy systems

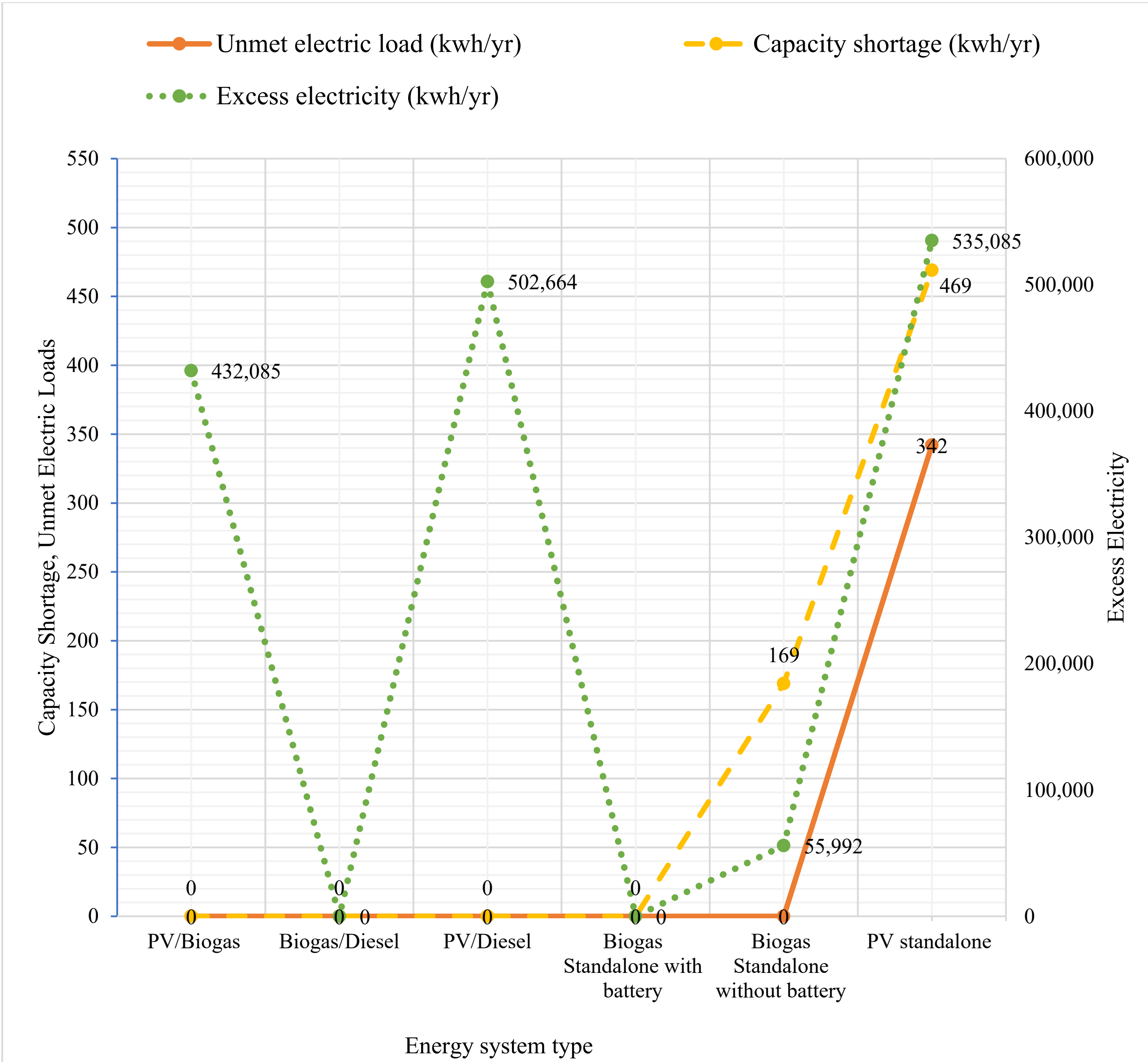
The highest NPC & COE from all systems is for Biogas standalone which in addition has third highest positive NO_x emissions (among 5 grid connected & 6 off-grid energy system types analyzed). Biogas-diesel and Grid-diesel schemes have the highest positive emissions of CO_2, CO, PM, SO_2, NOx among all systems analyzed. Grid system without outage considered has the lowest value of COE but still this is impracticable because of frequent annual grid outage is practically occurring. The next systems with lowest COE for the actual 252 annual outages with 3.11 hours mean repair time are Grid-PV and Grid-Biogas systems (Figure 5.4). Even though the Grid-PV system for 252 annual outages with 3.11 hours mean repair time has less COE than

Grid-biogas, it has 5th highest excess electricity among 5 grid connected & 6 off-grid energy system types analyzed & 1st highest excess electricity among grid-connected systems, Figure 5.5. Also, it has initial capital greater than the grid- biogas system. Grid-biogas system has zero excess electricity, 5th least in unmet electric load, 3rd least capacity shortage among all the systems analyzed. PV standalone, PV-diesel, PV-biogas, Grid-PV and Biogas standalone without battery backup systems have high excess electricity.

Highest capacity shortage and unmet electric load are resulted during the case of Grid/PV and grid system with outages considered. Biogas standalone, Biogas -diesel, PV-Diesel, PV standalone, & PV-biogas systems are economically expensive because of their high NPC as compared with the rest of systems.

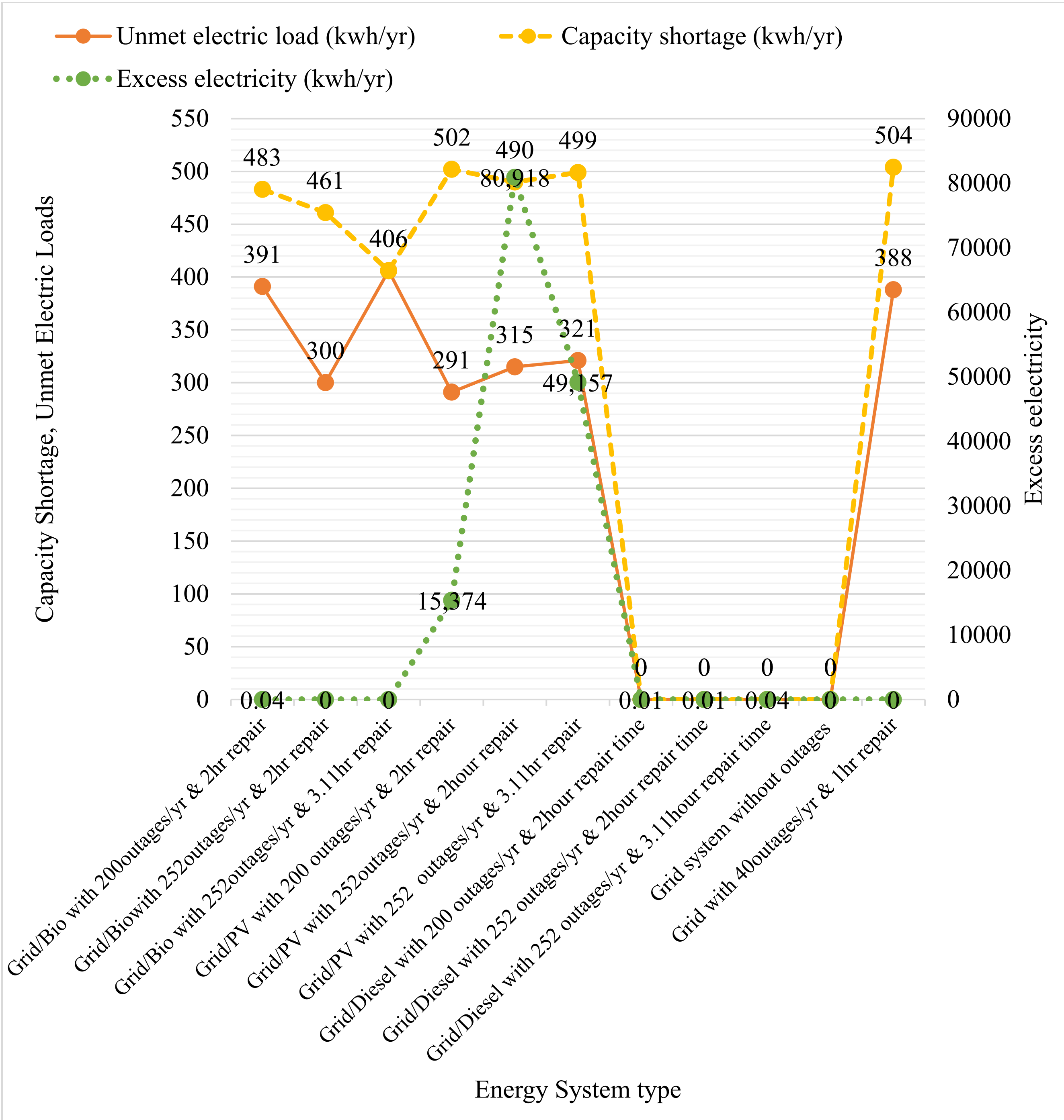
The Grid-Diesel option that is the one being used currently has a cost of at least 9,000 USD only for diesel fuel annually. This cost is estimated based on the frequency of grid outages per year & the amount of diesel fuel used during these outages and it has to be noted that this cost does not include other O & M (Operation and Maintenance) costs, replacement costs, penalties related to emissions.

Therefore, by taking the results discussed above in to account Grid-biogas systems are found optimal system among all the systems analyzed. This system has better negative carbon dioxide emissions next to biogas standalone system and third least CO & NOx emissions among other systems (Table 5.6). Since this optimal system has third least initial capital among all systems analyzed (off-grid and grid connected) and it has negative CO_2 emission, it can provide financial savings related with penalties or revenue on emission limits and it will provide reduced initial capital cost.



Unmet electric load (kwh/yr)
Capacity shortage (kwh/yr)
Excess electricity (kwh/yr)
Capacity Shortage, Unmet Electric Loads
Excess Electricity
550
500
450
400
350
300
250
200
150
100
50
0
600,000
500,000
400,000
300,000
200,000
100,000
0
432,085
502,664
535,085
469
342
169
55,992
PV/Biogas
Biogas/Diesel
PV/Diesel
Biogas Standalone with battery
Biogas Standalone without battery
PV standalone
Energy system type

a)



b)

Figure 5. 5: Capacity Shortage, Unmet Electric Loads & Excess Electricity for *(a)* Off-Grid and *(b)* Grid Connected Systems

CHAPTER SIX - CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Study of techno-economic feasibility and modeling & optimization of energy systems for KWWTP is conducted in this thesis work. The treatment plant has biogas resource that is not still converted to energy. On the contrary, the plant has high-energy demand of 1278.24 kWh/day primary loads. This demand will be expected to increase as the quality and amount of liquid waste entering to the plant varies which will depend on the number of population & their lifestyle.

National grid actually has frequent outages so it is necessary to have a backup power source. Currently the system gets electricity from the grid with a LCOE of 0.0329USD/kWh and backup power source of diesel gen-set that has an estimated fuel cost of about 9200 USD/year in addition to other operation and maintenance costs to supply power instead of grid during these outage times. In addition, it will have a significant emission amount and this can be estimated using the HOMER simulation for grid/diesel resulted a CO_2 emission of more than 60,000kg/year.

Optimized system by HOMER incorporates grid & biogas gen-set resource, has LCOE of 0.403USD/kWh which is less than that found simulated by grid-diesel which is the representation of actually been costed. This Optimal system provides lesser emission levels & less initial capital cost, no fuel cost, emission reduction through its lifetime. Grid-Biogas scheme will also ensure the self-energy supply for the plant demand because the proposed alternative energy resource for the main grid that is biogas is a product from the treatment plant's main operation.

6.2 Recommendations

In order to sustain the energy demand by WWTPs, it is a better to examine the self-supplying approaches using the energy potential of such plants rather than being dependent on diesel gen-set with increasing diesel fuel and/ or other fossil fuels. This will fulfil at least partial energy demand of the plants or even there will be a possibility of selling electricity produced for other consumers.

Works that are not covered with this research scope but related works suggested for future include;

1. Techno-economic viability of upgrading the produced biogas to increase its purity and its impacts on the entire system efficiency
2. Evaluating the performance of system proposed in this thesis as compared with system consisting CHP (Combined Heat and Power) system instead of biogas gen-set.
3. Study on CH_4 or other gaseous or particulate matter emissions from overall system operation such as pretreatment systems, anaerobic digestion system (UASB reactor and other related parts & accessories), sludge management & handling systems, and gas flare operation.
4. Study on mechanisms to sell electricity back to the grid and controlling facilities.

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APPENDICES

1. **Energy Consumption (kWh)**
   A) **Daily and Monthly**

Day	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1	1130.25	1592.55	1289.79	893.65	1550.40	1575.84	1336.32	1350.24	1458.24	1466.64	1048.80	1267.20
2	1120.23	1644.90	1164.30	1078.64	1523.52	1599.36	1185.60	1396.80	1693.44	1182.96	1162.80	1236.48
3	1073.87	1505.90	2088.97	991.70	1536.48	1505.28	1094.40	1443.36	1693.44	1513.20	1257.12	1221.12
4	1087.58	1899.55	887.72	1558.38	1489.92	1646.40	1198.08	1443.36	1693.44	1396.80	1117.20	1267.20
5	1107.55	1184.86	1603.36	2563.69	1552.32	1489.92	1244.16	1373.52	1629.60	1443.36	1140.00	1359.36
6	1338.26	1504.48	1657.67	1364.92	1505.28	1552.32	1326.96	1489.92	1693.44	1221.12	1244.16	1244.16
7	1147.51	1507.80	1573.19	1677.61	1481.76	1575.84	1359.36	1420.08	1505.28	1396.80	1208.40	1221.12
8	1098.99	2029.15	1715.93	1393.20	1505.28	1669.92	1336.32	1481.76	1646.40	1382.40	1037.76	1152.00
9	1720.49	2550.50	1388.00	1228.08	1552.32	1646.40	1359.36	1175.04	1740.48	1313.28	1341.60	1692.00
10	1372.21	1443.87	1585.90	1221.00	1443.36	1629.60	1359.36	1443.36	1599.36	1336.32	1360.80	1787.52
11	1023.93	1534.59	1591.31	1170.08	1552.32	1646.40	1359.36	1443.36	1669.92	1373.52	1534.08	2007.84
12	1095.11	1520.21	1045.96	1094.73	1556.25	1396.80	1308.48	1373.52	1559.76	1116.00	1331.04	2067.12
13	1035.28	1670.79	1086.65	1621.77	1314.18	1350.24	1428.48	1313.28	1559.76	1117.20	1451.52	2067.12
14	1115.53	1599.36	1127.35	1627.18	1030.48	1210.56	1267.20	1326.96	1326.96	1280.40	1244.16	1881.60
15	1094.23	1589.33	1685.97	1495.86	1313.28	1221.12	1383.84	1303.68	1373.52	1081.92	1185.60	1972.08
16	1024.34	1589.35	1523.24	1554.10	1652.88	1396.80	1326.96	1420.08	1443.36	1221.12	1227.60	2304.72
17	1142.57	1599.46	1590.61	1468.94	1505.28	1513.20	1396.80	1390.80	1373.52	1071.60	1272.24	2280.96
18	1079.88	1819.26	2184.61	1528.71	1198.08	1350.24	1326.96	1221.12	1536.48	1280.40	1326.96	2210.88
19	1067.94	1706.65	1100.31	1538.57	1373.52	1267.20	1290.24	1254.00	1458.24	993.60	1331.04	2304.00
20	1090.00	1601.38	1588.64	1258.47	1552.32	1254.00	1396.80	1489.92	1513.20	980.40	1345.20	1852.56
21	1048.86	1716.52	1541.63	1541.52	1513.20	1336.32	1350.24	1528.80	1504.80	1082.88	1336.32	1606.32
22	1023.24	1464.35	1735.91	1567.74	1267.20	1436.40	1373.52	1528.80	1350.24	1231.20	1336.32	1037.76
23	1066.80	1301.21	1386.20	1518.18	1528.80	1368.00	1313.28	1458.24	1208.40	1117.20	1267.20	1128.00
24	1056.29	1331.37	1224.42	1438.51	1336.32	1359.36	1303.68	1428.48	1393.92	1128.00	1267.20	1267.20
25	1077.34	1685.77	1405.85	1268.20	1646.40	1359.36	1350.24	1396.80	1350.24	970.08	1276.80	1376.16
26	1122.06	1141.00	1637.54	1853.28	1575.84	1294.56	1528.80	1396.80	1474.56	934.80	1244.16	1208.40
27	1140.10	1322.55	1585.78	1599.36	1646.40	1303.68	1434.72	1466.64	1536.48	957.60	1192.32	1221.12
28	1621.90	1658.72	1650.35	1152.00	1505.28	1254.00	1303.68	1373.52	1350.24	1173.12	1182.96	1267.20
29	1458.10	1240.86	1607.04	1152.00	1552.32	1280.40	1290.24		1421.28	1244.16	1185.60	1267.20
30	1661.49	1531.97	1327.70	1622.88	1528.80	1313.28	1313.28		1550.40	1162.80	1221.12	1299.60
31	1578.43	1521.45		1552.32		1350.24	1350.24		1350.24		1208.40	
Monthly (kWh)	**35993.16**	**47518.44**	**43654.36**	**44595.27**	**44289.79**	**44153.04**	**41196.96**	**39132.24**	**46658.64**	**36170.88**	**38886.48**	**47076.00**

B) List of assumed deferrable loads (kW)

S/N	list of loads /Equipments/	power rating *(KW)*	Qty
1	grit removal pumps	1.46	2
2	grit classifier	0.25	1
3	Drainage Pumps	3.5	2
4	trickling filter recirculation pumps (submersible pumps)	20	4
5	sludge recirculation pumps - submersible	9	4
6	dosing pumps	0.05	4
7	dosing pumps	0.022	3
8	Dilution unit (consists 1m3 steel tank, hopper for dry powder, a dosing screw & agitator)	2	1
9	drainage Pump	0.75	1
10	service water boosting pumps	5.5	4
11	Drum washer - for latrine sewage receiving	2.2	1
12	Grit classifier & screw conveyor	1.1	1
13	Latrine sewage lifting pumps - submersible pumps	5.2	3
14	submersible mixer in the latrine sewage pumping station	1.3	1
15	drum washer Service Water Boosting Pump - for latrine sewage area	2.2	1
16	lobe type positive displacement pumps	9.2	2
17	submersible mixer in the digested sludge pumping station	3.5	1
18	Drainage pump	0.75	1
19	Sludge Drying Beds Drainage Pumping Station Pump -submersible pumps	8.2	3

Biogas calorific Value measurement record

Reactor	Jul 13/2021		Aug 16/2021		Aug 25/2021		Oct 08/2021	
	CH_4 (%)	CV(MJ/Nm^3)	CH_4 (%)	CV(MJ/Nm^3)	CH_4 (%)	CV(MJ/Nm^3)	CH_4 (%)	CV(MJ/Nm^3)
1A	64.68	21	68.34	22	63.8	20	68.36	22
1B	63.93	20	68.15	22	63.11	20	67.72	21
1C	65.31	21	68.34	22	68.04	21	67.93	22
1D	64.1	21	69.57	22	65.7	21	67.31	22
1E	65.62	21	69.45	22	65.7	21	66.6	21
2A	65.21	21	69.26	22	64.37	21	64.4	21
2B	64.59	21	69.55	22	63.91	21	65.03	21
2C	65.33	21	68.46	22	65.78	20	65.79	21
2D	63.59	21	68.43	22	67.02	21	64.95	21
2E	65.28	21	68.27	22	64.14	21	65.2	21
3A	65.11	21	69.57	22	64.28	21	66.42	21
3B	65.73	21	69.47	22	62.99	20	66.3	21
3C	64.96	21	68.46	22	64.73	20	66.55	21
3D	65.09	21	68.96	21	63.53	20	67.05	21
3E	65.47	21	69.49	22	64.55	21	63.46	21

2. Solar irradiance data (W/m²) – monthly average hourly data

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
12:00 AM	0.51	0.51	0.51	0.52	0.52	0.51	0.51	0.51	0.50	0.51	0.51	0.51
1:00 AM	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.50
2:00 AM	0.51	0.50	0.51	0.51	0.51	0.51	0.50	0.50	0.51	0.51	0.51	0.51
3:00 AM	0.50	0.51	0.50	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.50
4:00 AM	0.50	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.50	0.51
5:00 AM	0.50	0.51	0.51	0.51	0.51	0.50	0.51	0.51	0.51	0.51	0.50	0.51
6:00 AM	1.04	1.18	3.48	10.40	13.90	11.96	7.77	4.84	8.67	11.01	7.15	2.49
7:00 AM	50.79	63.50	82.13	128.71	120.32	96.55	74.89	55.06	106.07	119.93	90.46	64.58
8:00 AM	201.23	239.67	259.18	314.46	272.51	238.73	217.57	173.69	263.43	309.42	257.63	210.72
9:00 AM	391.16	424.78	452.14	501.91	438.25	386.51	326.70	291.03	346.24	447.24	417.98	358.68
10:00 AM	561.64	611.14	614.78	635.09	563.24	492.52	384.37	354.00	450.15	594.90	548.93	461.79
11:00 AM	672.67	752.99	715.33	723.96	581.12	527.67	590.43	546.19	589.23	730.05	649.68	570.77
12:00 PM	730.71	778.29	722.64	713.83	585.04	466.65	611.36	635.44	604.21	778.53	646.74	566.87
1:00 PM	698.61	783.95	694.13	680.33	480.64	422.71	525.20	558.19	603.65	702.25	610.36	593.59
2:00 PM	622.92	686.27	591.75	565.12	286.10	295.72	389.71	448.00	509.51	603.62	543.12	515.01
3:00 PM	513.22	564.33	348.61	299.79	310.35	241.91	190.86	313.04	388.56	441.87	434.77	368.87
4:00 PM	339.59	366.00	331.38	285.14	213.08	156.49	125.12	207.14	234.92	275.24	243.49	245.41
5:00 PM	131.12	172.34	148.48	137.32	106.83	82.02	72.67	101.73	108.87	95.48	58.63	73.00
6:00 PM	11.14	23.61	20.75	21.97	17.87	18.08	19.94	20.32	10.31	4.69	2.70	4.17
7:00 PM	0.51	0.54	0.54	0.54	0.55	0.60	0.68	0.60	0.51	0.51	0.51	0.51
8:00 PM	0.51	0.51	0.52	0.52	0.51	0.51	0.51	0.52	0.51	0.51	0.52	0.51
9:00 PM	0.51	0.51	0.51	0.52	0.51	0.51	0.51	0.51	0.51	0.52	0.51	0.51
10:00 PM	0.50	0.51	0.51	0.52	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
11:00 PM	0.50	0.51	0.51	0.52	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
kWh/m²	**4.93**	**5.47**	**4.99**	**5.02**	**3.99**	**3.44**	**3.54**	**3.71**	**4.23**	**5.12**	**4.52**	**4.04**

3. Energy system components cost and specifications

A) Cost of components

Component	Specification		Cost (USD)
Solar PV	Model - LG Neon H LG385N1C-E6 Max. Power Pmax: 385 W Module Efficiency: 20.9 % System voltage: 1000 V MPP Voltage Vmpp: 35.5 V MPP Current Impp: 10.88 A	Cell Type: Monocrystalline / N-type Cell Configuration: 120 Cells (6 x 20) Weight: 18.5 kg Module Dimensions (L x W x H): 1768 x 1042 x 40 mm	1475 USD/kW (Cost as of 11th Aug, 2022, including cost of accessories and delivery)
Battery	Place of Origin: China Brand Name: Sunpal Model Number: 6-CNF-85Ah; 6-GFM(G)-85Ah Sealed Type: Sealed Maintenance Type: Free Cells Per Unit: 6 Voltage Per Unit: 12	Capacity: 85Ah@10hr-rate to 1.80V per cell @25°C Internal Resistance: Approx. 5.5 mΩ/6 mΩ Terminal: F8 Max. Discharge Current: 1275A (5 sec) Maximum Charging Current: 21.25A	300 USD/peace (Cost as of 12th Aug, 2022)
Converter	Model: Steca Grid 4803 Maximum dc input (from PV) – 1000v Grid side voltage: 320-480V	Rated frequency: 50/60HZ Maximum efficiency: 98.6% For more see the Appendix	800 USD/kW (Cost as of 12th Aug, 2022)
Diesel generator	Warranty: 2 Years Certification: ISO900, CE Place of Origin: Jiangsu, China Brand Name: Newtec Model Number: NPC-400GF Rated Voltage: 400/230V	Frequency: 50/60HZ Engine Model: DCEC KTA19-G2 Generator model: Newtec NTG-354 Controller: Smartgen, Deepsea,	67 per KW (Cost as of 11th Aug, 2022)

	Rated Current: 720Amp Rated power:500KVA, pf: 0.8 Speed: 1500/1800RPM	Deif Gen-set Noise: <75db Option: Super Soundproof, ATS Start: Electric Fuel Consumption:0.23 L/kwh	
Biogas generator	Warranty: 3months-1year Certification: CE, CE Place of Origin: Sichuan, China Brand Name: RT Model Number: RTF250C-41N	Rated Voltage: 230/400V Rated Current: 451A Rated power: 250 kw/343.75KVA Speed: 1500 or 1800 Frequency: 50/60 Hz	240 per kW (Cost as of 11th Aug, 2022)

B) Solar panel specification

https://www.europe-solarstore.com/solar-panels/manufacturer/lg/lg-neon-h-lg385n1c-e6-solar-module.html - accessed online on 11/08/2022

Key Properties:

1. Model: LG Neon H LG385N1C-E6 Solar Module
2. Max. Power Pmax: 385 W
3. Module Efficiency: 20.9 %
4. System voltage: 1000 V
5. MPP Voltage V_{mpp}: 35.5 V
6. MPP Current I_{mpp}: 10.88 A
7. Cell Type: Monocrystalline / N-type
8. Cell Configuration: 120 Cells (6 x 20)
9. Module Dimensions (L x W x H): 1768 x 1042 x 40 mm
10. Weight: 18.5 kg
11. Frame: Anodized Aluminum
12. Junction Box: IP68 with 3 Bypass Diodes
13. Connector: MC4 / Stäubli

C) Storage battery specification

https://www.alibaba.com/product-detail/Lead-Acid-Battery-12V-85Ah-Lead_62511811296.html?spm=a2700.galleryofferlist.normal_offer.d_title.71ff2888ZH4CSN – accessed online on 12/08/2022

12V 85Ah Specification		
Model	6-GFM-85Ah	6-GFM(G)85Ah
Cells Per Unit	6	
Voltage Per Unit	12	
Capacity	85Ah@10hr-rate to 1.80V per cell @25°C	
Weight	26.5 Kg	28.3 Kg
Internal Resistance	Approx. 5.5 mΩ	Approx. 6mΩ
Terminal	F8	
Max. Discharge Current	1275A (5 sec)	
Design Life	6~8 years	10~15 years
Maximum Charging Current	21.25A	
Reference Capacity	C10 85.0AH C3 65.1AH C1 47.0AH	C10 85.0AH C3 61.5AH C1 46.7AH
Float Charging Voltage	13.6 V~13.8 V @ 25°C Temperature Compensation: -20mV/°C/Cell	
Cycle Use Voltage	14.4 V~14.9 V @ 25°C Temperature Compensation: -30mV/°C/Cell	
Operating Temperature Range	Discharge: -15°C~50°C Charge: 0°C~40°C Storage: -15°C~40°C	Discharge: -20°C~60°C Charge: 0°C~50°C Storage: -20°C~60°C
Normal Operating Temperature Range	25°C±5°C	
Self-Discharge	Less than 3% at 25°C per month	
Container Material	A.B.S. UL94-HB, UL94-V0 Optional	

D) System converter specification

https://www.europe-solarstore.com/download/steca/coolcept__specifikation_EN.pdf - accessed online on 12/08/2022

	StecaGrid 3203	StecaGrid 4003	StecaGrid 4803	StecaGrid 5503
DC input side (PV-generator)				
Maximum input voltage	1,000 V			
Operating input voltage range	250 ... 800 V			
MPP voltage for rated output	300 V ... 800 V	375 V ... 800 V	450 V ... 800 V	510 V ... 800 V
Number of MPP-Tracker	1			
Maximum input current	11 A			
Maximum input power at maximum active output power	3,300 W	4,100 W	4,920 W	5,620 W
Maximum recommended PV power	4,000 Wp	4,900 Wp	5,900 Wp	6,700 Wp
DC side (storage system connection) [1]				
Voltage	680 ... 1,000 V (max. grid peak to max. PV voltage)			
Max. current	10 A			
AC-Ausgangsseite (Netzanschluss)				
Grid voltage	320 V ... 480 V			
Rated grid voltage	400 V			
Maximum output current	7 A		10 A	
Maximum active power (cos phi = 1)	3,200 W	4,000 W	4,800 W	5,500 W
Maximum active power (cos phi = 0.95)	3,040 W	3,800 W	4,560 W	5,225 W
Maximum active power (cos phi = 0.9)	2,880 W	3,600 W	4,320 W	4,950 W
Maximum apparent power (cos phi = 0.95)	3,200 VA	4,000 VA	4,800 VA	5,500 VA
Maximum apparent power (cos phi = 0.9)	3,200 VA	4,000 VA	4,800 VA	5,500 VA
Rated power	3,200 W	4,000 W	4,800 W	5,500 W
Rated frequency	50 Hz and 60 Hz			
Frequency	45 Hz ... 65 Hz (depending on regional settings)			
Night-time power loss	< 3 W			
Feeding phases	three-phase			
Distortion factor (cos phi = 1)	< 1 %			
Power factor cos phi	0,8 capacitive ... 0,8 inductive			
Characterisation of the operating performance				
Maximum efficiency	98.6 %		98.7 %	
European efficiency	97.9 %	98.1 %	98.2 %	98.3 %
Californian efficiency	98.3 %	98.4 %	98.5 %	98.5 %
MPP efficiency	> 99.8 % (static), > 99 % (dynamic)			
Own consumption	< 8 W			
Power derating at full power	from 50 °C (T_{amb})			
Safety				
Isolation principle	no galvanic isolation, transformerless			
Grid monitoring	yes, integrated			
Residual current monitoring	yes, integrated [2]			
Operating conditions				
Area of application	indoor rooms with or without air conditioning			
Ambient temperature	-15 °C ... +60 °C			
Storage temperature	-30 °C ... +70 °C			
Relative humidity	0 % ... 95 %, non-condensating			
Noise emission (typical)	<29 dBA			
Fitting and construction				
Degree of protection	IP 21 (casing: IP 51; display: IP 21)			
Overvoltage category	III (AC), II (DC)			
DC Input side connection	Phoenix Contact SUNCLIX (2 pairs)			
AC output side connection	Wieland RST25i5 plug, mating connector included			
Dimensions (X x Y x Z)	340 x 608 x 222 mm			
Weight	10 kg			
Communication interface	RS485; 2 x RJ45 sockets; connectable to Meteocontrol WEB'log or Solar-Log™; Ethernet interface			
Integrated DC circuit breaker	yes, compliant with VDE 0100-712			
Cooling principle	temperature-controlled fan, variable speed, internal (dustproof)			
Test certificate	see certificate download on the product page			

E) Biogas generator specification

https://www.alibaba.com/product-detail/High-efficiency-250KW-gas-generatorset_1600269953108.html?spm=a2700.details.0.0.6af518f3n6wn4J – accessed online on 11/08/2022

	Fuel type		Natural gas	Natural gas	Natural gas	Natural gas	Natural gas
Gen-set Model	Gen-set Model		RTF250C-41N	RTF300C-41N	RTF500C-42N	RTF750C-43N	RTF1000C-44N
	Rated power	kw	250	300	500	750	1000
		kVA	312.5	375	625	937.5	1250
	Reserve power	kw	275	330	550	825	1100
		kVA	343.75	412.5	687.5	1031.25	1375
	Gas consumption		3.2NkW/Nm^3	3.5NkW/Nm^3	3.2NkW/Nm^3	3.2NkW/Nm^3	3.2NkW/Nm^3
Engine	Engine Model		1-T12	MANE 2676	2-T12	3-T12	4-T12
	Number of cylinders * engineering * stroke (mm)		6-126X155	6-126X166	6-126X155	6-126X155	6-126X155
	Engine displacement (L)		11.596	12.42	2*11.596	3*11.596	4*11.596
	Starting Method		24VDC Electric Start				
	Intake Method		Booster intercooler				
	Fuel Control		Lean burn, closed loop control				
	ignition Control		Electronic control single cylinder independent high energy ignition				
	Speed control		Electronic speed regulation				
	Rated Speed		1500 or 1800				
	Cooling Method		Closed-Loop water cooling				
Generator	Rated Voltage (V)		230/400	230/400	230/400	230/400	230/400
	Rated Current (A)		451	541.2	902	1353	1804
	Rated Frequency (Hz)		50 or 60	50 or 60	50 or 60	50 or 60	50 or 60
	Supply Connection		3 Phases 4 Lines				
	Rated Power Factor		0.8(Delay)	0.8(Delay)	0.8(Delay)	0.8(Delay)	0.8(Delay)
Dimension	Net weight (kg)		3200	3600	9800	15200	18600
	(L*W*H) mm		4200X1500X 2450	4200X1500X 2450	6400X3000X 3000	10600X3000 X3000	10600X3000 X3000

F) Diesel generator specification

https://www.alibaba.com/product-detail/500-Kva-Diesel-Generator-Silent-Generators_1600212761991.html?spm=a2700.galleryofferlist.normal_offer.d_title.66df1265SRHip1&s=p - accessed online on 12/08/2022

Powered by Cummins engine KTA19-G2 with Stamford generator 400 kw 500kva Open or Silent 500kva diesel generator for farm use	
Engine Data	
Model	Cummins KTA19-G2
Type	6 Cylinder inline,4 cycle
Displacement	18.9 L
Aspiration	Turbocharged
Bore*Stroke	130X163 mm
Governor Type	Mechanical
Starting Voltage	24V
Lubricant Capacity	50 L
Fuel Consumption	0.23 L/kWh
Generator Data	
Model	Newtec NTG-354
Optional	Stamford, Leroysomer, MeccAlte, Marathon
Excited Type	Brushless, Self-Excited
Power Factor	0.8
Voltage Adjust range	>5%
Voltage Regulation	<±1%
Insulation Class	H
Protection Class	IP23
Control Panel	
Model	Smartgen,Comap or Deepsea
Protection	High/Low Voltage,High/Low Temperaturer,High/Low Frequency,Low fuel,Low Oil,Low coolant
Function	AMF,Synchronizing
Support	RS232,RS485,USB