Optimization and Feasibility Analysis of an Off-Grid Solar Photovoltaic Hybrid System for a Specific Coastal Area in Bangladesh.

A Thesis report is submitted in partial fulfillment of the requirements for the award of Degree of Bachelor of Science in Electrical and Electronic Engineering.

Submitted by

Name: Md.Sakhawat Hossain Sabbir
ID:211-33-1360
Name: Md.Rasel
ID:211-33-1365
Name: Md.Rafiuzzaman Rafi
ID:201-33-1169

Supervised by

Engr. Md. Dara Abdus Satter
Associate Professor & Head
Department of Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering
Faculty of Engineering
DAFFODIL INTERNATIONAL UNIVERSITY

JANUARY, 2025

DECLARATION

We hereby declare that this thesis "**Optimization and Feasibility Analysis of an Off-Grid Solar Photovoltaic Hybrid System for a Specific Coastal Area in Bangladesh.**" represents our own work which has been done by the students of the Department of Electrical and Electronic Engineering under the Faculty of Engineering of Daffodil International University in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering, and has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma or other qualifications. We have attempted to identify all the risks related to this research that may arise in conducting this research, obtained the relevant ethical and/or safety approval (where applicable), and acknowledged our obligations and the rights of the participants.

Signature of the candidates

22-01-2025

Name: Md.Sakhawat Hossain Sabbir
ID:211-33-1360

Rasel
22-01-25

Name: Md.Rasel
ID:211-33-1365

Rafi
22-01-2025

Name: Md. Rafiuzzaman Rafi
ID:201-33-1169

APPROVAL

The thesis entitled **"Optimization and Feasibility Analysis of an Off-Grid Solar Photovoltaic Hybrid System for a Specific Coastal Area in Bangladesh."** submitted by **Md.Sakhawat Hossain Sabbir (211-33-1360), Md.Rasel (211-33-1365), Md.Rafiuzzaman Rafi (201-33-1169)** has been done under my supervision and accepted as satisfactory in partial fulfillment of the requirements for the degree of **Bachelor of Science in Electrical and Electronic Engineering** in **January, 2025.**

Signed

22/01/25

Engr. Md. Dara Abdus Satter
Designation: Associate Professor & Head
Department of Electrical and Electronic Engineering
Faculty of Engineering
Daffodil International University

Dedicated

To

Our Parents

TABLE OF CONTENTS

List of Figures

LIST OF TABLES

LIST OF ABBREVIATIONS

HOMER - Hybrid Optimization Model for Electric Renewables

COE - Cost Of Electricity

GHG - Greenhouse Gas

IRR - Internal Rate of Return

ROI - Return On Investment

RETScreen - Renewable Energy Technology Screen

SHS - Solar Home Systems

VAWT - Vertical-Axis Wind Turbine

HAWT - Horizontal-Axis Wind Turbine

PV - Photovoltaic

SOC - State Of Charge

DOD - Depth Of Discharge

NOCT - Nominal Operating Cell Temperature

CP - Power Coefficient

RF - Renewable Fraction

CFL - Compact Fluorescent Lamp

HP - Horsepower

HRES - Hybrid Renewable Energy system

ELOAD - Energy Consumed by Load at Time

EGDE - Energy Generated by Diesel Generator

ISO - International Organization for Standardization

V_{mp} - Maximum Voltage of PV Panels

I_{mp} - Maximum Current of PV Panels

ACKNOWLEDGEMENT

First of all, we want to give thanks to **Almighty Allah**. With his blessing we are able to complete our work with best effort.

We want to pay our utmost respect to our Supervisor **Engr. Md. Dara Abdus Satter, Associate Professor & Head** of the **Department of EEE, Daffodil International University** for who has given us the chance to work on an impactful idea and taken care of every issue of development of this concept. Then we would like to take this opportunity to express gratitude to our supervisor for being dedicated in supporting, motivating and guiding us throughout this thesis. This thesis can’t be done without his useful advice and help. Also thank him very much for giving us the opportunity to work with this thesis.

We also want to convey our thankfulness to **Dr. Srimanti Roychoudhury, Associate Professor** of the **Department of EEE, Daffodil International University** for his support and encouragement. Apart from that, we would like to thank our entire class fellows for sharing knowledge; information and helping us in making this thesis a success. To beloved family, we want to give them our deepest love and gratitude for being very supportive and also for their inspiration and encouragement during our studies in this Institution.

ABSTRACT

In today's world, it is almost impossible to live without electricity. This paper represents an optimization of a solar PV hybrid system for off-grid. We have selected Char Andar, Patuakhali, a char area where electricity is almost non-existent during the day so that a solar hybrid system can be a significant solution there. Our proposed system is made for a primary load demand of 1212.36 kWh/day, having a residential peak load of 163.94 kW and commercial peak load of 11.78 kW. Among them, the residential load is 1147.60 kWh/day, and the commercial load is 64.76 kWh/day. HOMER modeling software has been used to design the off-grid system. Solar energy is considered the primary source of energy, wind energy is a subsidiary energy source, and a diesel generator is added as a backup energy source. A converter is used to convert power from DC to AC. The battery is obviously added to store energy. Most important parameters, such as Renewable Penetration (RP), are selected at 80% to reduce GHG emissions. Other parameters like COE, diesel fuel consumption, simple payback, IRR, and ROI were also considered so that the proposed system would be techno-economically feasible. From HOMER optimization, we get 660 kW PV, four 10kW wind turbines, and a selected 150kW diesel generator for a backup energy source. The energy generation cost is estimated at 0.0846/kWh. We also make financial assessments on RETScreen software and compare them with HOMER simulation results. From RETScreen software, we get a simple payback of 4.7 years by mainly analyzing the capital of PV, wind turbines, and diesel generators. In HOMER system optimization, we obtained a simple payback of 2.7 years. For economic feasibility, we preferred HOMER-optimized results.

Keywords: Cost Of Electricity (COE), Internal Rate of Return (IRR), Return On Investment (ROI), Green House Gas (GHG), Renewable Penetration (RP), Off-Grid Optimization.

CHAPTER 1
INTRODUCTION

1.1 Background

Bangladesh embraces energy-generating methods and mechanisms that are revenue-creating in nature as a means of ensuring that the basic living standards of the countrymen are not compromised. Shunning enormous progress, access to power is either poor or periodic in several large parts of rural Bangladesh, which restrains socioeconomic advancement. For nations with growing industrial demands, the serviceability of energy structure must be stable and sustainable for their long-haul monetary development.

Bangladesh is one of the countries where energy and power production do not meet consumption requirements. Seventy-seven percent of the population in Bangladesh has electricity. To sustain its 7% growth rate, it will require 34,000 megawatts of power by 2030 [24].

Blackouts, the pilferage of power, low efficiency of plants, high system losses, delays in the construction of new plants, and the renovation and maintenance of the existing ones are the challenges facing the electric power sector of Bangladesh. In fact, in the past decade, the nation has ranked behind its system's demand for producing units. Rural electrification also remains a challenge due to the cost and technical difficulties in extending the grid in remote, mountainous, and riverine regions, and Bangladesh has a per capita energy consumption lower than the global average. The nation has plenty of renewable energy sources, such as solar and biogas, that are adequate alternatives to conventional grid electricity.

Currently, implementation of the plan to reach the status of a middle-income country by 2030 in Bangladesh is underway. This task is closely connected to the requirement to modernize agriculture and develop industry since both require a regular and steady supply of power. Improved power services may enhance rural lives, create fresh job opportunities, and enhance wages. A major barrier, on the other hand, is that providing clean electricity doesn't require fossil fuel-powered plants or extended time frames for building out infrastructure.

Bangladesh has limited oil and an infinitesimal amount of oil and gas but has a vast potential for renewable energy sources (especially when it comes to hydropower, wind power, and solar power). Due to its cost-effectiveness, sustainability, and environmentally friendly qualities, the nation is now investing heavily in solar energy and exploring other forms of renewable energy. Solar power, however, is intermittent and dependent on weather and physical conditions, so an exclusive reliance on it could be catastrophic. Renewable energy generation, a sustainable electricity supply, needs to integrate multiple sources into the national grid.

Project rural electrification is aimed at the development of the country and the improvement of the economic conditions of rural communities. And jobs, health care, education, agro-processing, food storage, drinking water provision, and irrigation all follow behind access to electricity. Rural electrification is still costlier than urban electricity due to scattered communities and greater infrastructure requirements.

Solar, hydropower, and biomass have a substantial contribution to Bangladesh's current energy mix as renewable energy sources. In rural areas, though, the use of traditional biomass, such as firewood, agricultural waste, and cow dung, as an energy source is often substantial, leading to environmental degradation and deforestation. More can be done, according to the government, to improve energy efficiency and accessibility; per capita power consumption is still below the regional average.

The Bangladesh government is keen to enhance connectivity with respect to energy and explore the possibility of electricity sales to neighboring nations, including Nepal, India, and Myanmar. Despite these efforts, most rural Bangladeshi households are still off-grid and rely predominantly on biomass as a source of energy for their daily activities. This dependency hinders socio-economic improvements and creates environmental issues. Since rural communities are patchy, it's still captive-intensive and has been largely ignored when it comes to supplying grid-connected utilities to these areas. In order to overcome these barriers, the government should focus on the development of localized renewable energy options like decentralized solar systems to fulfill rural energy requirements in a cost-effective and environmentally conscious manner.

1.2 Renewable Energy Scenario in Bangladesh

Bangladesh is a densely populated developing country in South Asia. Liquid fuels and natural gas are the main sources of energy in the country. Across the country, the primary sources of energy are coal, natural gas, and refined petroleum products. Lots of natural gas is very affordable because it is a common resource, but gas will run out in the following ten to twelve years, taking into account existing supplies and patterns of consumption.

Bangladesh is a developing country that is struggling to provide power 24/7 to every citizen. Almost 45% of the population lives off the grid, with insufficient electricity and no transmission and distribution network infrastructure, while grid-connected areas face extensive load shedding. Bangladesh government initiatives in renewable energy to promote sustainable energy 80% of Bangladesh's total energy production comes from gas at present [25]. Natural gas is the primary fuel for most power plants in Bangladesh, and only a few use coal or oil. It comes as multiple units at a power plant in Bangladesh's port city of Chittagong have demanded to be shuttered due to a lack of gas supplies.

The only grid-connected renewable energy source is the Kaptai Hydropower Plant. It accounts for about 2.58% of total electricity generation [25]. Bangladesh is endowed with various renewable energy resources that can help with the growing energy crisis of the country [25]. The government targets to produce 2,000 megawatts of renewable energy by 2021. This is generating now715 MW of energy. Renewable sources, as of 2021, will make up 10% of all power by 2030.

28 MW of renewable energy was received from Dhaka, Rangunia 60 MW, Sharishabari 3 MW, Gangachhara 55 MW, Mymensingh 200 MW, Cox's Bazar 20 MW, and Teknaf 200 MW. Apart from that, solar home systems will be set up in Kaptai, Hatia, Thakurgaon, Ishwardi, and Sirajganj.

1.3 Problem Statement & Research Questions

Despite the country's wealth of renewable energy resources, many parts of Bangladesh still lack access to electricity, whether via standalone renewable energy systems or the national utility. There are two basic reasons for this problem: there is insufficient power generation to meet current demand; and the construction of grid infrastructure in remote locations is difficult because of financial and geographic constraints.It requires a significant amount of time, money, and effort to extend transmission lines from the electric grid to these isolated villages.

No society can afford to be deprived of communication, transportation, healthcare, education, energy, and water. These services require a constant source of electricity. The increasing energy production and consumption of the country is not enough to meet the growing energy demands as Bangladesh is highly reliant on a single source, natural gas. To resolve this situation, it is essential to expand and diversify the power generating system to include renewable energy sources.

Hybrid renewable energy systems are practical power-producing systems in remote and rural areas combining solar, wind, and various other renewable energy sources. Affordable renewable energy could directly affect the economic progress, poverty alleviation and quality of life of rural communities. With an emphasis on the adoption of renewable energy solutions, Bangladesh can pave the way for universal access to sustainable energy, particularly for its vulnerable rural communities.

Women often spend their time collecting water, collecting firewood, cooking for the family, and other chores. Also, there is cooking indoors exposed them to different diseases and possibly affecting the health of children and women as they live longer.

Renewables are the trends that are serious when it comes to power supply, especially due to the critical need of rural residents to have a reliable power supply for everyday use and for industrialized farming or running small and micro businesses. So, energy has now become a critical driver towards sustained growth of the country's economy.

1.4 Objectives & Scope of The Research

The target of this project is to design and optimize an off-grid solar hybrid energy system composed of solar PV, wind turbines, and diesel generators to provide energy for a rural area in Bangladesh. Eighty percent of the penetration of renewable energy is to reduce greenhouse gas emissions and promote sustainable energy research. The feasibility of the system is analyzed using key parameters like energy cost, diesel fuel consumption, payback time, internal rate of return, and return on investment. HOMER and RETScreen tools are applied to optimize system architecture and perform financial assessments to ensure a comprehensive analysis.

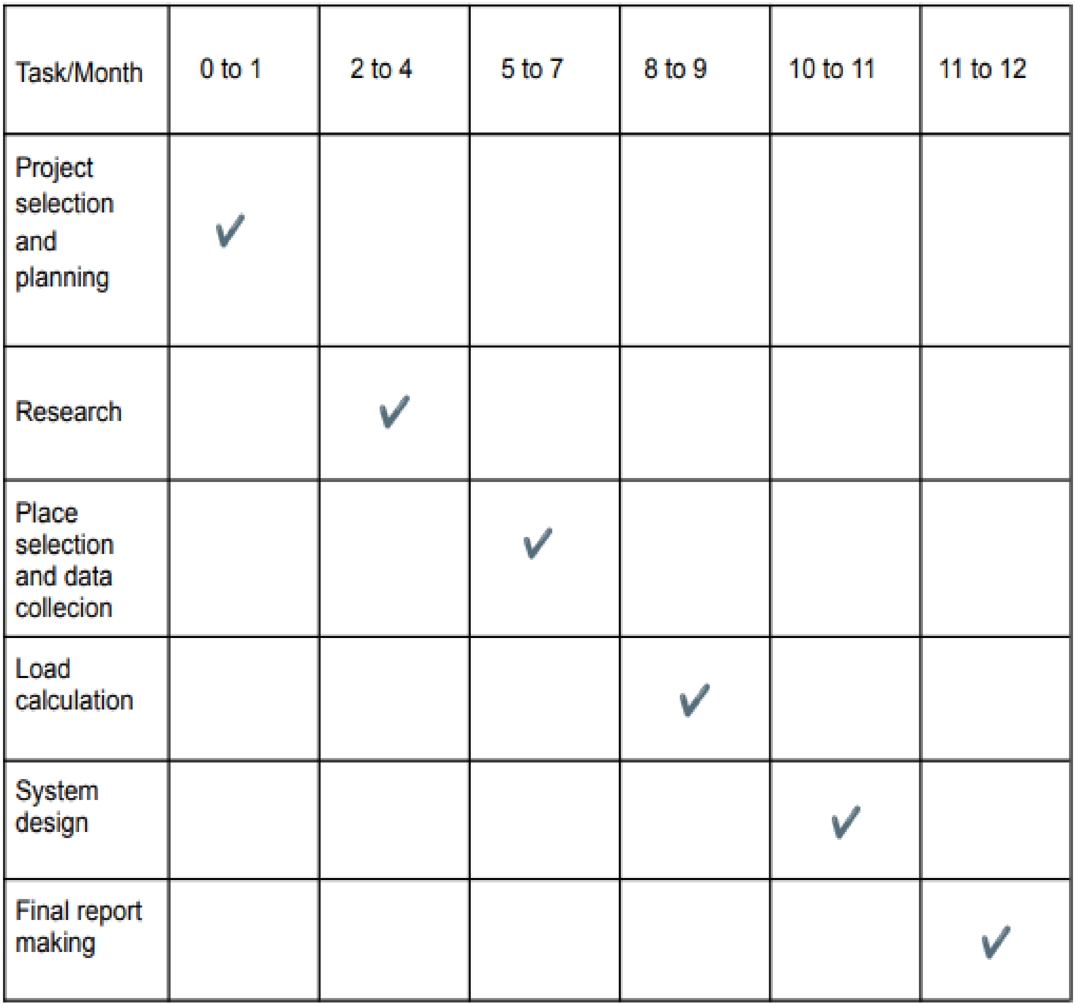
The study is conducted in an off-grid rural area in Bangladesh with an acute shortage of energy. It consists of constructing a system with solar photovoltaics as the primary source of energy, wind turbines, and then diesel engines as backups to guarantee the deliverance of energy. The research undertakes battery-powered energy storage technologies to enhance system stability. By comparing the performance of HOMER to RETScreen, the study ensures the accuracy and reliability of financial assessments. Also, it provides knowledge on replicable and scalable strategies that can be implemented in different geographical areas, facilitating ecologically sustainable development and renewable energy.

1.5 Importance & Contributions

This research is vital because it provides a sustainable, reliable, and cost-effective electricity generation method that could cater to the energy needs of the off-grid regions of Bangladesh. By integrating renewable energy sources such as solar PV and wind with diesel backup, the study ensures energy security and environmental sustainability with lower greenhouse gas emissions.

This research contributes in two ways. Its first output is a realistic optimal hybrid energy system design, based on rural energy needs with today's most advanced techniques, such as HOMER and RETScreen. It also provides a techno-economic analysis framework to provide stakeholders and policymakers with alternatives to replicate similar systems in other off-grid areas to promote a broader acceptance of the renewable energy solutions in Bangladesh and also elsewhere.

1.6 Implementation Schedule



Task/Month	0 to 1	2 to 4	5 to 7	8 to 9	10 to 11	11 to 12
Project selection and planning	✓					
Research		✓				
Place selection and data collecion			✓			
Load calculation				✓		
System design					✓	
Final report making						✓

CHAPTER 2

LITERATURE RIVIEW

2.1 Introduction

Hybrid renewable electricity systems (HRES) are the best option for reliable, inexpensive, and sustainable power for separated or off-grid areas. These systems also comprise a combination of renewable energy sources such as solar, wind, and biomass in order to provide a more reliable source of energy and lessen the reliance on traditional fuels. In this chapter, literature from previous studies in this field of study is analyzed. This paper presents a literature survey in order to build a basic understanding of HRES, identify what research gaps are present, and provide context on the study carried out in Andar Char, Patuakhali, in Bangladesh. “Mains energy is not easily extended here; however, it will be an amazing bearer for novel energy products as it can take advantage of renewables to fulfill the resident and business minimum energy requirements.

2.2 Related Research

With the growing demand for energy, combined with the global effort to meet sustainable energy targets, research into hybrid renewable energy systems is booming. These are explored in a number of studies considering feasibility and economic viability in various (often different) areas. Zeinab Abdallah M. Elhassan, for example, investigated a standalone PV system of 54 kWh/day primary load and a 5.3 kW peak load intended for residential applications in Khartoum, Sudan. With a COE of 20.1, the system's potential for urban households was also showcased, though expensive in standalone systems [3]. In a similar way, Ani Vincent Anayochukwu examined a PV-diesel hybrid system for an off-grid Nigerian Catholic Church. The system addressed a daily load of 117.4 kWh and a COE of $10.842/kWh. The study highlighted the economic benefits obtained from using hybrid systems to reduce dependency on diesel generators but emphasized the need for cost optimization [4]. Rohit Sen added to this field by studying off-grid electricity generation in India. The configuration of these hybrids can be tailored to meet load requirements for residential, commercial, agricultural, and other loads, as highlighted in his work. This adaptability was underpinned by extensive load evaluations and optimization methods[1]. Further, Vendoti Suresh modeled and optimized hybrid systems for rural electrification in Karnataka, India. Through methods such as HOMER and advanced mathematical modeling, he tested a variety of combinations of systems and showed that it is indeed possible to achieve low prices when creating a backup energy system made up of a combination of solar, wind, biomass and biogas[2]. In Greece, G.P. Giatrakos developed a sustainable energy plan of Karpathos Island. They studied a 100% renewable energy system combining solar, wind and hydrogen storage. Although this model was exhibited as fully energy autonomous, it also required a considerable investment and proved hardly applicable to resource-poor regions[6]. Based in Bangladesh, Shuvankar Podder worked on the technical and economic analysis of a solar-wind hybrid system in coastal Chittagong. The study reported a COE of $0.292/kWh , indicating that the system could provide a solution to the energy needs of remote coastal areas along with the green house gas emissions[5].

These studies lay a solid groundwork for hybrid renewable energy system strengths and weaknesses. They sing the praises of such systems used in a variety of geographic and socio-economic settings, and note limitations in cost, scale and adaptability.

2.3 Compare and Contrast

Similar objectives to improve energy access and sustainability using HRES are outlined in the reviewed studies. But differences in their processes and results offer important lessons. That of Sudan and Nigeria studied only for standalone and PV-diesel hybrid systems while most of the solutions in their modeling were for small-scale power needs with moderate success in cost optimization[3,4]. Conversely, studies in India and Greece investigated more extensive hybrid structures, utilizing solar, wind, biomass, and hydrogen storage to realize higher flexibility and energy autonomy [1, 6].

The analysis of the solar-wind hybrid in Chittagong, Bangladesh, concluded that the solar-wind hybrids could reach a cost of energy (COE) $0.292/kWh. This outcome indicates the advantages of tapping into abundant natural resources found in coastal areas but does not go off to explore larger scale uses[5].

This study is unique compared to them as it investigates the previously uncharted area of the char of Andar, Patuakhali, Bangladesh, which has remarkable potential for renewables. The present study analyzed a residential load of 1147.60 kWh/day and a commercial load of 64.76 kWh/day, addressing an application at a larger scale. It had the lowest COE of 0.0846, which ensures its economic feasibility and great scalability, paving the way for subsequent research. In addition, with the use of HOMER Pro software for optimization, it was possible to optimize exactly for actual conditions in the region.

Although there has been progress made in HRES, there are still gaps in scale, innovative storage solutions and site-specific adaptability. These gaps present an opportunity to explore configurations that are cost-effective for larger populations while being reliable and sustainable. Andar Char does directly speak to these issues; it provides a replicable model for rural electrification in contexts like this one.

2.4 Summary

In this chapter, existing works on hybrid renewable energy systems were reviewed, underscoring their versatility and disruptive potential. Although previous research showed the feasibility of HRES across various settings, they did exhibit limitations in cost, scalability, and adaptability. This paper is built on this previous study by investigating an untouched location in Andar Char taking into account abundant renewable resources for a highly economically feasible approach. This research will fill the gaps in decision making for renewable energy solutions in the field with a COE value of 0.0846 $ and contributes a significant focus on larger scale scenarios, paving new ways for the renewable energy sources in remote and marginal areas of the world.

CHAPTER 3
METHODOLOGY

3.1 Study Area Introduction

Andar Char is a lively village in the southern coastal region of Bangladesh which is under Barisal Division. It belongs to Patuakhali administrative division. Char Montaz Union, Rangabali Upazila, Patuakhali District. Andar Char, located in the coastal region of the Bay of Bengal at **21°52.3′N and 90°31.3′E**, serves a small village of 1,907 residents(approximately), 435 households. There is all the basic/minimal infrastructure necessary to live and thrive on all sides – there is a primary school, there is a madrasa, there are four mosques, there is a launch ghat for transport and trade, a bazar and a camping site that has potential as a local tourism destination. Andar Char, for all the bustle of community life here, suffers from poor quality energy. The overwhelming majority of residents depend on inefficient and unsustainable Resources such as kerosene and biomass for their power. The village's unique landscape, attractive conditions in terms of solar radiation exposure and moderate wind speeds provide substantial renewable energy project opportunities. Sustainable hybrid energy systems can transform Andar Char. Such initiatives, as reports have found, can contribute to uplift the livelihood of its community, stimulate economic activities and set the stage for broader regional development in that unserved coastal zone.

Figure 3.1: Map of Study Location (Andar Char)

3.2 System Design & Components

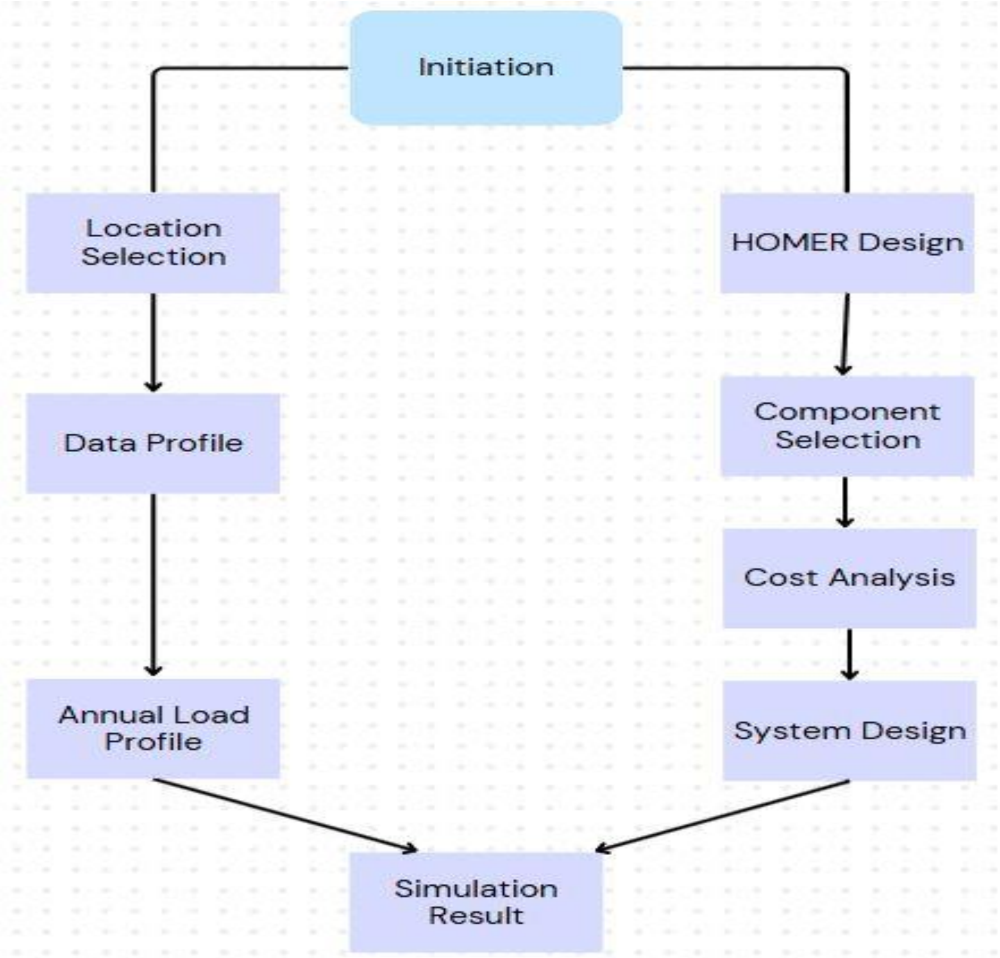


Figure 3.2: Workflow for System Design and Analysis

The process of creating an off-grid hybrid energy system is depicted in the flowchart. Initiation is the first step, and it divides into two concurrent workflows:

Location Selection: In this route, an appropriate site is chosen, a data profile is gathered, and an annual load profile is created. Then, the load profile data is used in HOMER.

HOMER develop: This course focuses on utilizing the HOMER tool to develop systems. Component selection, cost analysis, and system design are all included, and costs and relatable components are optimized in HOMER for effectiveness. Both routes come together to generate a simulation result that sheds light on the viability and efficiency of the hybrid energy system.

3.3 System Architecture

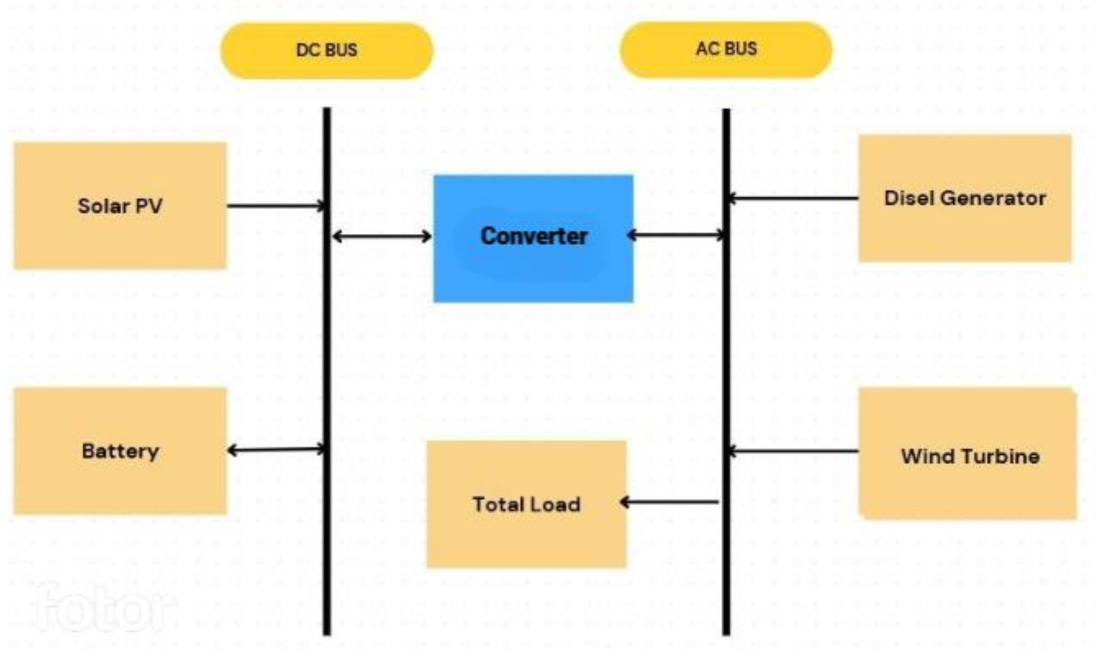


Figure3.3: Solar Hybrid Power System Architecture

In order to distribute energy efficiently, the hybrid energy system integrates several conventional and renewable energy sources using DC and AC buses. The DC bus receives direct current (DC) from solar photovoltaic cells and batteries, while the AC bus receives alternating current (AC) from wind turbines and a diesel generator. Bidirectional energy flow is made possible by an inverter, which connects the DC and AC buses and transforms DC electricity into AC for devices that need alternating current. With the battery storing extra energy and the diesel generator supplying backup power when renewable output is insufficient, the system prioritizes the use of renewable energy sources while guaranteeing a steady and dependable energy supply to fulfill the overall load requirement.

3.4 Component Details

3.4.1 Solar PV Systems

The PV system is one of the most widely used technology for directly converting Solar PV energy into electrical energy utilizing efficient semiconductor cells. The primary component of modern photovoltaic cells is crystalline silicon, a semiconductor that is found in large quantities in the earth's crust and is non-toxic. Crystalline silicon cell modules are incredibly dependable, long-lasting, fuel-free, and noiseless power generation devices. The only limitless source of electricity for PV is solar energy. One-sixth of solar energy may be converted into electrical power via photovoltaic cells. PV systems are environmentally benign and devoid of moving components. PV cells can have a lifespan of more than 30 years [15]. PV systems improve the quality of life in communities by supplying power to isolated locations without connection to the utility grid. The P-type (hole) and N-type (electron) doped semiconductor layers of a photovoltaic cell are separated from one another by a junction. The direction of current flow across the junction is determined by the spontaneous electric field that forms at the border. For a photovoltaic system to generate electricity, sunlight must flow through a transparent glass cover and antireflective coating. The strategy created to capture solar PV energy was mostly based in the West and called for building a centralized power plant and sending power to customers via transmission wires. The power output of a solar photovoltaic system is divided by the amount of solar radiation that reaches the solar array area to determine its energy efficiency.

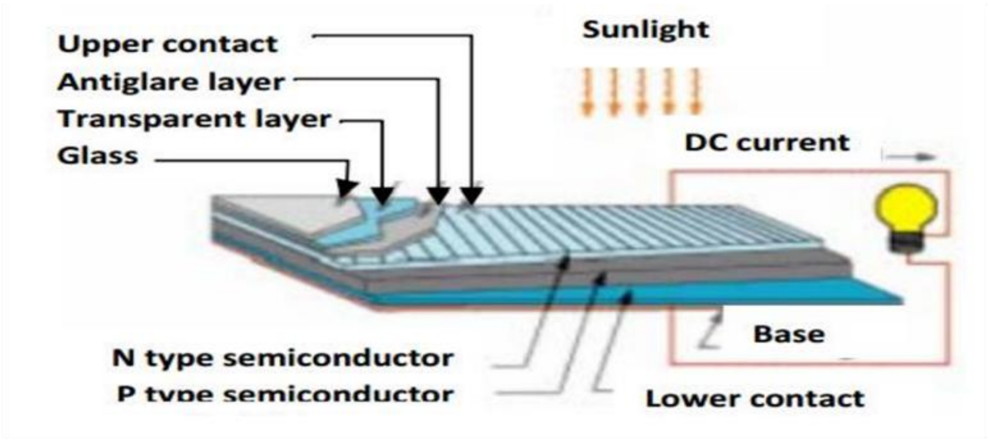


Figure 3.4-a: Typical PV Cell **[15]**

3.4.2. Types of Solar PV Cells

PV cells are composed of many different components, the key one being silicon, which is found in abundance in the earth's crust and extracted from sand. The size and conversion efficiency of the PV cell, as well as the strength of the local sunshine, determine how much electricity is generated.Using [16] the material and the manufacturing process, PV cells made of silicon are classified into the following groups.Uncontaminated silicon single crystals that have been separated from ingots are used to make monocrystalline photovoltaic cells. One obvious distinction from the poly-crystalline panels is that it is black in color and has trimming around all of its corners. Because it is composed of a single crystal, this form of PV cell is the most efficient, but it is also the most costly. Where minimal energy sources are needed, it performs better. The drawback of this method is that its manufacturing takes longer. First, high quality silicon is heated to a super saturated condition, and then a seed crystal is inserted into the molten silicon to create monocrystalline silicon.Finally, using the Czochralski technique, gently extract the seed crystal from the melted monocrystalline to get silicon ingot. The crystal is then cut into pieces to create cells, modules, and arrays. With a PV cell surface area of 1 m2, this technology can convert 1000W/m2 of solar energy into around 140W of electricity [15].

Smaller amounts of silicon crystal blocks are combined to create polycrystalline photovoltaic cells. When there is a little shadow, they outperform the monocrystalline. With a PV cell surface area of 1 m2, this technology can convert 1000W/m2 of solar energy into around 130W of electricity [15]. Compared to monocrystalline cells, this form of cell is produced more efficiently. To create the crystals, molten silicon must be poured into blocks, which are subsequently sliced into slabs. Due to monocrystalline solar panels' higher efficiency per area than multicrystalline ones, polycrystalline solar panels are bigger than monocrystalline panels to get the same power. Accordingly, single crystalline PV panels are more beneficial when compared to other PV panels in order to achieve better output.

3.4.3 The Photovoltaic Module and Array

Photovoltaic solar cells constitute the fundamental components of a solar panel.Most often a smaller PV Cell could generate about a watt of electrical energy. A single solar cell generates a voltage of 0.5 to 0.6 volts. Multiple solar cells are connected in series to build a photovoltaic module, resulting in sufficient output voltage.Photovoltaic systems typically function at multiples of 12 volts;modules are generally engineered to optimize performance in these systems.When photovoltaic cells are arranged in series, the output voltage is the aggregate of the individual output voltages from each cell in the module, while the output current remains constant. Figure 3.4-a just shows a schematic representation of photovoltaic cell interconnection into modules, and then array assembly.

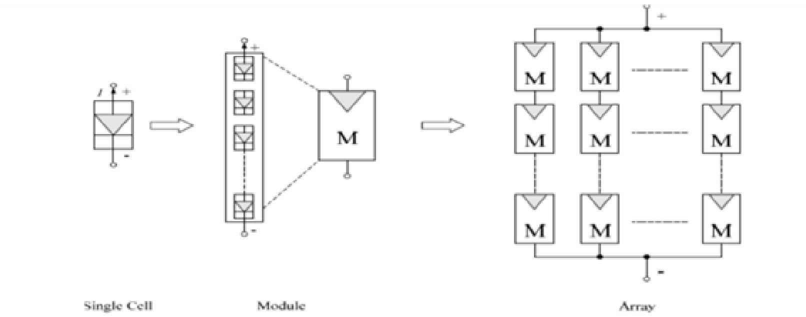


Figure 3.4-b: Diagrammatic Overview of the PV Array, Module, and Cell **[17]**

The dimensions of the solar panel and the number of solar cells dictate its power rating. The photovoltaic cells may be characterized by a nominal operating cell temperature when assembled into a module. At an open circuit temperature of 20°C, with an air mass of 1.5, irradiance of 800 W/m², and wind speed below 1 m/s, the NOCT represents the temperature of the photovoltaic cell [18, 19]. Modules must be interconnected to create an array, as seen in (Figure 3.4-b),when voltages or currents beyond those provided by a single module are required. While arrays linked in parallel provide more current, those connected in series generate elevated voltages. When modules are arranged in series, it is crucial to verify that each module functions at its maximum power output at the same current due to the increase in voltage.Similarly, when modules are coupled in parallel, they deliver significant power at the same voltage due to the increase in current. Consideration of shading effects on the panels during peak sunlight hours is essential when deciding to install solar panels. Power output is decreased by the shading effect, which might possibly harm the cells. Installing PV panels away from structures, trees, and other obstructions is generally advised. Temperature is the second crucial factor to take into account while installing solar panels. Solar panels lose electricity when they heat up because the efficiency of solar cells decreases with temperature. In order to cool the solar panel during the hot sun hours, the mounting method for the panels should provide air circulation.

3.4.4 Equivalent Electrical Circuit of PV Cell

Figure 3.4-c shows the electrical circuit of a typical photovoltaic cell. The V-I characteristics curve illustrates how the diode current, solar-generated current, The

shunt resistance and shunt-leakage current are linked in series and parallel by the internal resistance that builds in the circuit while the system is running.

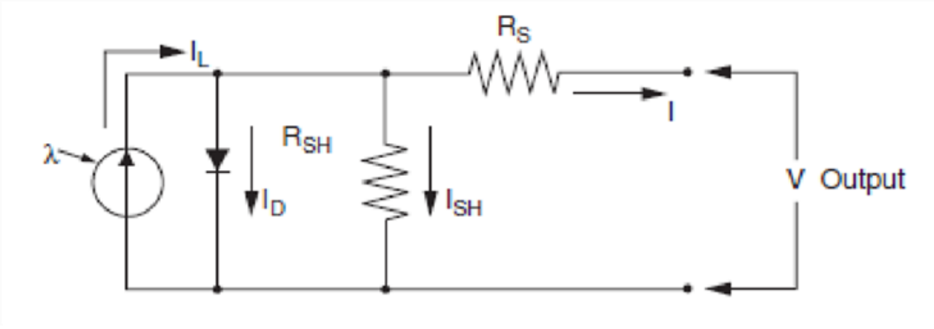


Figure 3.4-c: Equivalent Circuit of Photovoltaic Cell **[19]**

The following mathematical formulas [19] represent the various parameters of the solar cell shown in the analogous circuit.

$$I = I_L - I_d - Ish \qquad (3.01)$$

I: PV output current [A] is where
I_L: current created by the sun [A]
I_d: Current in the diode [A]
I_{sh}: Current of shunt-leakage [A]

A slight alteration to the internal resistance built up in the cell can significantly lower the PV panel's yield efficiency, although altering the shunt resistance has no effect on the output voltage [19]. The following additional mathematical formulas can be used to calculate the cell's output current.

$$I = D_L - I_o \left[e^{\frac{Q.V_{oc}}{K.T}} - 1 \right] - \frac{V_{oc}}{R_{SH}} \qquad (3.02)$$

The final item, which denotes the shunt current, can be removed during real operation hours since it is so little in relation to the diode and solar-produced currents [18, 19]. In this type of model, the cell's temperature fluctuations are regarded as uniform [20].

The following is how the diode current and open circuit voltage are calculated, respectively.

$$V_{oc} = V + I.R_{SH} \tag{3.03}$$

$$I_D = I_o\left[e^{\frac{QV_D}{KT}} - 1\right] \tag{3.04}$$

Where:

I_o: Reveres the diode's saturation current [A]

Q: Charge of electrons [C]

K: J/k, or Boltzmann's constant

V_D: The diode's voltage [V]

T: Temperature at the cell junction point [k]

V_{oc}: Open circuit voltage of the cell [V]

By reducing the open circuit voltage to zero, the short circuit and solar-generated currents remained equal in size, enabling the calculation of the cell's short circuit current. The below mathematical equation represents the diode saturation current (I_o), which remains constant at a certain temperature[19].

$$I_0 = \frac{I_{SC}}{e^{Q.Voc}-1} \tag{3.05}$$

The cell current is provided as follows at any solar irradiation if the module's short circuit current is obtained from the cell's data sheet.

$$I_{sc} = \left(\frac{G}{Go}\right) I_{sc,Go} \tag{3.06}$$

Where:

I_{sc}: Current in the short circuit [A]

G: Irradiance from the sun [W/m2]

I_{sc},Go: Standard test condition for short circuit current [A]

Go: Sunlight intensity under typical test conditions [1000W/m2]

The fill factor is a criterion used to evaluate the performance of photovoltaic cells. This suggests that elevated open circuit voltage(V_{oc}),short circuit current(I_{sc}) and filling factor(FF) values indicate an effective photovoltaic system. The fill factor of a solar photovoltaic system is dictated by the technology and design of the panel. Simultaneously reducing the maximum current, maximum voltage, or Both negatively affect the parameter or damage that controls the fill factor, hence reducing the yield power.Equation 3.07 from [21] may be used to determine the output power of the PV system.

$$P_{mp} = I_{mp} * V_{mp} \tag{3.07}$$

$$FF = \frac{V_{OB} * I_{SC}}{P_{mp}} \tag{3.08}$$

Where:

V_{mp}: Maximum potential voltage (PV)
I_{mp}: The maximum current that photovoltaic panels are capable of producing
PV,OC: Open circuit temperature coefficient
P_{mp}: Maximum power of photovoltaic panels
FF: Fill factor (FF)

Furthermore, the impact of solar radiation and ambient temperature at the specific location must be taken into account when assessing the photovoltaic output power. The maximum current (Imax) and maximum voltage (Vmax) formulae shown in equation 3.07 may be derived from the expression found in [22].

$$\mathrm{Vmp} = \mathrm{Vmp.ref} * \mathrm{Pv, oc}(\mathrm{Tc} - \mathrm{Tc, ref}) \tag{3.09}$$

$$\mathrm{Imp} = \mathrm{Imp, ref} * \mathrm{Isc, ref}(\mathrm{Tc} - \mathrm{Tc, ref}) \tag{3.10}$$

Where:

Vmp.ref: Potential voltage at standard condition [V]

Imp,ref: Maximum current of PV panels under normal circumstances

I_{SC},ref: short-circuit current of photovoltaic panels under conventional conditions

T_C: Operating temperature of cell

T_C, ref: Reference temperature of cell

Figure 3.4-d displays the I-V and P-V characteristics curves of a typical PV module.

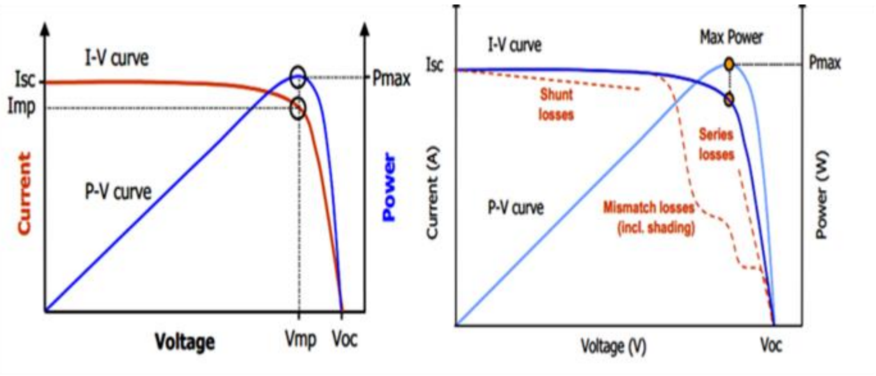


Figure 3.4-d: PV Cell's I-V Characteristic Curve Variation with Various Loss Categories **[23]**

According to figure 3.4-d in the right graph, the solar PV system's homogeneous soiling and non-uniform shading cause the series losses and shunt losses and mismatch losses, respectively.

3.5 Wind Turbine

Wind turbines are machines convert the kinetic energy of the wind into mechanical energy, and in turn into electrical energy. Typical parts of the turbine are the tower, rotor, nacelle and yawing device. To accomplish that, it simply needs to grab the wind energy via those blades, creating a difference in pressure that causes a drive train connected to them to spin. Another important function is yawing, or the rotation of the rotor into the wind direction. The torque produced is connected to a gearbox that adapts the rotational speed, and a generator translates the mechanical energy into electricity, so wind turbines are vital for the generation of renewable energies.

3.5.1 Classification of wind turbine rotors

As shown in Figure (3.5-8) wind turbines can be classified into two types according to the orientation of the axis of rotation in relation to wind direction**[7].**

1. Vertical-axis turbines (VAWT)
2. Horizontal-axis turbines. (HAWT)

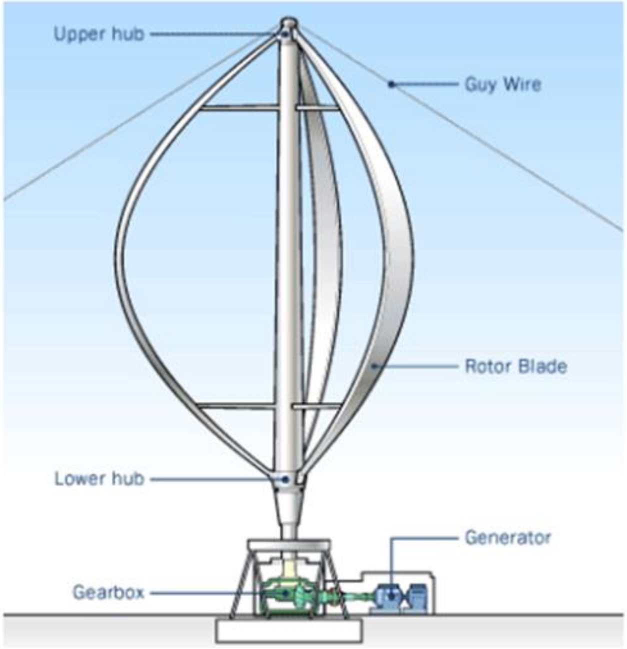


Figure 3.5-a: A Typical VAWT

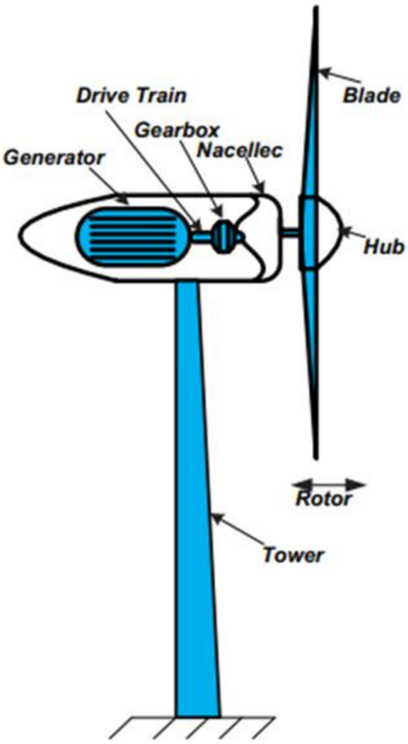


Figure 3.5-b: A Typical HAWT

Wind turbines generate electricity when the wind speed exceeds the cut-in speed (the lowest velocity of wind). When wind velocity increases, the electricity generated by wind turbines output does up to the rated wind speed (the peak speed of the wind turbine when the turbine is producing the maximum power). There are safety measures that prevent the turbine from producing power above the cut-off wind speed. Pitch Regulation: To control the pitch of wind turbines, two overspeed or power control systems are required - an active control mechanism or an electronic control system is used to reduce the pitch of the wind turbine to the aerodynamic efficiency level. The basic principle is that if wind speed tries to exceed rated speed, the pitch control system engages to rotate the blades about their axis of rotation. When above the rated wind speed, the system automatically feather the blades. Altered attack angle would impinge that capability for the rotor. In an effort to address this, the control system response should be faster for the variations in wind speed to ensure that the wind turbine blades are not functioning outside of the usable margin. In pitch controllable turbines, this energy utilization is much more efficient because through their blades pitching angle we can achieve a better utilization of

The wind velocity under mild conditions. Since shown in Figure(3.5-c), as the wind speed begins to grow the output of the turbine grows until it reaches rated wind speed, and so when the rated wind speed is surpassed, the output becomes steady power.

Regulation of the stall:

This pitch control system involves deflecting the blade form along its longitudinal axis to improve angle of attack, rather than actively controlling it. The lift make symptoms Angle of attack equivalent that (air sticks for the upper side of the blade. that inhibits lift on the blades and leads to blade stall, a no-go condition for normal flight. The rotor blades specially designed to control the output in such a way that The turbine's aerodynamic efficiency drops, leaving the turbine blades in the wake as the wind speed increases. The output power, wind turbine spinning speed and aerodynamic torque reduce with the higher wind. FSpeed as depicted in this Figure.3.5-c

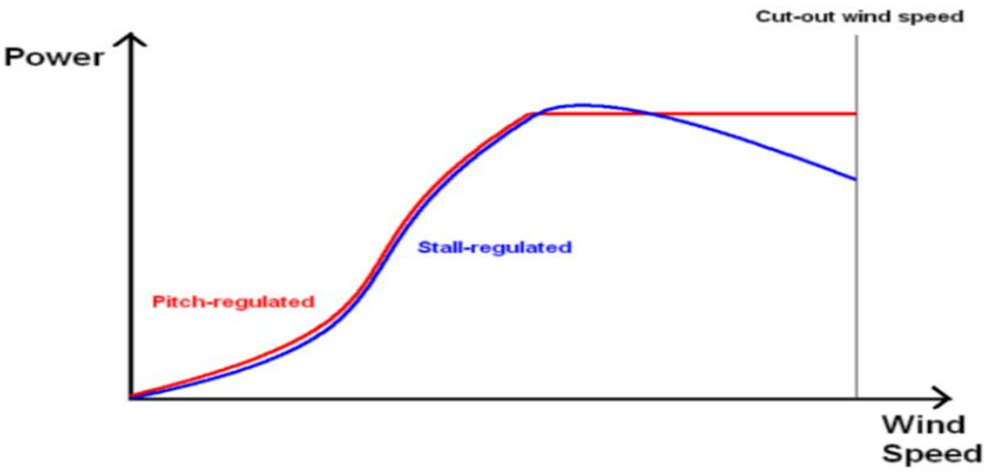


Figure 3.5-c: Wind Turbine Power Control Mechanisms **[8]**

Vertical-axis wind turbine (VAWT)

The earliest windmills were based on a vertical-axis framework. So far, this type has only been employed in small-scale installations. The most common type of VAWT is the Darrius rotor. as shown in Fig. (3.5-a).

Advantages of the VAWT are :

1. Maintenance for ground-mounted generators and gearboxes is straightforward;
2. Wind direction does not matter (yaw control is not necessary); and
3. Blade design is simple and cost-effective to produce.

Disadvantages of a VAWT are:

Not self-starting, so a generator must first be spinning as a motor.

1. Non-regulable blade overspeed;
2. Strong oscillatory component in aerodynamic torque;
3. Less efficiency (the blades lose momentum as they fly out of the wind).

Horizontal-Axis Wind Turbines (HAWT)

The most widely seen modern turbine uses a horizontal-axis design. HAWT, supported by towers, as shown in Fig.3.5-b . To intercept the higher speed winds that flow above the ground, the tower is needed to lift the wind turbine.

Advantages of the HAWT:

1. Reduced cost-to-power ratio,
2. increased efficiency, and
3. the ability to turn the blades.

Disadvantages of the HAWT:

1. A tower would prevent servicing of the generator and gearbox, and
2. but the need for yaw or tail drive makes for a more complex design.

Lift power: It functions orthogonal to within the path of circulation and is due to it is uneven move of the perforated profile for even distribution9,10. Drag driven devices are easier to design but less efficient, lift driven devices are more efficient but harder to design. According to wind kinetic energy is extract, turbine blades can enhance windings pressure difference from above and beneath each blade to gain lift force.

Drag Force: It is the force acting parallel to the flow of a wind. One of the most commonly used winds turbines is the Savonius rotor which operates based on drag force exerted on the rotor to generate electricity. Even any basic workshop can make it easily. where the drag force on the open cylinder side surpasses that on the concave surface.

Like a formulation of the theoretical power contained in the wind (When it comes to equations — one of the same), from [9, 10, 11, 12].

$$P = \frac{1}{2} \rho A V^3 \quad (3.11)$$

Where:

P: Power available in the wind [W]

V: Wind velocity [m/s]

A: Rotor swept area (m^2)

ρ: Density of air [kg/m^3]

This formula delineates the possibility of power density or specific power at a certain location, contingent upon air density and wind speed:

$$P / A = = \frac{1}{2} \rho V^3 \quad (3.12)$$

Where:

P / A: Power density [W/m^2]

$$P_0 = \frac{1}{2} m_a (v_1^2 - V_3^2) \quad \mathbf{(3.13)}$$

Where:

Po: Utilization of wind turbine mechanical power [W]

V_1: Wind Flow Velocity at the Upper Side of the Rotor [m/s]

V_3: Wind flow velocity beneath the rotor [m/s]

m_a: Mass flow rate of air [kg/s]

Thus we can use equation 3.14 to calculate the air mass flow rate considering the wind speeds on each side of the rotor.

$$m_a = \rho A \left(\frac{v_1 + v_3}{2} \right) \quad \mathbf{(3.14)}$$

Equation 3.15 provides the power that the wind turbine has extracted.

$$P_0 = \frac{1}{2} \rho A V_2^2 (V_1 - V_3) = 2 \rho A V_2^2 (V_1 - V_3) \quad (3.15)$$

When the wind velocity at the rotor's surface is calculated using the equation

3.16, the wind turbine's maximum power is extracted.

$V_2 = (2 / 3) V_1$ (3.16)

This demonstrates that the wind turbine's downwind speed is:

$V_3 = (1 / 3) V_1$ (3.17)

Where:

V_1: represents the wind velocity at the frontal surface of the wind turbine rotor.

V_3:is the wind speed downstream following the rotor's power extraction.

V_2:Upstream wind speed prior to the wind turbine machine drawing power

3.5.2 The Law of Betz

The theoretical maximum 0.59, which means no more than 59% electricity generated would reach by the wind mill any wind turbine design. Cpmax = 0.59 is known as the "power coefficient". Moreover, wind turbines cannot function up to that upper threshold. The discrete values of Cp for the different types of turbine vary with the wind speed at which that turbine operates. In practical scenarios, most wind turbines are between 0.35 and 0.45 even for the best-designed equipment, but fall short of the Betz Limit [14].

$$Cp = (\text{maximum power extracted}) / (\text{power available in the wind})$$

$$= (\rho\ A\ V_1^3\ (8/27)) / (\tfrac{1}{2}\ \rho\ A\ V_1^3) = 16 / 27$$

Cut-in Wind Speed: The cut-in wind speeds for Velocity Turbines are where they will start generating electricity and are usually between three to five meters per second. The wind velocity at which this phenomenon commences called the cut-in wind speed. Wind turbines will cease operation below this wind velocity.

Cut-off Wind Speed: It is a value past which the wind turbines must cease producing power to prevent any damage[13].The cut-off speed for nearly all turbines is 25 m/s.

Nominal / Rated Wind Velocity: Speed of the wind when it achieves rated power. So, the strongest contributor in the power curve is actually this wind speed. The generation when climbing rotor blades will allow this higher wind speed control of output power above, this. It may sound complicated but this is simply the case that the lower rated speeds produce more energy, it will have a greater (up to rated wind speed) output between cut-in and rated. Most turbines are rated for wind waves of 11.5 – 15 m/sec [11].

Argument: The wind is just cut-out wind and no wind turbine machine can survive the wind. Although this is not part of power curve it's essential to describe turbine design wind at 50-60 m/sec the speed at which the turbines can survive [13].

3.6 Converter

Power conditioning units are electronic devices (DC-DC/AC or AC/DC). DC/DC converters, are an electronic device that converts a DC voltage or current in to a needed DC voltage and frequency output. The reason this type of converter is needed is because it is not practical to use transformers to step up or down the DC voltage. The DC/AC converter converts the generated DC voltage or current from the hybrid system to a routine AC type voltage output. Power inverter is the name of a power converter of this kind. The other is basically the opposite of the inverter so it is typically known as the rectifier and serves the purpose of AC/DC conversion. So, it converts the AC input voltage into a DC output voltage. In this type of work furthermore converter is treated as a bidirecctional one which can be a component of hybrid systems and can be of the DC/ AC converter 40 or of the AC/DC 41 type defined as "bidirectional". The bi-directional converter used in this is for 2 currents for e.g. when a DC output comes from the battery & PV the converter reverse this to a improved AC to enhance the charging from wind or diesel generator. The most important factor to determine the capacity of the inverter is the determination of all the loads demanding from all users that can work simultaneously, but in this case the paper inverter could be sized smaller than the load that could be powered because of the supplying of the electricity from a diesel generator and the wind turbine directly to the consumers. There are a two power electronics components in the solar PV and wind power systems, rectifier and inverter. An inverter converts the direct current electricity produced to alternating current electricity, making this the type of electricity connected to individual household appliances.

3.6.1 Converter Modeling

The converter can be operated as a rectifier and an inverter through the proposed configurations that are proposed in this study. Households receive electrical load in the form of alternating current (AC). All mathematical models introduced in this section are based on [34]. The inverter also consumes power with an effective mathematical model for the photovoltaic system and battery bank is described as follows.

$$E_{PVG-IN(t)} = E_{PVG(t)} * \eta_{INV} \tag{3.18}$$

$$E_{BAT-INV(t)} = \left[\frac{E_{BAT(t-1)} - E_{LOAD(t)}}{\eta_{INV} * \eta_{DCHG}}\right] \tag{3.19}$$

Where:

EPVG-IN(t): Energy production from inverter [kWh]

EPVG(t): Energy production from photovoltaic generator [kWh]

ηINV: Efficiency of the inverter

EBAT-INV(t): Energy output from the battery [kWh]

ELOAD(t): Energy expended by the load side [kWh]

ηDCHG: Efficiency of battery discharge

EBAT(t-1): Energy stored in the battery at time t-1 [kWh]

The rectifier converts surplus AC electricity from the wind and diesel generators into DC for battery charging.

$E{\_}_{REC-OUT(t)} = E_{REC-IN(t)} * \eta_{REC}$

$E_{REC-IN(t)} = E_{SUR-AC(t)}$ (5.10)

The AC excess energy at any given moment is expressed by the equation 5.11.

$E_{SUR-AC(t)} = E_{WEG(t)} + E_{DEG(t)} - E_{LOAD(t)}$ (5.11)

Where:

EREC-OUT(t): Rectifier Energy Output[kWh]

ηREC: Rectifier Efficiency
EREC-IN(t): Rectifier energy input[kWh]
ESUR-AC(t): Excess energy of AC source [kWh]
EWEG(t): Wind generator energy [kWh]
EDEG(t): Diesel generator energy[kWh]
ELOAD(t): Energy use of load[kWh]

The mathematical modeling of the converter incorporates key factors like energy output from the PV generator ($E_{PVG(t)}$), battery discharge efficiency (η_{DCHG}), load demand ($E_{LOAD(t)}$), and surplus AC energy ($E_{SUR-AC(t)}$). These equations provide a framework for optimizing energy flow, balancing supply and demand, and improving the overall efficiency of the hybrid system.

Hybrid systems leverage these DC-AC Bus transitions through the converter's network of functions to efficiently incorporate renewable/non-renewable energy. This improves energy supply reliability while also lowering reliance on fossil fuels, creating sustainability and savings. Thus, converter modelling being part of hybrid operation is another crucial factor for active energy conversion and facilitating the transition towards renewable energy systems

3.7 Battery Storage

Incorporating energy storage devices into the hybrid framework is essential for maintaining a dependable equilibrium between energy generation and consumption. These systems facilitate the acquisition and storage of surplus energy from renewable sources for subsequent use. Surplus energy generation usually transpires during times of elevated solar irradiation or vigorous wind activity—typically during daylight hours—when energy demand is relatively diminished. This stored energy is subsequently utilized to mitigate shortages at nighttime or instances of diminished solar exposure, decreased wind activity, or gloomy weather.

Energy storage can be accomplished by diverse methods, including chemical processes (e.g., batteries or hydrogen storage), potential energy systems (e.g., pumped hydro or compressed air), electrical systems (e.g., capacitors), or mechanical systems (e.g., flywheels). The principal attributes employed to assess storage technology for the majority of energy systems are as follows [26]:

Energy Storage Capacity [kWh or Ah]: This measure denotes the total energy that the system can store. In practice, a battery's actual capacity frequently falls short of its rated capacity due to factors such as quick discharge, which diminishes effective capacity, or progressive drain, which enhances it.

Charge and Discharge Rates [kW or A]: These rates measure the power at which energy is stored in or withdrawn from the system. The fluctuations in these rates are contingent upon the storage method, the quantity of energy stored, and the length of energy transmission. Generally, charging rates are inferior to discharging rates in the majority of systems.

Lifespan: The durability of storage devices is assessed according to metrics such as the count of charge-discharge cycles, the duration of operational years, or the cumulative energy throughput (kWh or Ah) throughout the device's lifespan.

Round-Trip Efficiency: This metric indicates the energy losses experienced during storage and retrieval operations. Round-trip efficiency quantifies the ratio of energy output to the energy input necessary for charging. High-efficiency systems minimize energy loss and decrease total storage expenses.

Energy Density [Wh/kg and Wh/m^3]: This attribute denotes the quantity of energy that can be stored per unit of mass or volume, whereas Power Density [W/kg] quantifies the rate at which energy may be released per kilogram of the storage device.

These attributes are essential for delineating, choosing, and enhancing energy storage solutions to fulfill the operational requirements of hybrid energy systems

Table-3.7 : Energy Storage Types: Advantages and Constraints **[26]**

Various Storage Technologies	**Advantages**	**Constraints**
Lead-acid	Market accessibility, reasonable expenses, superior performance-to-cost ratio	Restricted lifespan
Lithium-Ion Batteries	Compacted size	High prize
Sodium-Sulphur Battery	High efficiency	Appropriate for extensive electrical appliances
Flow Batteries	Can be completely depleted	High expenses

3.7.1 Battery Bank

Among the energy storage technologies presented in Table 3.7, the lead-acid battery is the most commonly employed choice for standalone systems, owing to its cost-effectiveness, established reliability, and advantageous cost-to-performance ratio. These batteries are offered in multiple capacities, featuring terminal voltages of 6V, 12V, and 24V. The longevity of a battery is profoundly influenced by the depth of discharge, which denotes the degree of energy expended at a given moment. During adverse climatic conditions, energy demands are fulfilled by the batteries; however, if the battery experiences significant exhaustion, the diesel generator compensates for the energy needs while recharging the battery, contingent upon the power management system permitting cycle charging. Deep-cycle batteries often discharge 80-85% of their capacity, retaining a reserve of 15-20%. A multitude of factors affects the dimensions of a battery system, including:

- Daily energy utilization
- Length of autonomy
- Maximum depth of discharge
- Temperature modification
- Nominal battery capacity and durability

To employ a segment of the battery's stored energy, its capacity must consider the necessary Depth of Discharge (DOD). Energy disruptions from renewable sources during periods devoid of sunlight or wind require a battery bank capable of supplying autonomy for several hours or days. This condition is theoretically delineated by the subsequent equations [29,30].

3.7.2 Battery Capacity Calculation

$$C_B = \frac{E_L S_D}{V_B (DOD)_{max} T_{cf}\, \eta_B} \tag{3.20}$$

Where,

C_B: Battery capacity [Ah]

E_L: The electrical load measured in watt-hours [Wh]

S_D: Longevity of battery[days]

V_B: Voltage of the storage battery [V]

$(DOD)_{max}$: Highest discharge rate

T_{cf}: Correction factor of temperature

η_B: Battery efficiency [%]

The battery's state of charge is contingent upon the energy produced by solar photovoltaics, wind velocity, and load demand. Consequently, the state of charge can be ascertained utilizing the equation presented below. Battery charge status: When charging, if the energy output from solar panels and wind generators exceeds the load demand, the battery capacity at a specific time t can be expressed by the following equation.

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1)(1-\sigma) + \left[E_{gen}(t) - \frac{E_{L(t)}}{\eta_{inv}}\right]\eta_B \tag{3.21}$$

The battery is in a draining condition because the electricity provided by renewable resources is insufficient to meet the load requirement, as calculated by the following equation.

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1)(1-\sigma) + \left[\frac{E_{L(t)}}{\eta_{inv}} - E_{gen}(t)\right] \qquad (3.22)$$

$$E_{gen}(t) = E_{pv}(t) + E_{wg}(t) \qquad (3.23)$$

Where,

SOC(t): State of battery capacity at hour (t) [Wh]

SOC(t-1): State of battery capacity at hour (t-1) [Wh]

σ: Battery hourly self-discharge rate. The manufacturer gives a self-discharge of 25% over six months for a storage temperature of 20°C **[29,30]]**

$E_{L(t)}$: Load requirement at time (t)

η_{inv}: Inverter efficiency (in this paper assumed as constant, 95%)

η_B: Battery charging efficiency (during discharging the efficiency is equal to 100% and during charging is set from 20 to 80% depending on the charging current).

$E_{gen}(t)$:Total energy from wind and PV generated [kWh]

$E_{PV}(t)$: Energy generated from PV [kWh]

$E_{WG}(t)$: Energy generated from wind [kWh]

3.7.3 Autonomy Period:

The autonomy period of a battery bank can be expressed by the following mathematical expression. It is the ratio of battery bank size to the load demand [27].

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} (1 - q_{min/100}) \left(\frac{24hr}{day}\right)}{I_{prim,ave}\left(1000 \frac{Wh}{kWh}\right)} \qquad (5.16)$$

Where,

A_{batt}: Autonomy of battery [hr]

N_{batt} :Number of batteries

V_{nom}: Nominal voltage of a single battery

Q_{nom}: Nominal capacity of a single battery

q_{min}: Minimum state of charge for the battery bank

$I_{prim,ave}$: Mean primary electricity demand[kWh/day]

3.8 Backup Generator

The backup generator is part of the hybrid system suggested in this thesis. What Is a Generator: A generator is an electrical machine that changes kinetic energy of combustion engines into electric energy powered by different energy sources. Burning engines are the simplest way to transform oil into energy given its low set-up capital. A backup generator adds on to the renewable power generation and helps to reduce energy shortage at high times when renewable supply is being interrupted and the battery is unable to supplement. The costs of operating generators substantially exceeds that of generation via renewable sources. One such important consideration in the hybrid system is making the consideration of the availability of fuel and the efficiency of the combustion engine when integrating with the motor. Physical backup generators allow the design of power systems that either have very little or no reliance on storage batteries. As described in [31], the generator runs best under full capacity, so it should be on only when the energy storage (batteries) are at 20% of their total charge. Two major types of generators are DC generators and AC generators. AC equipment are grouped into asynchronous and synchronous generators or motors according to [32]. A synchronous generator is a machine that converts mechanical energy to an alternating current electricity. They offer precise control of frequency and voltage. Runs at synchronous speed and also provides the necessary alternating current. They sustain the electrical energy required for civilization. It is suitable for grid-connected and off-grid power generation systems [33]. A synchronous generator is supplied through a constant-speed engine that synchronizes the frequency required of the generator's output voltage. Here are the formulae for generator fuel curve and efficiency curves. The fuel curve shows how much fuel the generator will consume in the process of generating power. The generators' fuel consumption is computed using the following mathematical equation (in units per hour) [27].

$$F = F_0 . Y_{gen} + F_1 . P_{gen} \tag{3.24}$$

Where:

- F_0: The fuel curve intercept coefficient units/hr/kW
- $Y_{(gen)}$: Fuel curve slope units/hr/kW

- F_1: Rated capacity in kW
- $P_{(gen)}$: Electric output in kW

The file topic appears to pertain to fuel consumption and efficiency in energy generation systems. Specifically, it addresses parameters in the fuel curve equation, which is commonly used in power generation and energy management to estimate the fuel consumption based on electric output. Here is a brief explanation of each parameter:

1. F_0 (Fuel Curve Intercept Coefficient)
   Represents the baseline fuel consumption that occurs regardless of the electric output. It accounts for operational overheads like idling and maintenance requirements. Units: units/hr/kW.

2. $Y_{(gen)}$(Fuel Curve Slope)
   Indicates the rate at which fuel consumption increases with an increase in electric output. It reflects the system's operational efficiency. Units: units/hr/kW

3. F_1 (Rated Capacity)
   The maximum electric output capacity the system is designed to handle. This serves as an upper limit for performance. Units: kW

4. $P_{(gen)}$ (Electric Output)
   Refers to the actual electric power output at any given moment. It fluctuates based on demand and system performance. Units: kW

This framework is crucial in energy management, allowing for optimization of power generation systems by minimizing fuel consumption while meeting demand. It also supports cost analysis, efficiency tracking, and environmental impact assessments in energy production systems.

3.9 Design Specifications, Standards and Constraints

PV Module Design

The photovoltaic (PV) module is designed to produce energy at a capacity of 1 kW per module, with a cost of $417 per kW. Monocrystalline panels are recommended for their high efficiency to optimize energy generation. The layout must consider the distance between panels to minimize shading and improve ventilation, ensuring sustained output. The slope of the panels should be adjusted to the site’s latitude, and the azimuth angle must face south in the Northern Hemisphere to maximize solar exposure. Additionally, PV modules have to be placed on a suitable place on our targeted study location.

Wind Turbine Design

The wind turbine system consists of four 10 kW turbines with a total capacity of 40 kW. Each turbine's hub height should range between 30 and 50 meters, based on the local wind profile, to capture maximum wind energy. The rotor blade diameter must be optimized for efficiency, and horizontal-axis wind turbines are preferred for their proven reliability and performance in energy conversion. The design must also consider local wind speeds to maximize energy generation while adhering to IEC 61400 standards.

Battery Storage System

Battery storage is crucial for maintaining a renewable fraction of 80% and ensuring energy availability during low resource periods. Lithium-ion batteries are recommended over lead-acid batteries due to their higher efficiency, longer lifespan, and reduced maintenance. Each battery has a capacity of 12V and 200Ah, priced at $258.33 per unit. The system must be designed to store sufficient energy to support the load during renewable generation dips while staying within the cost and space constraints.

Bidirectional Converter

A bidirectional converter is essential for managing the flow of energy between the DC and AC systems. This converter facilitates DC-to-AC conversion for loads and AC-to-DC conversion for charging the battery system. The converter must meet IEEE 1547 and UL 1741 standards to ensure compatibility with grid requirements and safety compliance.

Backup Diesel Generator

A 150 kW diesel generator serves as a backup power source to ensure system reliability during extended periods of low renewable energy availability. The generator's role is limited to emergencies, minimizing fuel consumption and carbon emissions. The system design prioritizes renewable energy sources to reduce dependency on the diesel generator while maintaining operational reliability.

Renewable Fraction and Emission Reduction

The hybrid system is designed to achieve a renewable fraction of at least 80%, ensuring that the majority of energy generation comes from clean sources. This configuration minimizes reliance on the diesel generator, significantly reducing carbon emissions. The system must be optimized to maintain environmental sustainability while meeting load requirements.

❖ Standards and Compliance

The design adheres to international standards for components and systems. PV modules must comply with IEC 61215 and IEC 61730 for performance and safety. Wind turbines follow IEC 61400 guidelines for structural and operational integrity. Batteries are designed to meet IEC 62619 and UL 1973 standards for safety, while the converter aligns with IEEE 1547 and UL 1741 for grid compatibility. The entire system integrates ISO 50001 standards for energy management and sustainability.

❖ Constraints and Challenges

The design must stay within the budget while ensuring all components meet the required specifications. Space availability is a critical constraint for the placement of PV panels and wind turbines. The system must also balance energy storage capacity without exceeding cost and space limitations. Regulatory compliance with local grid codes and environmental standards must be ensured, alongside the need to meet load demand reliably.

3.10 System Assessment

Table-3.10.1 Load Estimation for Andar Char

Load Type	Electrical Load Type		Quantity	Ratting
Residential Load	Each House	CFL Light	3	20w
		Fan	2	75w
		Power Socket	1	70w
	Each Mosque	CFL Light	8	20w
		Fan	12	75w
		Power Socket	4	70w
		pump	1	1.5HP
Commercial Load	Primary School	CFL Light	30	20w
		Fan	32	75w
		Power Socket	6	70w
		pump	1	1.5HP
	Madrasa	CFL Light	12	20w
		Fan	8	75w
		Power Socket	4	70w
		pump	1	1.5HP
	Bazar	CFL Light	45	20w
		Fan	25	75w
		Power Socket	35	70w
		pump	1	1.5HP
	Launch Ghat	CFL Light	6	20w
		Fan	2	75w
		Power Socket	2	70w
		pump	1	1.5HP

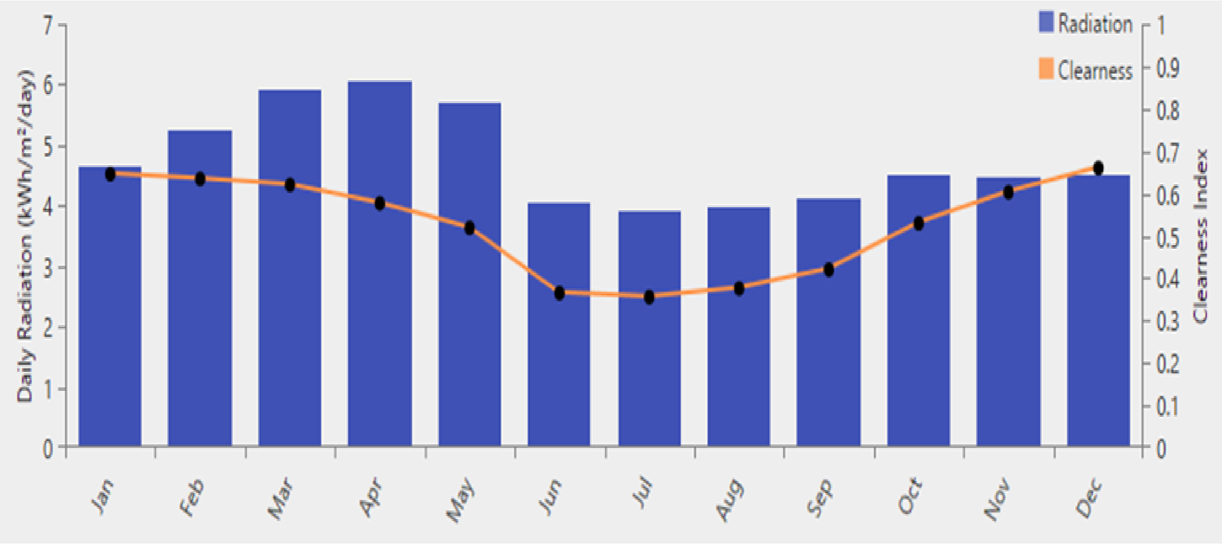


Figure 3.10-a : Solar Radiation Over a Year

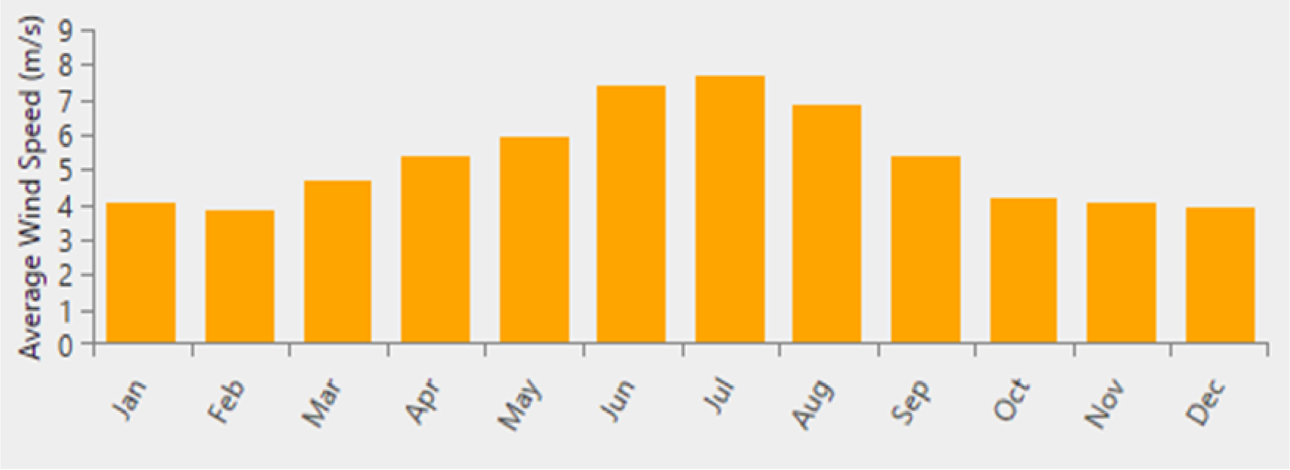


Figure 3.10-b: Average Wind Speed Over A Year

(These bar graphs are collected from HOMER software)

Residential Load:

Table-3.10.2**:** Daily Residential Load Data of Andar Char

Hours	**Load (kW)**	**Hours**	**Load (kW)**
0	57.050	12	22.500
1	56.700	13	46.300
2	57.200	14	45.750
3	56.900	15	18.700
4	56.800	16	20.200
5	67.620	17	21.320
6	38.300	18	81.000
7	30.000	19	94.100
8	28.000	20	96.000
9	21.000	21	85.300
10	18.000	22	56.000
11	17.500	23	55.400

Peak Load Periods: The maximum load is reached for the 20:00 hour (8 PM) with a value of 96.00 units and for the 19:00 hour (7 PM) with a load of 94.10 units. They are understandably in much greater demand at night because that is when most households or commercial activities take place.

Low Load Periods: The minimum load is 17.50 units at 11:00 hours (11 AM), followed by 10:00 hours (10 AM) with 18.00 units. This indicates a decrease in power consumption in mid-morning, likely indicating diminished activity in residential and/or commercial settings.

Fall into the Early Morning Controversy: Between 0:00 hours (midnight) and 5:00 hours (5 AM), the load remains at pretty constant levels, around 67.62 units at 5 AM, which can also be explained with domestic heating, cooling, or lighting during early morning times.

Afternoon and Evening Trends: Through the day, it builds very gradually from 20.20 at 4 PM until peak levels are recorded later in the evening. This gradual increase aligns with higher energy consumption as residents return home or businesses run during their hours of activity.

Nighttime Drop:

After 21:00 hours (9 PM), there is a substantial decrease in load, falling from 85.30, measured at 21:00 hours (9 PM), to 56.00 units at 22:00 hours (10 PM) and 55.40 units at 23:00 hours (11 PM). It shows that energy use is falling as people wind down their daily activities.

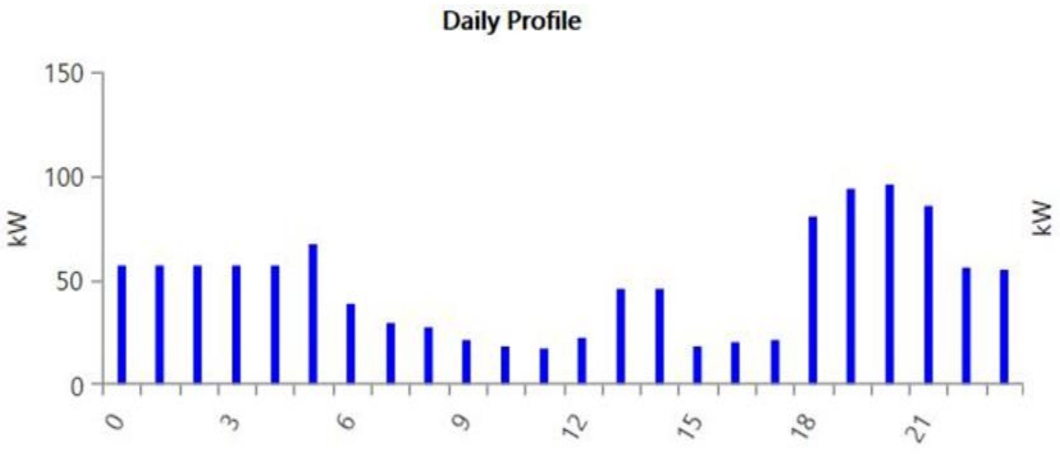


Figure 3.10-c: Daily Residential Load Profile

Major Highlights:

Peak usage time: Evening hours (7 PM to 9 PM) demand the most energy supply and should be considered in system design.

Low Utilization Time: Between mid-morning hours (10 AM to 11 AM), the demand is extremely low, indicating opportunities for machine optimization or load balancing.

General Trends: Load demand has strong cyclicity, with early morning peak, late afternoon peak, and evening peak periods compared to the mid-morning and early afternoon hours.

Commercial Load:

Table-3.10.3**:** Daily Commercial Load Data of Andar Char

Hours	**Load (kW)**	**Hours**	**Load (kW)**
0	0.140	12	4.270
1	0.140	13	3.410
2	0.140	14	3.30
3	0.140	15	4.115
4	0.140	16	5.640
5	2.160	17	3.920
6	1.990	18	4.960
7	0.590	19	5.150
8	1.730	20	3.095
9	3.50	21	1.30
10	6.70	22	0.790
11	6.760	23	0.680

Peak Load Hours:

The peak load occurs at 11:00 hours (11 AM) with 6.760 kW, closely followed by 10:00 hours (10 AM) with 6.70 kW. These hours indicate significant demand, potentially due to increased business or operational activities during late morning.

Lowest Load Hours:

The minimum load is observed during the early morning hours of 0:00–4:00 (12 AM–4 AM) with a steady load of 0.140 kW. This indicates minimal energy consumption, likely representing only base load requirements for essential operations.

Morning Load Trends:

From 5:00 hours (5 AM) onward, the load begins to increase, rising from 2.160 kW to 3.50 kW by 9:00 hours (9 AM). This gradual rise reflects the start of daily activities, leading up to the peak load during late morning.

Afternoon Load Fluctuations:

After the peak load at 11:00 hours, the load decreases to 3.410 kW by 13:00 hours (1 PM) and stabilizes in the range of 3.30–4.27 kW between 12:00 and 15:00 hours (12 PM–3 PM). This reflects steady energy use, likely due to consistent midday activity.

Evening and Nighttime Dynamics:

In the evening, the load reaches another high of 5.640 kW at 16:00 hours (4 PM) and remains elevated around 4.96–5.15 kW between 18:00 and 19:00 hours (6 PM–7 PM), possibly due to evening business operations or lighting needs. Post 21:00 hours (9 PM), the load decreases significantly to 0.680 kW by 23:00 hours (11 PM), signaling the end of most activities for the day.

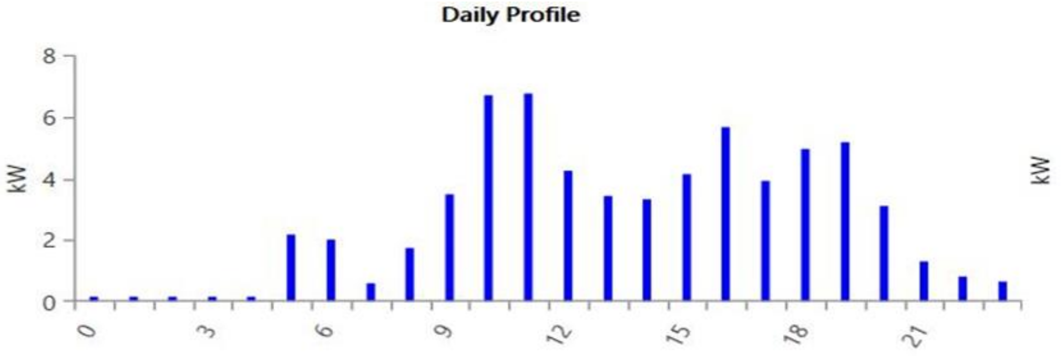


Figure 3.10-d: Daily Commercial Load Profile

Key Observations:

High Energy Demand: Peak demand occurs during 10–11 AM (~6.7–6.76 kW), reflecting intense commercial activity.

Energy Saving Opportunity: Moderate demand between 1–3 PM (3.3–4.3 kW) allows for load balancing or conservation.

24/7 Power: Low, consistent load (~0.14–0.6 kW) overnight (12–5 AM) reflects essential operations.

Commercial Influence: Energy trends align with commercial hours, peaking during activity and dropping after-hours.

3.11: Simulation Setup

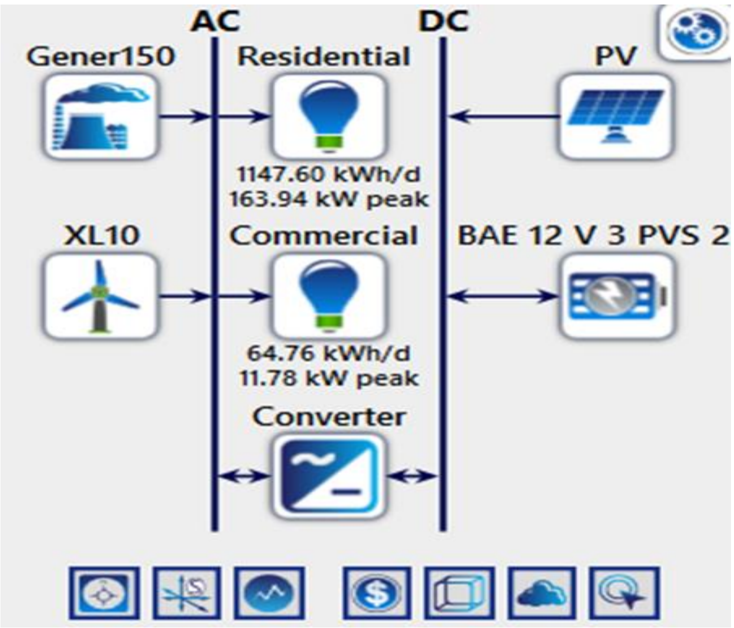
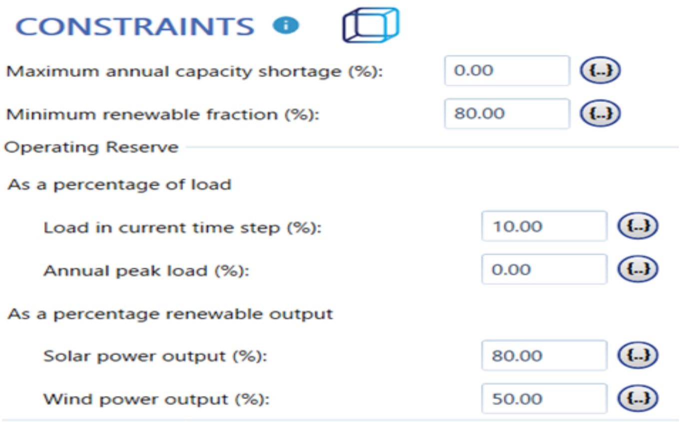


Figure 3.11-a: Simulation Schematic Setup

The AC side includes a 150 kW diesel generator (Gener150) and a 10 kW wind turbine (XL10), supporting residential (1147.60 kWh/day, 163.94 kW peak) and commercial (64.76 kWh/day, 11.78 kW peak) loads. The DC side features a photovoltaic (PV) array and a battery storage system (BAE 12 V), managed via a bidirectional converter for energy flow between AC and DC systems.



CONSTRAINTS

Maximum annual capacity shortage (%): 0.00

Minimum renewable fraction (%): 80.00

Operating Reserve

As a percentage of load

Load in current time step (%): 10.00

Annual peak load (%): 0.00

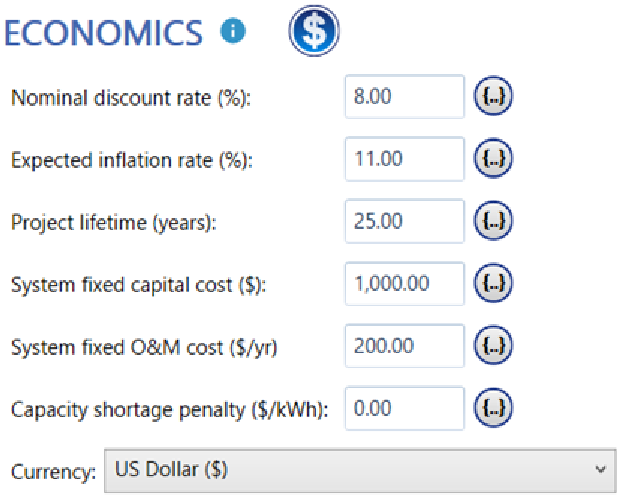
As a percentage renewable output

Solar power output (%): 80.00

Wind power output (%): 50.00

Figure 3.11-b: Constraint Parameters

We keep the minimum renewable fraction (RF) to 80% to provide green power. The Minimum Solar Output is kept at .80 as it is our main source of renewable energy.



ECONOMICS

Nominal discount rate (%): 8.00

Expected inflation rate (%): 11.00

Project lifetime (years): 25.00

System fixed capital cost ($): 1,000.00

System fixed O&M cost ($/yr) 200.00

Capacity shortage penalty ($/kWh): 0.00

Currency: US Dollar ($)

Figure 3.11-c: Economic Parameter

The project lifetime is 25 years. The inflation rate is assumed to be around 11% as it fluctuates slightly [35].The Capacity Shortage penalty is kept at 0.00 dollars because of the off-grid system.

3.12 Overview

This methodology emphasizes the design, evaluation, and experience of hybrid energy systems (HESs) in the coastal village of Andar Char, Bangladesh. Through data and modelling, this study shows the importance of integrating solar photovoltaics, wind turbines, batteries and diesel generators for residential and commercial energy needs. The system features a renewable fraction minimum of 80%. Energy efficiency, component optimization, and regulatory compliance are key design elements. Performance Data of AC and DC System with Full Cycle Carrier (FCC) in Software (HOMER) Supporting Simulation. This model enables enhanced energy access and socio-economic growth for underserved populations.

CHAPTER 4

RESULTS & DISCUSSIONS

4.1 Results

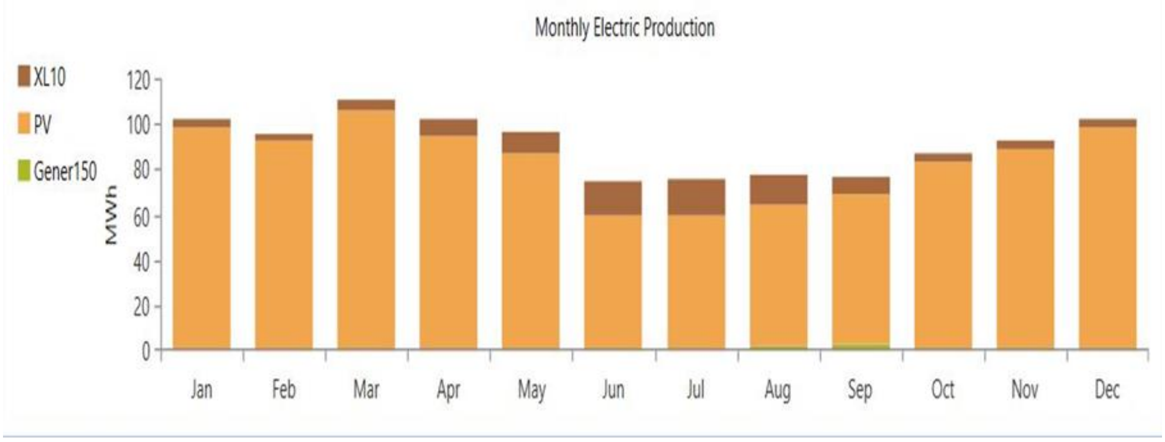


Figure 4.1-a: Monthly Electric Production from Solar, Wind, and Diesel Sources

Monthly electricity production figures are broken down by PV (solar), XL10 (wind), and Gener150 (diesel) in the chart below. Solar photovoltaic dominates on energy generation for the whole year, peaking during March. Wind (XL10) offers consistent input, and the diesel generator (Gener150) hardly operates, only becoming visible in months with low renewable output, such as June and July. The system continues to promote stable production that focuses on relying on renewables, with diesel as an interim power source for user reliability. This combination does a fine job of enabling a sustainable process with few fossil fuel needs.

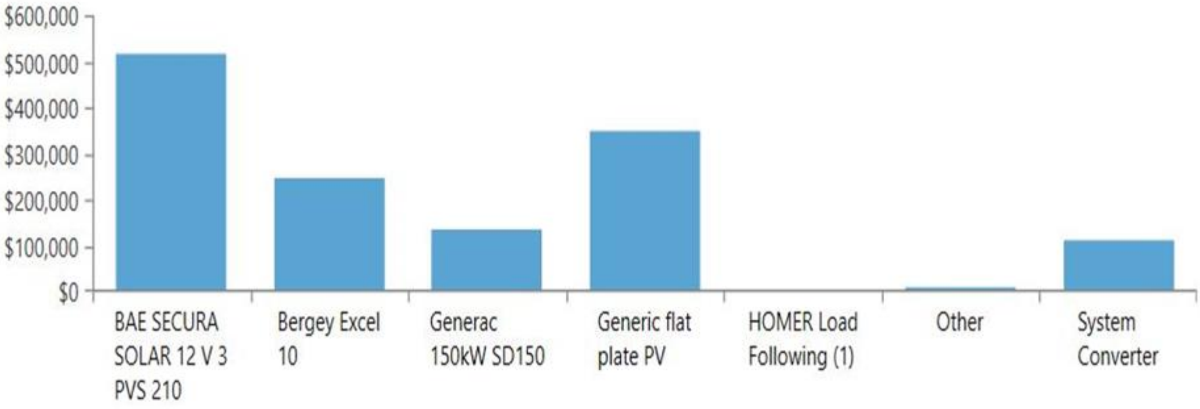


Figure 4.1-b: Cost Distribution of Components in a Hybrid Energy System

The attached chart is the cost breakdown of a hybrid energy system. The BAE SECURA Solar Battery is the most expensive, at more than $500,000, and Generic Flat Plate PV panels, indicating a dependence on solar energy and storage for the system. The Bergey Excel 10 Wind Turbine and Generac 150 kW Diesel Generator are both affordable, as are the System Converter and other items, contributing little to the overall cost. The cost allocation allows for investment in the components of renewable energy while promoting sustainability and efficiency, supported by wind and diesel systems at equal expense.

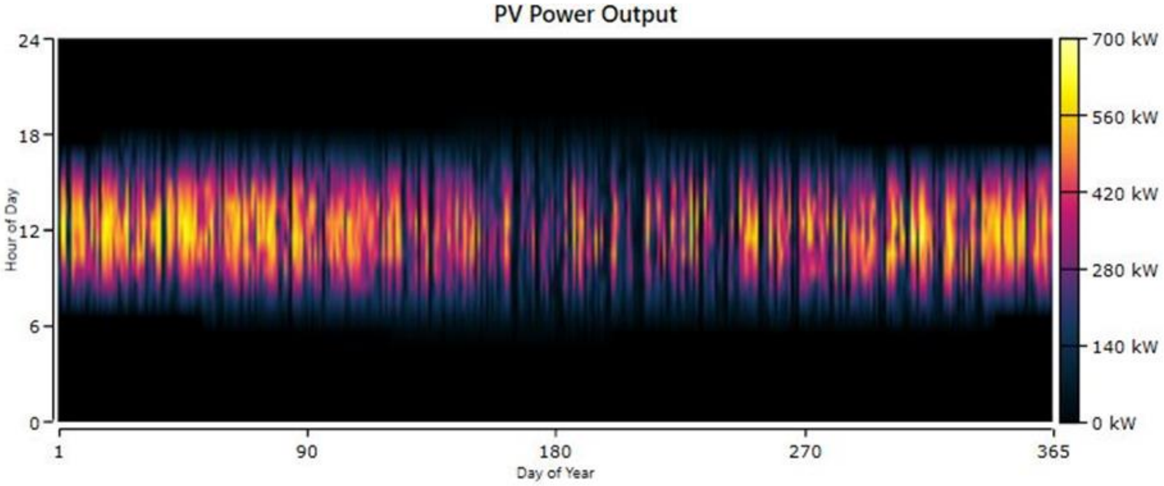


Figure 4.1-c: PV Power Output

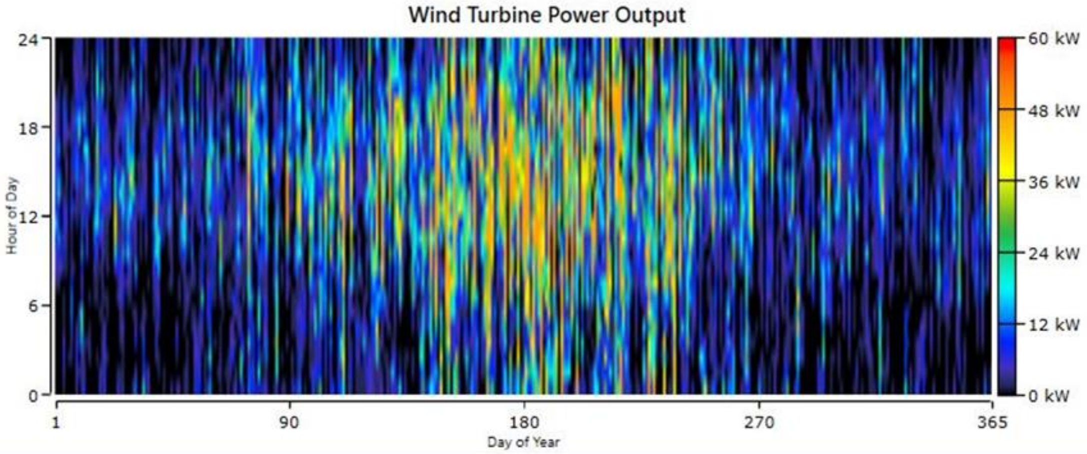
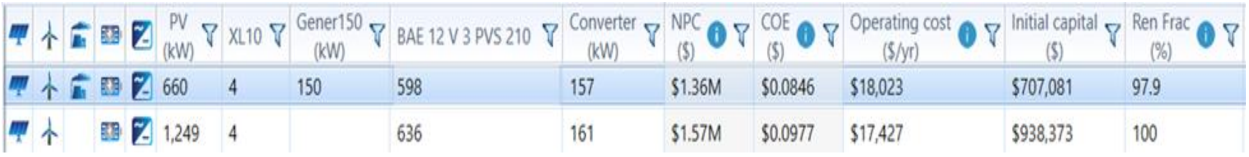


Figure 4.1-d: Wind Turbine Power Output



PV (kW)	XL10	Gener150 (kW)	BAE 12 V 3 PVS 210	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
660	4	150	598	157	$1.36M	$0.0846	$18,023	$707,081	97.9
1,249	4		636	161	$1.57M	$0.0977	$17,427	$938,373	100

Figure 4.1-e: Outputs of HOMER

4.2 Discussions

Our optimized system per-unit electricity cost is **$0.0846,** which is equivalent to **10.15 BDT/kWh** (assuming an exchange rate of 1 USD = 120 BDT). Our per-unit energy cost is lower than other optimized COEs. For instance,

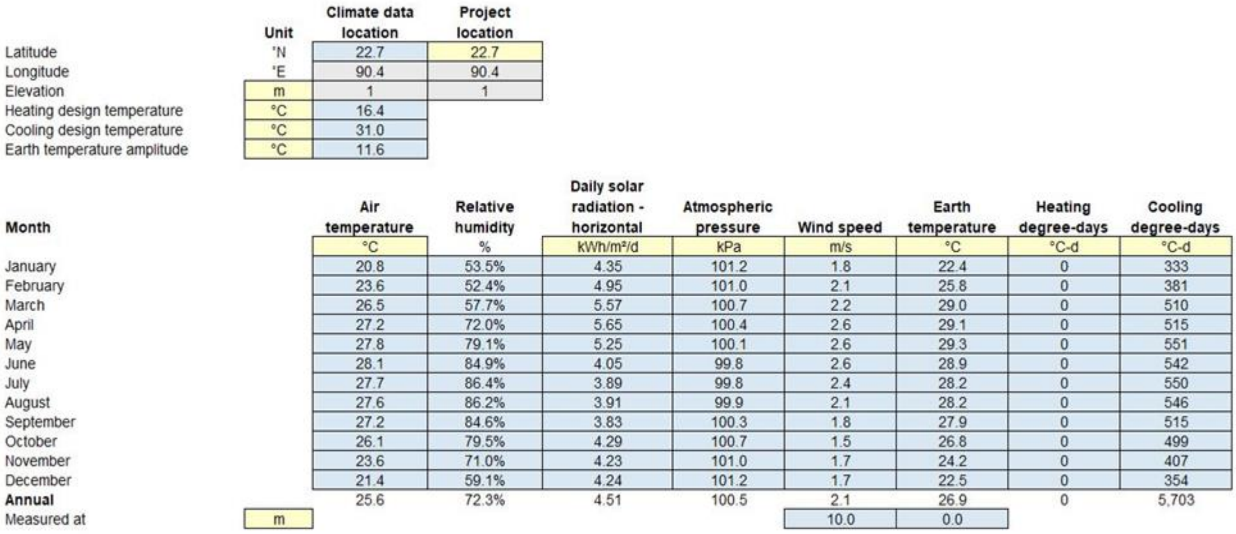
A study on an off-grid hybrid energy system in Sonadia Island reported a COE of $0.411 per kWh, approximately 49.32 BDT/kWh [36].

The Levelized Cost of Electricity (LCOE) for new utility-scale solar projects ranges from $97 to $135 per megawatt-hour (MWh), equivalent to approximately 11.64 to 16.2 Bangladeshi Taka (BDT) per kWh, considering an exchange rate of 1 USD = 120 BDT [37].

Because of our superior cost efficiency, our optimized system is economically feasible.

Chapter 5
Case Study and Data Analysis

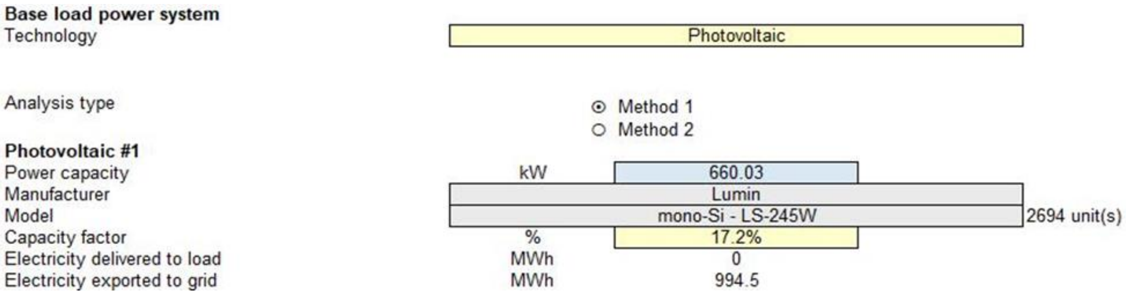
5.1 RETScreen Case Study



	Unit	Climate data location	Project location
Latitude	˚N	22.7	22.7
Longitude	˚E	90.4	90.4
Elevation	m	1	1
Heating design temperature	°C	16.4	
Cooling design temperature	°C	31.0	
Earth temperature amplitude	°C	11.6	

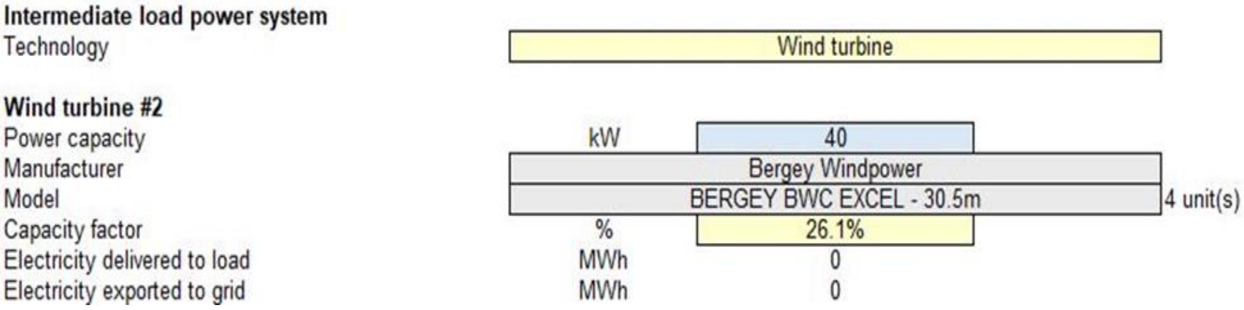
Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		20.8	53.5%	4.35	101.2	1.8	22.4	0	333
February		23.6	52.4%	4.95	101.0	2.1	25.8	0	381
March		26.5	57.7%	5.57	100.7	2.2	29.0	0	510
April		27.2	72.0%	5.65	100.4	2.6	29.1	0	515
May		27.8	79.1%	5.25	100.1	2.6	29.3	0	551
June		28.1	84.9%	4.05	99.8	2.6	28.9	0	542
July		27.7	86.4%	3.89	99.8	2.4	28.2	0	550
August		27.6	86.2%	3.91	99.9	2.1	28.2	0	546
September		27.2	84.6%	3.83	100.3	1.8	27.9	0	515
October		26.1	79.5%	4.29	100.7	1.5	26.8	0	499
November		23.6	71.0%	4.23	101.0	1.7	24.2	0	407
December		21.4	59.1%	4.24	101.2	1.7	22.5	0	354
Annual		25.6	72.3%	4.51	100.5	2.1	26.9	0	5,703
Measured at	m					10.0	0.0		

Figure-5-a: Climate data of study area



Base load power system			
Technology		Photovoltaic	
Analysis type		⊙ Method 1 ○ Method 2	
Photovoltaic #1			
Power capacity	kW	660.03	
Manufacturer		Lumin	
Model		mono-Si - LS-245W	2694 unit(s)
Capacity factor	%	17.2%	
Electricity delivered to load	MWh	0	
Electricity exported to grid	MWh	994.5	

Figure 5.b: Specifications for PV



Intermediate load power system			
Technology		Wind turbine	
Wind turbine #2			
Power capacity	kW	40	
Manufacturer		Bergey Windpower	
Model		BERGEY BWC EXCEL - 30.5m	4 unit(s)
Capacity factor	%	26.1%	
Electricity delivered to load	MWh	0	
Electricity exported to grid	MWh	0	

Figure 5-c: Specifications for Wind

We selected the parameter’s value as same as we input in HOMER software so that we can compare simple payback both software’s optimized results.

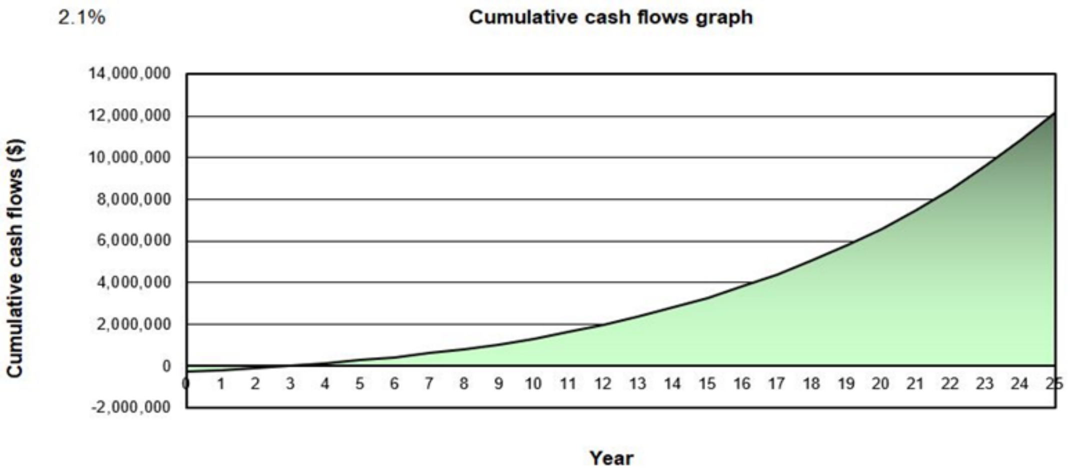


Figure 5-d: Cumulative cash flow graph

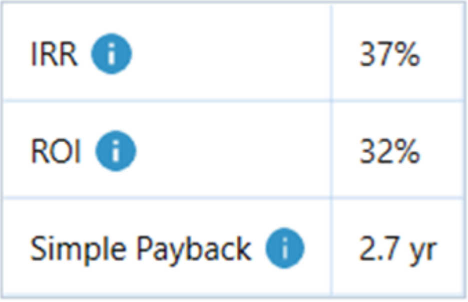
Cumulative Cash Flow Graph indicates good financial status of the project over 25 years, as cash flow starts off negative (as a result of the large initial capital requirement) but then breaks through into positive territory / payback around year 3, speaking of a short payback period in terms of behaviour is a good thing. After breakeven the cash flow expansion remains consistent, steepening sharply after year 10, reaching over $12 million in year 25. This demonstrates that the project is quickly breaking even and will generate consistent growth with high returns in the long term, which makes it a very low-risk, high-reward investment.

Financial viability		
Pre-tax IRR - equity	%	44.0%
Pre-tax IRR - assets	%	30.9%
Simple payback	yr	4.7
Equity payback	yr	2.9

The financial viability metrics indicate a pre-tax IRR of 44.0% for equity and 30.9% for assets which reflect strong returns. The project has a simple payback period of 4.7 years and a shorter equity payback period of 2.9 years which highlights quick recovery of investment and profitability.

5.2 HOMER Case Study

Economic Matrices



IRR ⓘ	37%
ROI ⓘ	32%
Simple Payback ⓘ	2.7 yr

This image shows some important financial performance measures for an investment:
Internal Rate of Return (IRR): 37%
This means the project offers an excellent return rate, far greater than the usual threshold of viability, and thus implies a high degree of profitability.
Return on investment (ROI): 32%
The 32% ROI indicates that the project returns more than cents on the dollar, making this a profitable business.
Simple Payback: 2.7 years
The cost of the investment will be completely covered by returned in only 2.7 years, clearly demonstrating a short payback period and a low risk.

HOMER (Hybrid Optimization of Multiple Energy Resources) focuses on the optimization of hybrid energy systems with in-depth analyses of cost-effectiveness and technical feasibility. In a single system, for example, HOMER reports an IRR of 37%, an ROI of 32% , and a simple payback period of 2.7 years. The system's ability to recover costs quickly and the high financial return is also unsurprising news to investors in search of quick returns.

RETScreen, a clean energy management software, offers a holistic analysis based on the pre-tax IRR of equity and assets. For a similar system, RETScreen yields an equity IRR of 44% and one for assets of 30.9%, a simple payback of 4.7 years, and an equity payback of 2.9 years. These numbers highlight solid long-term profitability but with a potentially longer payback period than HOMER's system. By emphasizing equity as well as asset performance, RETScreen provides a more complete financial picture, revealing important information for evaluating the long-term feasibility of an investment.

5.3 Lesson Learned

Key findings are,

I. HOMER has a faster payback period (2.7 years) and slightly lower equity returns than RETScreen.

II. RETScreen offers more comprehensive financial insights (both at equity and specific to investment assets IRRs) but also has a longer simple payback.

III. HOMER is more suited for quick-return investors, while RETScreen caters to those focusing on long-term viability.

It is essential to document lessons learned from this study or similar projects for use in future successes. This means understanding both what went well (a high IRR and short payback period) as well as aspects which require improvement (delays, unplanned over budget). They should focus on improving financial forecasting, adhering to schedules and effectively managing resources. This will have tremendous value when working on future/ similar projects, so that you more accurately ensure financial success.

CHAPTER 6

IMPACT ASSESSMENT

6.1 Possible Proposal Impacts

Social Impact

Reliability of Electricity: The hybrid system will provide reliable energy access in Char Andar, where there is usually no electricity during the day. It can improve the residents' quality of life by enabling them to participate in productive industries, receive better education through lighting and powered electronic devices, and experience better healthcare.

Environmental Impact

Reduction in Greenhouse Gas (GHG) Emissions: With 80% Renewable Penetration (RP), the system significantly reduces the reliance on diesel generators, minimizing carbon emissions and other pollutants.

Promotion of Renewable Energy: Using solar and wind as primary and subsidiary sources sets a precedent for sustainable energy solutions in similar remote or underdeveloped regions.

Preservation of Natural Resources: Reducing diesel fuel consumption decreases dependency on fossil fuels, contributing to the conservation of finite natural resources.

Economic Impact

Lower Cost of Energy (COE): The estimated energy generation cost of 0.0846 USD/kWh is highly competitive and affordable for the local community compared to grid expansion or solely diesel-based systems.

Job Creation: The installation, operation, and maintenance of solar panels, wind turbines, and batteries create job opportunities, fostering local economic development.

Economic Feasibility: HOMER optimization demonstrates a simple payback period of 2.7 years, making it an economically viable investment. Similarly, RETScreen estimates a payback of 4.7 years, reinforcing the system's profitability.

Return on Investment (ROI): A high ROI suggests that the hybrid system would attract potential investors or funding, enhancing project scalability in other off-grid areas.

Long-Term Impact

Energy Independence: The hybrid system reduces dependency on external grid connections or diesel imports, fostering energy independence for Char Andar.

Scalability and Replication: A successful project in Char Andar can serve as a model for other regions in Bangladesh and similar contexts globally, addressing the challenges of energy poverty sustainably.

Climate Change Mitigation: By prioritizing renewable energy sources, the project contributes to Bangladesh's commitments under international climate agreements such as the Paris Accord.

6.2 Ethical and Environmental Issues

Environmental Concerns

Lower carbon footprint: Using renewable energy sources is responsible for low air pollution and greenhouse gas emissions, as it is not fossil fuel-based.

Land Use: Proper land selection can minimize the impact on local ecosystems and biodiversity.

Moral Concerns

Electricity Equity: Ensure that disadvantaged and minority groups have equitable access to electricity.

Cultural Sensitivity: Cultural sensitivity incorporates the community and regional customs/requirements while designing and implementing the project.

6.3 Existing Codes or Standards

Solar PV Standards: Genuinely mean reliable and safe solar panels under IEC 61215 and IEC 61730. UL 1973 and IEC 62619 Responsible Battery Life and Use Standards

Energy Conversion Standards: To enable grid synchronization and energy flow, use converters and inverters that comply with IEEE 1547 and UL 1741 standards.

A Scoping Review of Renewable Energy Projects in Environmental Risk Assessment—Unraveling Environmental Regulations.

6.4 Additional Issues

Stakeholder Engagement: Bringing in local stakeholders ensures the project meets unique needs and has long-term acceptance.

Scalability: The system can be scaled to more rural regions by providing a reproducible national or broader-scale adoption model.

Educating and Capacity Building: Training local technicians to operate and maintain the system will ensure its sustainability and reduce dependence on outside help.

Strategy Alignment: The project aligns with the national renewable energy strategy, supporting government objectives for clean energy growth.

CHAPTER 7

CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions

The aim of this thesis is to design a stand-alone renewable hybrid power system for 1907 types of people in a specific Bangladeshi village called Char Andar. The horizontal global radiation potentials and wind speed are based on NASA data. These stats are fairly recent, recorded over a 24-hour span between 2023 and 2024. According to the report analyzing hourly data and monthly average profiles of both sources, the potentials of solar and wind energy are highly confirmed to be suitable for the generation of electric power by HOMER. The annual average wind speed and the annual average solar radiation in the system were 5.28 m/s and 4.76 kWh/m²/day, respectively.

It was and is still a daunting challenge for any developing country, such as Bangladesh, to provide rural electrification. Hybridization of renewable energy technologies to meet the energy needs of the country could provide sustainable solutions. The renewable hybrid schemes are not as cost-effective as conventional fuel-based plants and grid-connected power systems. Yet, the importance of saving the environment, the current standard of living in the countryside, and the surge of oil in the global market have driven the creation of viable, green options; thus, renewable energy technologies are already a mainstay.

The hybrid energy system can confidently, effectively, and sustainably address energy problems in deprived regions, as demonstrated by its implementation and dissemination. This system, which is comprised of solar photovoltaics, wind turbines, battery storage and a diesel engine, minimizes environmental effects and delivers dependable access to energy, harnessing the village's favorable solar and wind conditions. By having 80% of the applied energy coming from renewable energies and greatly reducing dependency on fossil fuels, this system meets worldwide standards of effectiveness, security and reliability. By using HOMER software to model and optimize the technical robustness and economic feasibility of the design, economic and sustainable design are balanced with low-cost, reliable operation.

The ability to access reliable energy can uplift the quality of life, reduce energy poverty, and ensure economic growth, which have their own positive socio-political touch. By developing a replicable model that can be implemented in other isolated or marginalized communities, this project builds towards greater national and international strides for the transition to renewable energy and sustainable development. Thus, the hybrid energy system for Andar Char offers a viable, sustainable solution to the energy challenges confronted by rural communities, thus bringing a ray of hope for better living standards and regional development.

7.2. Recommendation

Renewable energy resources are available throughout the country and have the potential to provide power through grid-connected and off-grid systems as they vary from site to site. Using off-grid solutions to generate electricity from local renewable resources alleviates the power shortfall the country experiences. Yet some challenges will still exist in implementing such systems, including but not limited to infrastructure, community financing, the risk-taking propensity of investors, and a lack of information regarding the use of renewable resources. The government (federally and at the state level) pushes to subsidize the various strategies of the grid and off-the-grid renewable energy technology systems to try to overcome the energy deficit. Moreover, it is also important to increase the purchasing power of renewable energy for rural communities by increasing their income. Although air pollution, land degradation, etc., and low living conditions of rural inhabitants are given attention, the deployment of renewable hybrid energy systems in Bangladesh's rural areas is essential. The government's current electrification efforts are focused primarily on large-scale power plants, particularly ones using coal and natural gas, while a handful of wind and solar farms fit that category. Independent PV systems are now available for individual residences in isolated places. However, these systems are often deficient in long-term sustainability and reliability. A more cost-effective and eco-friendly solution that ensures round-the-clock access to quality power while focusing on solar and wind energy hybridization. Apart from addressing the immediate energy needs of rural communities, this initiative aligns with the country's goals for sustainable development and environmental conservation.

7.3 Future Work Recommendations

- ❑ Further effort is required in the pre- and post-HOMER domains. We think it may be possible to create a standardized approach for evaluating demand in off-grid locations and obtaining stakeholder viewpoints. Simulations may be advanced to the next level of development by introducing demand scenarios. Likewise, a methodical approach to evaluating the business case for the optimal solution and issues pertaining to its supply might contribute to a broader understanding of micro energy systems. The complexity of today's power system increases in tandem with the number of dispersed sources, and the control system consistently enhances the system's functionality. In power systems, dispersed sources provide operational flexibility, but if they are not properly controlled, they cannot guarantee stability or reliability. Additional study and analysis might be conducted only on the modeling and configuration of DC power systems, which would comprise SHS, DC loads, and a large-scale DC generator powered by biomass. The design and development of MG 45 control systems, as well as the droop control technique, are essential elements of every SHS energy management system. Analyze the reliability and flexibility of an adaptive droop control model. In the future, the" NET METERING" process will be appropriate for properly using our system's excess electricity.

REFERENCES

[1] Off-grid Electrility Generation with Renewable Energy Technologies in India: An Application of HOMER DOI: 10.1016/j.renene.2013.07.028)

[2] Modelling and optimization of an off-grid hybrid renewable energy system for https://doi.org/10.1016/j.egyr.2020.01.013 electrification in a rural areas

[3] Zeinab Abdallah M Elhassan, Muhammad Fauzi Mohd Zain, Kamaruzzaman Sopian, and AA Abass. Design and Performance of Photovoltaic Power System As Renewable Energy Source for Residential in Khartoum, International Journal of Physical Sciences Vol. 7(25),pp. 4036-4042, 2012.

[4] Feasibility Assessment of a PV-Diesel Hybrid Power System for an Isolated Of Grid Catholic Church DOI 10.7770/ejee-V1N3-art526. ISSN: 0719-269X.

[5] The Technical and Economic Study of Solar-Wind Hybrid Energy System in Coastal Area of Chittagong, Bangladesh dx.doi.org/10.1155/2015/482543

[6] Sustainable energy planning based on a stand-alone hybrid renewable energy/hydrogen power system: Application in Karpathos island, Greece doi.org/10.1016/j.renene.2009.05.019

[7] Handbook of renewable energy technology January 2011DOI: 10.1142/9789814289078

[8] Windsim, Wind Turbine Regulation Mechanisms, 2010. http://user.windsim.com

[9] Mukund R Patel. Wind and Solar Power Systems: Design, Analysis, and Operation, CRC, 2005.

[10] Thomas Ackermann et al. Wind Power in Power Systems, volume 140. Wiley Online Library, 2005

[11] Hermann-Josef Wagner, Jyotirmay Mathur. Introduction to Wind Energy Systems: Basics, Technology and Operation, Springer; 2009.

[12] Sathyajith Mathew. Wind Energy: Fundamentals, Resource Analysis and Economics, 2006.

[13] Pramod Jain. Wind Energy Engineering. McGraw-Hill, 2011.

[14] Caisheng Wang. Modeling and Control of Hybrid Wind/Photovoltaic/Fuel cell Distributed Generation Systems, PhD thesis, Montana State University, Bozeman, 2006.

[15] Andrej Cotar, et al. photovoltaic systems, commissioning party: IRENA- Istrian regional energy agency; January 2012

[16] Wade Byrd. Solar Electric System Basics, 2007.http://lacleantech.net/solar_electric_systems.pdf

[17] Caisheng Wang. Modeling and Control of Hybrid Wind/Photovoltaic/Fuel cell Distributed Generation Systems, PhD thesis, Montana State University, Bozeman, 2006

[18] Roger A Messenger & Jerry Ventre. Photovoltaic Systems Engineering. CRC, 2003.

[19] Mukund R Patel. Wind and Solar Power Systems: Design, Analysis, and Operation, CRC, 2005.

[20] Dolf Gielen. Electricity Storage and Renewables for Island Power, a Guide for Decision Makers. IRENA, 2012.

[21] JL Gray, A Luque, and S Hegedus. Handbook of Photovoltaic Science and Engineering. Eds. West Sussex, England: John Wiley & Sons, 2003.

[22] Farshid Mostofi and Hossein Shayeghi. Feasibility and Optimal Reliable Design of Renewable Hybrid Energy System for Rural Electrification in Iran, International Journal of Renewable Energy Research, 2(4), 574–582, 2012

[23] Solmetric corporation. Guide to Interpreting I-V Curve Measurements of PV Arrays, Solmetric, 2011.

[24] M. A. H. Jaky, M. M. Rahman, and A. S. Islam, “Development of renewable energy sector in Bangladesh: Current status and future potentials”, Renewable and Sustainable Energy Reviews, vol. 79, pp. 1194–1199, 2018.

[25] W. Englemenn, N. Faxon, M. Joarrder, and M. Sarker, “Energy scarcity and potential of renewable energy in Bangladesh”, Renewable and Sustainable Energy Reviews, vol. 41, pp. 1667– 1699, 2016.

[26] Dolf Gielen. Electricity Storage and Renewables for Island Power, a Guide for Decision Makers. IRENA, 2012.

[27] HOMER, the Micro-Power Optimization Model; ver.2.68Beta, NREL; 2009.

[28] LE Weldemariam. Gen-Set/Solar/Wind Hybrid Power System of Off-Grid Power Station for Rural Applications. PhD thesis, Master’s thesis, Department of Electrical Power Engineering, Delft University of Technology, Delft, The Netherlands, 2010.

[29] A Kaabeche, M Belhamel, and R Ibtiouen. Optimal Sizing Method for Standalone Hybrid PV/Wind Power Generation System. Revue des Energies Renouvelables (SMEE’10) Bou Ismail Tipaza, pages 205– 213, 2010.

[30] Said Diaf, Djamila Diaf, Mayouf Belhamel, Mourad Haddadi, and Alain Louche. A Methodology for Optimal sSizing of Autonomous Hybrid PV/Wind System. Energy Policy, 35(11):5708–5718, 2007.

[31] Paul Gipe. Wind Power, Volume 28. Multi-Science, 2004.

[32] KevinWhitehead. Generator and Exciter Basics, 2009.

[33] LE Weldemariam. Gen-Set/Solar/Wind Hybrid Power System of Off-Grid Power Station for Rural Applications. PhD thesis, Master’s thesis, Department of Electrical Power Engineering, Delft University of Technology, Delft, The Netherlands, 2010.

[34] Deepak Kumar Lal, et al. Optimization of PV/wind/Micro-Hydro/Diesel Hybrid Power System in HOMER, International Journal on Electrical Engineering and Informatics, 3(3), 307–325, 2011.

[35] I. S. Chowdhury, "Inflation in Bangladesh Climbs to 11.38% In NOV," Iqbal Sobhan Chowdhury, Dhaka, 2024.

[36] M. S. Hossain, "Assessment of an Optimum Off-grid Hybrid Energy System for Electrification in a Rural Area of," in *International Conference on Mechanical, Industrial and Energy Engineering*, Khulna, 2022.

[37] S. H. Zahid, "Solar system cheapest option for BD: BNEF," Syed Manzur Elahi, Dhaka, 2025.

[38] M. K. Hossain, "BD STALL," [Online]. Available: https://www.bdstall.com/details/jinko-tiger-pro-550-watt-mono-facial-solar-panel-98458. [Accessed 02 January 2025].

[39]A.Rahim,"TAHAESHOP,"[Online].Available:https://www.tahaeshop.com/public/index.php/products/rahimafrooz-itb-200-ah-tubular-battery . [Accessed 28 12 2024]. Battery

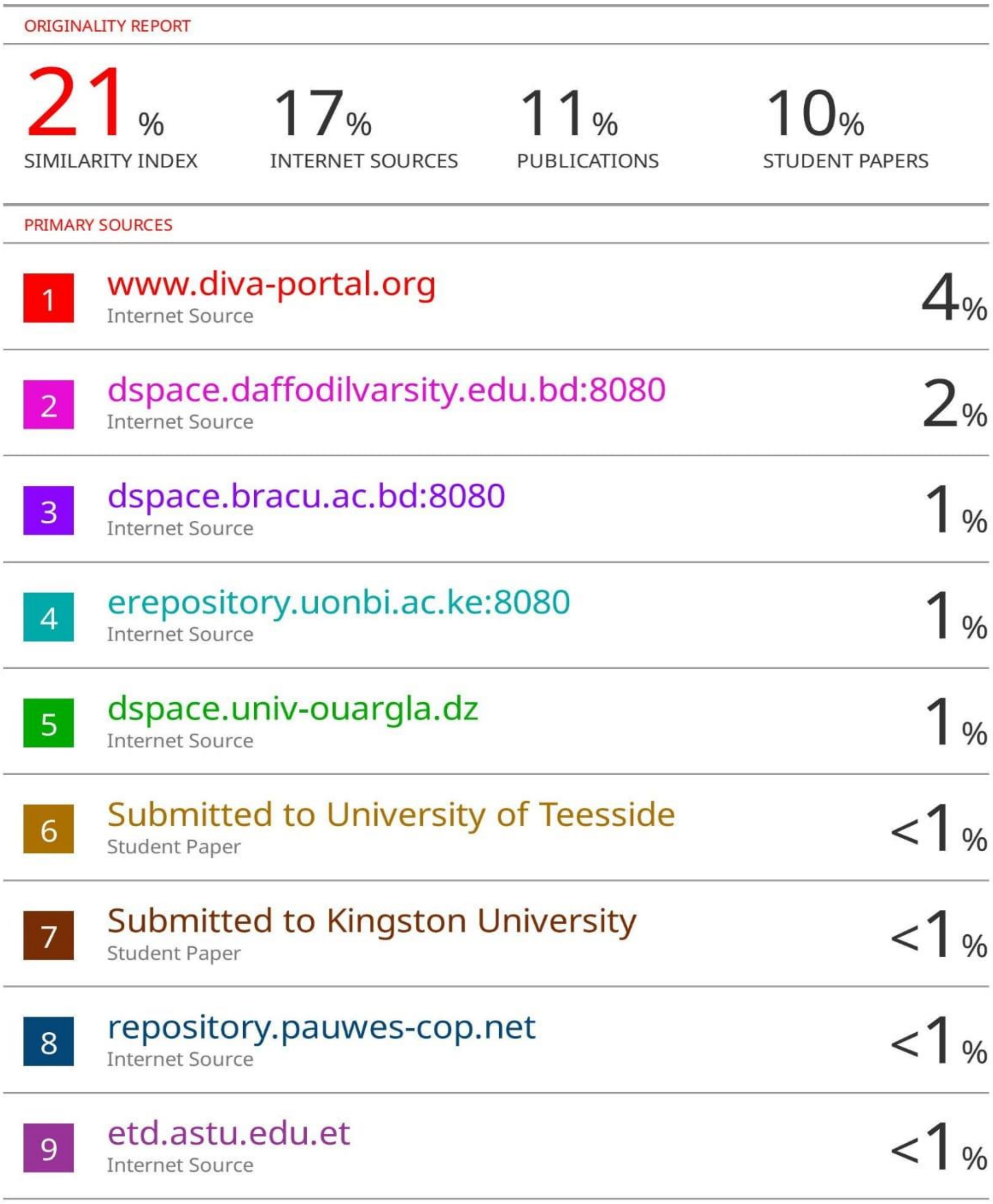
[40]N.P.B.E.Team,"NANOPOWER,"[Online].Available:https://nanopowerbd.com/index.php?route=product/product&product_id=73. [Accessed 28 12 2024].

[41]Kramer,"Wattuneed,"January2025.[Online].Available:https://www.wattuneed.com/en/wid-turbine/25379-wind-turbine-antaris-12-kw-network-0768563818073.html.

[42]D.V.Ga.,“PDG,”02January2025.[Online].Available:https://www.pdgenerators.com/product-page/perkins-150-turbo-kw-diesel-generator.

APPENDIX A

TURNITIN REPORT



ORIGINALITY REPORT

21%	17%	11%	10%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.diva-portal.org Internet Source	4%
2	dspace.daffodilvarsity.edu.bd:8080 Internet Source	2%
3	dspace.bracu.ac.bd:8080 Internet Source	1%
4	erepository.uonbi.ac.ke:8080 Internet Source	1%
5	dspace.univ-ouargla.dz Internet Source	1%
6	Submitted to University of Teesside Student Paper	<1%
7	Submitted to Kingston University Student Paper	<1%
8	repository.pauwes-cop.net Internet Source	<1%
9	etd.astu.edu.et Internet Source	<1%

APPENDIX B

COMPLEX ENGINEERING PROBLEM SOLVING AND ENGINEERING ACTIVITIES

Complex Engineering Problems (P) Solving		
	Attributes	Statement from students
P1	Depth of knowledge required	An off-grid solar photovoltaic-hybrid system's optimization and feasibility analysis for a specific rural region in Bangladesh requires a sound background of renewable energy technologies, electrical engineering fundamentals, and energy systems modeling. The study employs sophisticated aspects like hybrid energy systems, HOMER Pro software optimization, and RETScreen-based financial assessment. These are primarily technical aspects regarding the integration of solar, wind, and diesel systems requiring knowledge of energy conversion processes, mathematical modeling, and system dynamics. Adding battery storage and bi-directional converters adds even more degrees of freedom and requires an understanding of the energy storage mechanism and control system.
P2	Range of conflicting requirements	The process of designing the hybrid energy system involves a trade-off between technical, economic, and environmental objectives. These conflicting requirements Of course, affect on the minimum cost of electricity (COE) and the penetration of renewable energy to reduce greenhouse gas emissions. At the same time, it must be inexpensive enough for the community but high-tech enough that it can be trusted to grow with the needs of the community. The requirement for different energy demands including residential (1147.6 kWh/day) and commercial loads (64.76 kWh/day) with differing climatic circumstances illustrates the clear differences between conflicting technical and socio-economic needs.
P3	Depth of analysis required	It requires a comprehensive study of the system components and their inter relations. The optimization process models energy generation, storage, and distribution in fine detail. The financial metrics like payback period, internal rate of return (IRR), and return on investment (ROI) are calculated to ensure that the system is not only economically viable but also sustainable. Such analysis volume is also high due to mathematical modeling of battery and converter operation to provide precise energy flow control.

P4	Familiarity of issues	To that end, the study targets some specific challenges faced by Bangladesh, especially by coastal Andar Char in rural electrification. Common challenges in the context include unreliable supply of energy, reliance on biomass and kerosene and the socio-economic limitation of the community and so on. But these are also still very much globally relevant, especially in remote and underdeveloped regions. Understanding the availability of renewable energy resources in Andar Char, such as solar and wind potential, and local socio-economic dynamics is key to the success of the project.
P5	Extent of applicable codes	This project meets the engineering standards and codes for renewable energy systems. This design meets safety and performance standards for solar PV, wind turbines and diesel generators. It also integrates requirements for battery storage and inverter/converter efficiency. Financial evaluations follow widely accepted economic models and practices in the field of renewable energy feasibility studies, meeting technical as well as financial performance frameworks.
P6	Extent of stakeholder involvement and conflicting requirements	It makes the project more challenging due to the need to engage various stakeholders such as local residents, government agencies, and technical experts. For example, affordability for residents, scalability for policymakers, and technical feasibility for engineers are often competing objectives. Tackling these factors would need a participatory approach, without which the ground-level concerns of community members would never be able to be translated into something that is within the framework of national renewable energy targets and technical restrictions.
P7	Interdependence	Due to the synchronous working of various components and systems, an interaction property exists in this project. It is essential for solar PV, wind turbines, diesel generators, batteries, and converters to work together to guarantee the reliability and sustainability of energy. For example, energy produced by solar and wind systems depends heavily on environmental factors and must work seamlessly with battery storage and diesel generators to balance supply and demand. Also, economic viability and environmental impact are directly related to each component's technical performance. Dynamic simulation preserves essential insights into similarly interconnected mechanisms, financial incentives, risk exposures, and ordering logics that must simultaneously enable stakeholders to cooperate in order to realize the successful implementation of this hybrid system, revealing some of the complex interdependencies that a truly successful solution to challenging engineering obstacles requires.

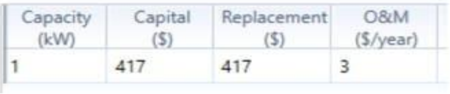
Complex Engineering Activities (A)		
	Attributes	Statement from students
A1	Range of resources	Three types of energy sources are used: renewable energy (solar, wind), fossil fuel-based backup generators, and advanced energy storage systems. It uses software tools like HOMER Pro and RETScreen for system optimization and financial analysis. To enable system efficiency and cost-effectiveness there is a requirement of resource allocation and domain knowledge of connection of hardware components such as PV panels, wind turbines, diesel generators and batteries.
A2	Level of interaction	There are multiple components and stakeholders interacting on the project. To maintain energy flow and reliability among the solar PV system, wind turbines, batteries, and diesel generators, technical interaction between these parties is required. In addition, cooperation between engineers, local residents, policymakers, and financial analysts guarantees a technical, economic, and social-focused design for the system. In real project status it is very seldom a smooth task but indeed if the effective communication and coordination is there then, conflicting requirements can be sorted out and can achieve the project goals.
A3	Innovation	Advanced tools HOMER Pro and RETScreen are employed in the optimization and financial assessment of the intervention respectively stochastic bidirectional converters and energy storage are combined for enhanced reliability, establishing this architecture as a model solution for scalable rural electrification.
A4	Consequences of society and environment	This system improves rural life by offering reliable electricity, supporting economic development, and increasing access to basic services while lowering greenhouse gas emissions through renewable energy adoption.
A5	Familiarity	This system improves the quality of life in rural areas, ensures access to reliable electricity that can spur economic growth and data access, and enhances access to services while reducing greenhouse gas emissions with renewable energy.

APPENDIX C

COMPONENT'S DATASHEETS

HOMER SOFTWARE

PV [38]



Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	417	417	3

Life Time : 25y

Derating Factor :80%

Tracking system: No Tracking

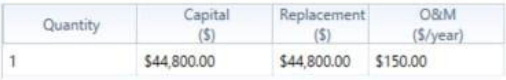
Slope : 21.87 Deg

Azimuth: 0 Deg

Ground Reflectance: 20%

Quantities : 660

Wind Turbine [41]



Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	$44,800.00	$44,800.00	$150.00

Life Time : 25y

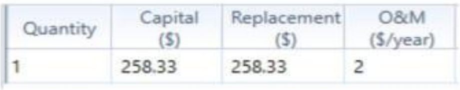
Name : The Bergey Excel 10

Rated capacity (kW) : 10

Manufactured: Bergey Windpower

Hub Height : 30m

Battery [39]



Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	258.33	258.33	2

Quantities : 598

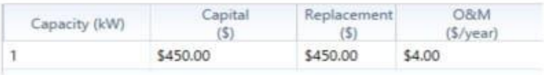
Voltage : 12v

Nominal Capacity: 200Ah

Battery life: 10y

Throughput (kWh): 4190200

Converter [40]



Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	$450.00	$450.00	$4.00

Size : 200kw

Life Time : 20y

Inverter Efficiency: 95%

Rectifier Relative Capacity: 100%

Rectifier Capacity: 95%

Generator [42]

Initial Capital ($): 25,833.00
Replacement ($): 25,833.00
O&M ($/op. hour): 5.000
Fuel Price ($/L): 1

Capacity: 150kw

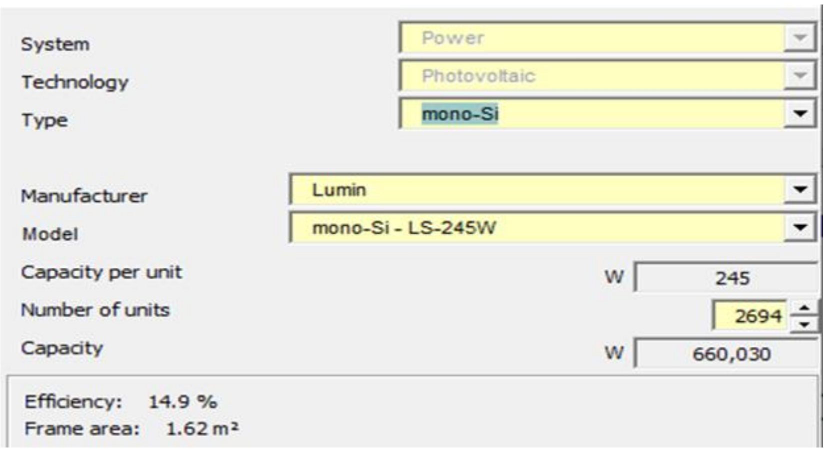
Fuel type: Diesel

Fuel Curve Intercept: 3.15L/hr

Life Time (Hours): 25000

RETScreen SOFTWARE

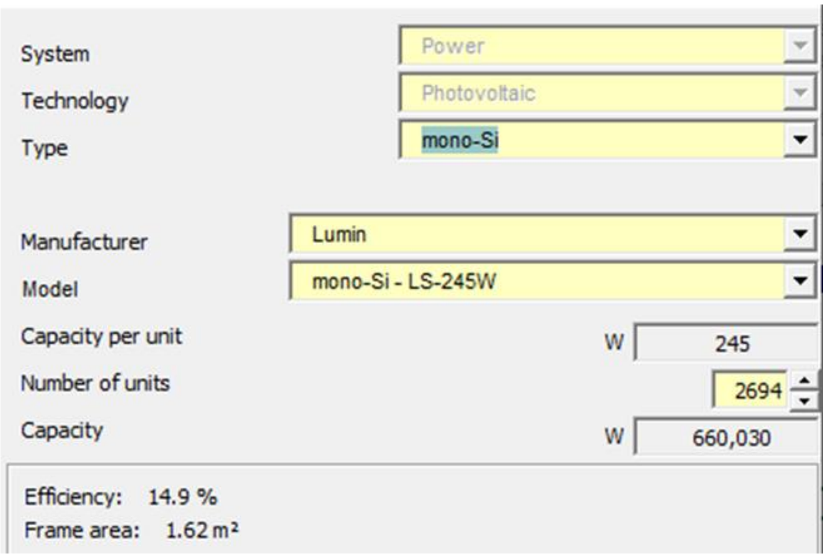
PV



System: Power
Technology: Photovoltaic
Type: mono-Si
Manufacturer: Lumin
Model: mono-Si - LS-245W
Capacity per unit: W 245
Number of units: 2694
Capacity: W 660,030

Efficiency: 14.9 %
Frame area: 1.62 m²

Wind Turbine



System: Power
Technology: Photovoltaic
Type: mono-Si
Manufacturer: Lumin
Model: mono-Si - LS-245W
Capacity per unit: W 245
Number of units: 2694
Capacity: W 660,030

Efficiency: 14.9 %
Frame area: 1.62 m²