DESIGN AND FEASIBILITY ANALYSIS OF AN ON-GRID AND OFF-GRID SYSTEM FOR HOSPITAL BUILDING: A CASE STUDY ON DHAKA MEDICAL COLLEGE

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List of Acronyms

HRES	Hybrid Renewable Energy Systems
PV	Photovoltaic
SHS	Solar Home System
NREL	National Renewable Energy Laboratory
DMC	Dhaka Medical College
CCU	Coronary Care Unit
OPD	Outpatient Department
OT	Operation Theatre
ECG	Electro Cardiogram
HDU	High Dependency Unit
SWD	Short Wave Diathermy
MWD	Micro Wave Diathermy
MRI	Magnetic Resonance Imaging
GHI	Global Horizontal Irradiance
NASA	National Aeronautics and Space Administration
HFO	Heavy Fuel Oil
O&M	Operation and Maintenance
NPC	Net Present Cost
LCOE	Levelized Cost of Electricity

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Abstract

Access to reliable and clean energy is essential for economic development, better healthcare facilities, building more equitable and inclusive communities, and being resilient against climate change. Intending to expand the use of renewable energy in Bangladesh, using an optimization tool named HOMER, we designed an off-grid and on-grid solar project at the rooftop of Dhaka Medical College and determined its economic feasibility. The load profile was calculated for 20 operation theatres (OT) and 50 wards of the old hospital building. The average energy consumption was found to be around 4454.6 kWh/day, with a peak load of 185.6 kW at a load factor of 54%. In the off-grid scheme consisting of solar panel, diesel generator, converter and battery, it is possible to generate 2,168,861 kWh electricity annually, out of which PV supplies 1,619,195 kWh (74.7%), and the rest, 549,666 kWh (25.3%), is supplied by the diesel generator. In this case, the NPC, LCOE and operating cost of the system are approximately 3,941,506 $, 0.179 $/kWh and 192,368 $/yr, respectively and the renewable fraction is 64.4%. In the on-grid scheme, formed of solar panel, converter and battery, a total of 2,548,458 kWh electrical energy is generated annually, out of which PV supplies 1,619,799 kWh (63.9%), and the rest, 928,659 kWh (36.1%), is provided by the grid. The NPC, LCOE and operating cost of the most optimized system are found to be 2,127,556 $, 0.06748 $/kWh and 96,460.62 $/yr, respectively. Here, the renewable fraction obtained is 58.1 %. Our analysis showed that while the on-grid is a cheaper option, the off-grid is a better alternative for generating a larger fraction of clean energy. A detailed sensitivity analysis has also been conducted to observe the effect of some variable parameters like discount rate, inflation rate, grid power price, diesel price and average solar radiation on the NPC and LCOE to achieve better insights into our work.

Chapter 1

Introduction

1.1 Background

With the dawn of the industrial revolution, man began to exploit the huge energy concentrated in natural resources such as- coal, oil, and natural gas to produce electrical energy. Since then, the demand for electrical energy has only been shooting upwards. The world's electricity consumption reached 3084 kWh per capita in 2013, which is a 42.3% increment compared to 1990, a trend more prominent among emerging economies [1]. Most of this electricity is produced from various fossil fuels. Fossil fuels are a limited resource which also produces irreversible damage to the environment by producing various greenhouse gases, like carbon dioxide, nitrous oxide, methane, etc. Hence, more and more countries are shifting towards a more sustainable source of electricity. Currently, some of the largest sources of sustainable energy are – solar power, wind, geothermal and hydropower. Fig.1 shows the statistics of energy consumption around the world.

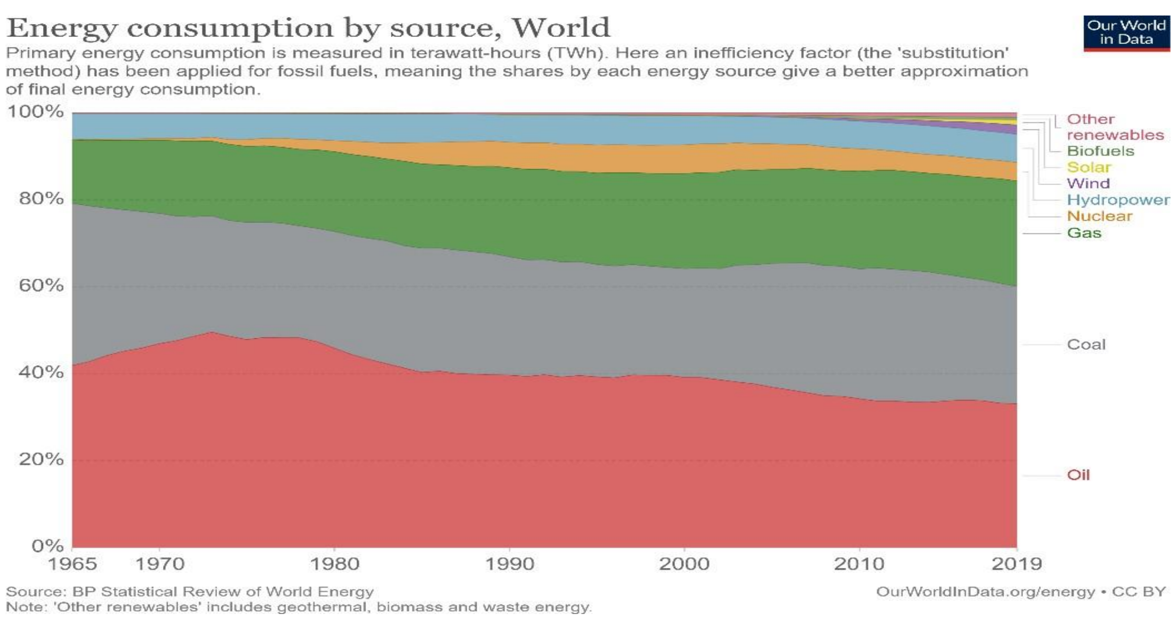

Fig.1. Global Statistics of Energy Consumption

Among all these, solar power is gaining popularity due to ease of access, leading to lower costs for installation and operation, with small and medium-sized panels becoming more practical for remote locations as well as for large projects. So, there is a growing trend of installing remote solar panels to provide electricity in a particular area or buildings.

Among commercial buildings, hospitals are the highest consumer of electricity per floor area [2]. From conducting various complicated operations to refrigerating important vaccines and medicines and having functional life support systems, hospitals require continuous access to electricity for various heavy loads. Hence, hospitals shifting to solar energy will be a huge step for Bangladesh in its journey of moving towards renewable energy.

1.2 Current Energy Statistics of Bangladesh

After the independence of Bangladesh in 1971, only 3% of the population had access to electricity. Since then, there has been massive development in the energy sector. Simultaneously, the rise of various industries, (e.g., garments industry, cotton, leather) has led to rapid urbanization, increasing the demand of electricity. Trying to keep up with this rising demand of electricity, the rate of electrification has been increased to 70% as of 2015 (Bangladesh: Increasing Access to Energy). As of September 2019, the national grid of Bangladesh supplies 21,419 MW of electricity. Nevertheless, the demand of electricity is expected to rise to 34,000 MW by 2030 to sustain the current GDP growth of over 7% [3].

Currently, the main source of electricity in Bangladesh are its limited fossil fuels. About 80% of the current in the national grid is generated from natural gas [4]. Hence, Bangladesh mostly depends on its limited resources and imports to meet 4.28% of the demand [5].

1.3 Renewable Energy

1.3.1 Overview of Renewable Energy

Renewable energy indicates harnessing energy from natural resources replenished and tends to be less harmful for the environment since they do not emit any greenhouse gases, like carbon dioxide, carbon monoxide, etc. Long-term use of fossil fuel as a primary source of energy has already heavily depleted our ozone layer. Hence, to avoid any more irreversible damage to the environment more and more countries are shifting towards renewable and ‘clean’ energy resources.

1.3.2 Global Status of Renewable Energy

Over the past 20 years, a diverse range of renewable energy support policies have been adopted in 145 countries with an aim to gradually transition to a cleaner source of energy. As of 2015, the annual investment in renewable energy reached $270 billion in 2015 [6]. Many countries have already made major strides in the field of renewable energy. Germany targets to generate 80% of electricity from renewable sources by 2050, whereas Denmark targets to reach 100% by 2035 [7]. In the health sector, in 2019, the world’s largest hospital solar PV project has been installed in at the Abdali Medical Centre in Jordan. The system consists of 25,090 Philadelphia Solar Polycrystalline 325-W panels and Philadelphia Solar Mounting Structure solutions and generates 8.2 MW of energy [8]. In New Wales, Australia, thirty-seven health facilities statewide have been fitted with solar panels under the $5.5 million NSW Health Solar Program. A further eight hospitals and nine ambulance stations were set to reap savings and efficiencies through a $14.5 million expanded solar upgrade program. This initiative is expected to save $2.6 million in energy bills and reduce emissions by around 9,445 tons CO_2 per year [9].

1.3.3 Solar Energy

Man has been harnessing solar energy for his benefit since ancient times, but about 100 years ago solar power was first used commercially. It has been used to generate electricity, heating and cooling and ventilation among other purposes. Nevertheless, it is gaining massive popularity in recent times and is expected to be the leading source of renewable energy by 2050. The mass availability of solar power makes it a lucrative renewable source of energy. The earth receives about 3,400,000 EJ of solar power annually which is between 7000 and 8000 times the annual global primary energy consumption. 0.1% of this energy converted into electricity with 10% efficiency could provide 10,000 GW of electricity, while the global total requirement is around 6000 GW [10].

1.3.4 Solar Energy Status in Bangladesh

Bangladesh is one of the global forerunners in the Solar Home System (SHS). However, there has not been much development in other sectors. Currently, in Bangladesh, only 0.45% of the total energy is generated from renewable resources, whereas globally, from renewable sources, about 3.45% of the total energy is generated [11].

Bangladesh is located between 20.30 and 26.38° north latitude and 88.04 and 92.44° east longitude and the daily solar radiation varies between 3.8 and 6.5 kWh/m^2. On average, the country has 300 sunshine days and sunlight of 4.0 - 6.5 kWh irradiance. Hence, it can be said that Bangladesh receives ample sunlight throughout the year, making solar energy a very reliable form of energy for Bangladesh. Photovoltaic cells and generators can be used to harness the available solar energy to establish various small- and large-scale projects to meet the local demand.

One of the major factors behind the lack of progress in the field of solar power generation in Bangladesh is the lack of available free spaces. Implementing large-scale solar projects require huge areas of land. Bangladesh is a densely populated country where most of the lands are used for agriculture. Hence, for widespread solar projects in Bangladesh, it is essential to utilize every available free space.

1.4 Hybrid Renewable Energy Systems (HRES)

Hybrid renewable energy systems are stand-alone power systems which are used to generate electricity in remote areas, mostly using renewable energy technologies. A hybrid renewable energy system consists of two or more renewable energy sources to generate increased system efficiency for greater balance in energy supply [12]. We have used on-grid and off-grid hybrid systems. On-grid systems are implemented using solar inverters or microinverters, and the generated electricity is supplied to the public electricity grid. Hence, if the system fails to produce power, electricity is pulled from the main grid making on grid systems a more reliable system of electricity. Again, when excess electricity is produced, the extra power is supplied to the grid, for which it can be compensated. On the other hand, an off-grid system is formed of solar inverters and batteries. In this case, the excess electricity is stored in a battery for later use [13].

Chapter 2

Literature Review

A number of notable works have been conducted in HomerPro in the medical/healthcare sector. *B.Dursun et.al* has performed a techno-economic and environmental assessment of renewable energy options for Somalia Turkey Hospital [14], with the help of diesel generator, wind turbines, PV and battery in different configurations in HOMER. *K. Rezapour et al.* has used eQUEST and HOMER software [15] to analyze the techno-economic, energy efficiency, and environmental parameters of several distributed generation systems using components like fuel cells, micro-turbines and PV systems, for a hospital building in Tehran of Iran. *Ighravwe et.al* [16] has used HOMER software and the WASPAS method to determine the most optimized Hybrid Renewable Energy System, for healthcare centers in 6 rural locations of Nigeria. *S. S. Raghuwansh et.al* [17] has worked on the design and economic analysis of an off-grid PV system for a remote healthcare center at Madhya Pradesh, India using Homer software.

Chapter 3

Aims and Objectives

3.1 Our Proposal

To widen the scope of use of renewable energy in Bangladesh and create a more reliable power source for the betterment of its healthcare facilities, we propose to set up a hybrid renewable system in the rooftop of the old building of Dhaka Medical College. We have selected the old hospital building as it is a key consumer of electricity. The simulation has been completed using simulation software named HomerPro.

3.2 Motivation Behind Our Proposal

One of our key motivations behind our proposal is that Bangladesh must increase its production of electricity to sustain its current GDP growth. However, if it is done through traditional fossil fuel power plants, it will be a huge burden of Bangladesh's limited fossil fuel resources and being harmful to the environment. Hospitals have the highest energy consumption per unit floor area among commercial buildings since they require a continuous flow of energy for conducting life-saving operations to having functional instruments and refrigeration of medicines and vaccines. Hence, we chose a hospital building as our research site. Moreover, Bangladesh has adequate sunshine days and sunlight, an ideal condition for setting up a solar project. So, we chose solar energy as the form of renewable energy for our research.

3.3 Objectives of our Research

The main objectives of our research are:

- To design an off-grid and on-grid solar project at the rooftop of Dhaka Medical College and determine its economic feasibility.

- Determine a way to expand the power sector of Bangladesh without causing harm to the environment through the implementation of renewable sources of power.
- Create a reliable source of clean energy for hospitals for the betterment of the healthcare system.

3.4 Thesis Outline

Our project mainly starts with some introductory talk and statistics of renewable and solar energy around the world and in Bangladesh. HRES systems have also been described. The second chapter includes a literature review on some previous works in this field. The third chapter describes the aims and objectives and motivation of our selected research work. The fourth chapter basically deals with the methodology, workflow and operating schemes of our project. The fifth chapter includes a description of the technical components required for our design along with their specifications and also some other necessary input parameters. The sixth chapter discusses on the results obtained after optimization of our models. It also covers the sensitivity and cash flow analysis as well as the electrical and emission summary. The seventh and last chapter includes the conclusion and gives insight into the future possibilities of this project.

Chapter 4

Methodology

In the twenty-first century, access to reliable energy sources is the backbone of the economy and development of a nation. However, a developing country like Bangladesh still has a lot to improve in this sector. Despite significant strides being made in recent years, Bangladesh is still unable to meet the country's rising energy demands. In this chapter, the proposed on-grid and off-grid hybrid system modeling is highlighted. The proposed system is on the rooftop of the old building of Dhaka Medical College and aims to fulfill its basic energy demand. The proposed modeling system details are stated for the study of power quality monitoring, feasibility, and economic analysis.

4.1 Basic Workflow of Our Project

First, the input parameters and the technical components are specified based on our requirements and simulation. Then, using the information provided, HOMER examines all possible combinations of the system design in a single run and determines the best possible systems according to the optimization variable of choice. After this step, a sensitivity analysis is carried out where various variable input parameters like diesel price, discount rate are changed, and then the effect on the output is observed.

4.2 HOMER Software

For designing our model, we have used Homer Pro 3.11.2; a microgrid analysis tool developed initially by the United States (US) National Renewable Energy Laboratory (NREL), which can simulate cost-effective microgrid system projects for both off-grid and grid-connected systems [18]. It has gained popularity for the designing, simulation, and feasibility analysis of any renewable energy model and hybrid systems. Homer Pro requires simulation, optimization, and sensitivity analysis. It is used to simulate the most feasible system comparing all possible combinations of the resources and components chosen for our design. At the simulation stage, all the input parameters are fixed along with the required equipment, and then simulation is carried out. In the optimization step, HOMER examines all possible combinations of the system to determine the most economically feasible design based on the Net Present Cost (NPC). Finally, a sensitivity analysis is carried out, which determines the effect of various variable factors by changing input parameters like diesel price, discount rate and observing the output response to these alterations. Before these steps, a pre-Homer analysis [19] is performed, which involves the collection of solar and wind resources data, load profile data and other required input parameters like the diesel price, random variability parameters and other similar information. Again, HOMER also provides a wide range of choices for converters, generators, PV modules, batteries, wind turbines, and other equipment, enabling vast flexibility in system design. Moreover, this software also performs economic and environmental analysis for the systems.

4.3 Operation Schemes

4.3.1 Off-grid Scheme:

Off-grid schemes are entirely independent and not connected to the main grid or power system's utility [20]. It is formed of solar inverters, microinverters and batteries. This system generates a higher percentage of clean energy since it is an entirely self-sufficient unit without relying on the main grid. The excess energy supplied is stored in a battery for later when use, for cloudy days or winter season, when we get limited solar power. Off-grid systems are a less reliable source of electricity since they cannot pull from the main grid in power failure or shortage. On the other hand, in case of a severe storm or other similar mishaps, failure of the main grid does not affect this system. Hence our power access remains unchanged, while the rest of the area faces a blackout [21]. Fig.2 shows the rough schematic of the off-grid model.

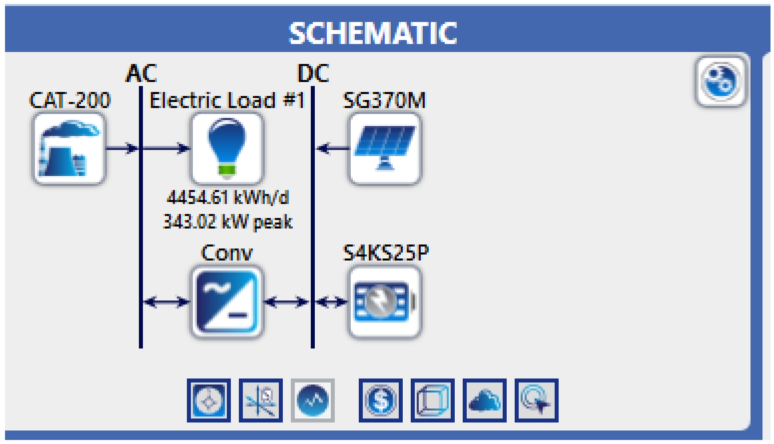

Fig.2. Off-grid model schematic

4.3.2 On-grid Scheme:

On-grid schemes are systems that are tied to the main power grid [20]. It is formed of solar inverters and microinverters. The power generated from this system will be used in the hospital to perform all their daily activities, whereas any excess energy generated will be supplied to the grid. Through this, credit can be generated, and the hospital can earn money from the local authorities based on the amount of power they supply. Similarly, in case of any shortage or system failure, power can be pulled from the main grid. For these reasons, on-grid systems are considered more reliable sources of energy. However, a major disadvantage of this scheme is that the percentage of energy generated from renewable sources is less compared to the off-grid system. Hence, on-grid system is less efficient in terms of the percentage of renewable energy used to generate power. Fig.3 shows the schematic for the on-grid model.

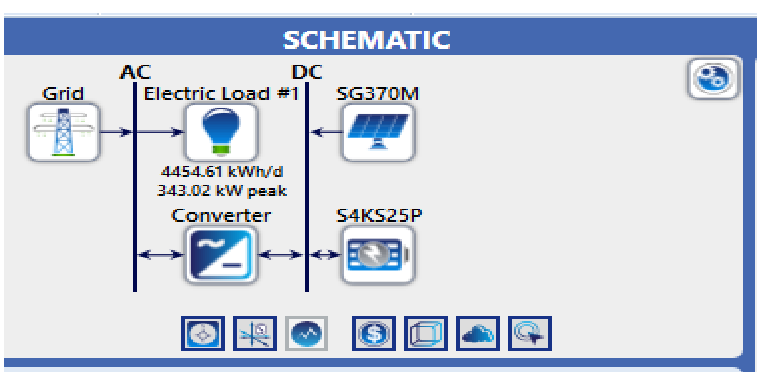

Fig.3. On-grid model schematic

Chapter 5

Input Parameters and System Components

5.1 Site Details

The site selected for our work is Dhaka Medical College (DMC), located in Bakshibazar in the city of Dhaka, the capital city of Bangladesh. The coordinates for the selected location are 23.7257° N, 90.3971° E. The selected building for our proposed design is the old hospital building, where most of the medical activities take place, and also, the patient pressure is high in the old building. The rooftop of the old building has a rooftop area of 149302 square feet or approximately 13870 square meters. A satellite view of DMC from google map is given in Fig 1.

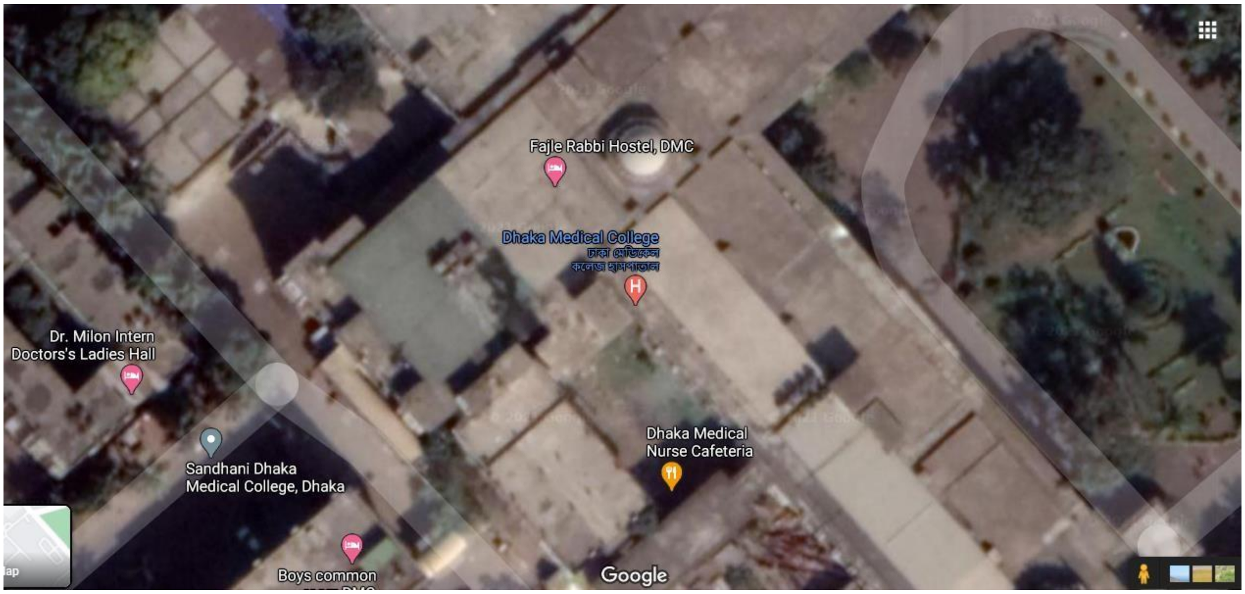

Fig. 4. Location of Dhaka Medical College from Google Map

5.2 Medical Equipment Data

The information on medical instruments has been collected from the Master Register of medical equipment of DMC, and the engineering section of the medical has provided the data on electrical appliances. The rough list of medical equipment is given in Table.1. The load given may be subjected to change in the future. Lights, fans and central Air Conditioners are the major electrical appliances considered.

These equipment require a considerable amount of electricity. The electricity consumption data for these equipment were taken from multiple sources from the internet [22-51]. From the gathered data, a rough estimation of the daily load requirements has been calculated and implemented on the HOMER software. Here operating time for each instrument has been collected and estimated for the total load profile. The total hourly load requirement is given in Table 2.

Table 1. List of Equipment

Department/Unit	**Number of equipment**
Urology O.T Complex	4
Orthopedic O.T	7
ENT O.T	10
General Post-Operative Ward	5
Dental OPD	3
Dental and OMS	3
Ward-315 Hepatology	1
Emergency O.T Complex	22
Hematology and BMT unit	21
Cardiology	2
CCU	39
Cardiology cath lab O.T	4
Autoclave Room	6
Clinical Pathology	11
Blood Transfusion Medicine	3
Physical Medicine and Rehabilitation	18
C/S OT	6
Burn O.T	1
Burn HDU	28
NS O.T Ward-103	4
Emergency O.T	2
ENT Emergency O.T Ward no-303,304	6

Table 2. Total Hourly Wattage

Equipment	No of Equipment	Power (Watt)/per equipment
Anesthesia Machine	13	1200
Diathermy Machine	13	350
X Ray View Box	25	30
Pulse Oxymeter	20	24
ECG Machine	20	80
Complete Dental Unit	4	1405
Ultrasound Machine Complete Unit	14	550
OT Light	13	50
Hematology Analyzer	6	230
Electropheresis	2	500
Electrolyzer	2	480
Bio Safety Cabinet	2	271
Centrifuge	6	380
Echomachine	3	480
Bedside Monitor	50	72
Central Monitor	4	35
Defibrilator	4	200
Angiogram machine	3	400
Autoclave Machine	6	630
CBC Auto Analyser	7	480
Hematology Analyzer	2	230
Water Bath	1	400
Apheresis Machine	1	840
SWD (Short wave Diathermy Machine)	1	800
MWD (Micro Wave Diathermy Machine)	3	360
Laser	1	80
Radiant Warmer	4	250
Electric Power Bed	12	100
Ventilator	30	64
Haemodyalysis machine	20	1760
Bronchoscopy	3	50
Electro Surgical Bi-Lap	1	300

Pinpoint Endoscopy Imaging System	2	240
MRI	2	2500
CT scan	1	72000
X-Ray	4	5000
Ultrasonogram	6	200
Colposcopy	2	500
Water Pump	8	100
Air Plant	3	24
Refrigerators	10	116
Phototherapy machine	6	600
Water distiller	1	1000
Light bulbs	680	60
Fans	600	80
Energy bulbs	80	15
Air Conditioner	40	1676

5.3 Load Profile

Load profile indicates plotting graph of the variation of the load from the electrical equipment against a specific amount of time. As the load can vary depending on the time of the day and temperature, it is beneficial to look for a daily load profile across which plots the electrical load variation across 24 hours. Again, the load will vary depending on the weather and the season as well as the increasing demand in electricity. Thus, monthly and yearly load profiles help plan and eventually implement solar power generation system and how it will perform over time. A load profile can provide an objective look at the demand for electricity on a specific time of the day, month or season. For our data collection, we have considered the location of the old hospital building and its electrical equipment.

Here, 10% random variability [19] has been considered for hour to hour and day to day basis in the software. With the load data and variation data given, load profile with varying times (daily, monthly and yearly) has been plotted by the software.

5.3.1 Daily Load Profile

The daily load profile has been plotted through the software shown in Fig.5. From the figure, we can assume that the electricity consumption is generally high from 9 am to 12 pm because most of the electrical appliances remain in operation in the morning and the patient pressure also remains high during this period. It is found that the average energy consumption for the old hospital building is around 4454.6 kWh/day.

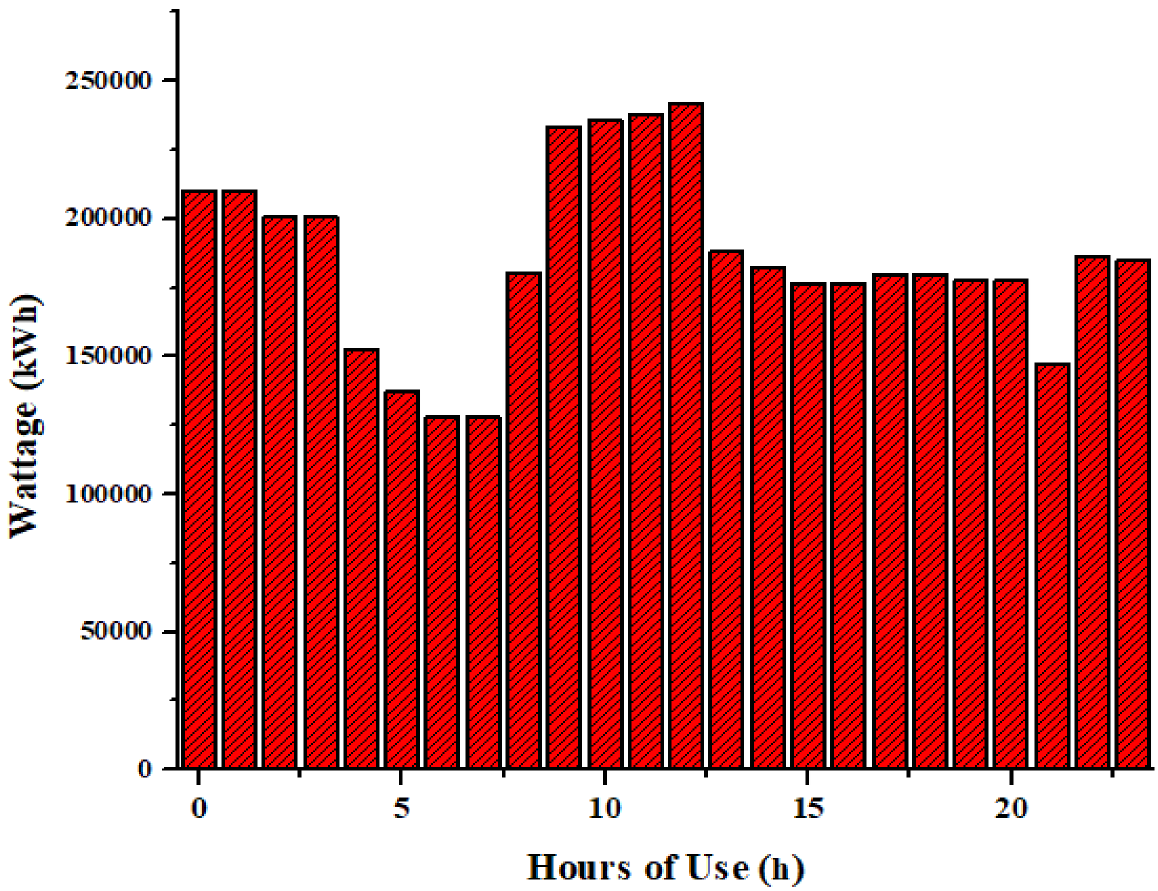

Fig.5. Daily Load Profile

5.3.2 Monthly Load Profile

The monthly load profile is shown in Fig.6. From the load profile graph, we can see that electricity consumption is usually high, around June to August. Electricity consumption usually ranges from 187.55 kW to 192.29 kW per day on average and peak hits 328.02 kW.

The consumption is usually low from November to January, where electricity consumption is around 114.72 kW and 116.82 kW on average.

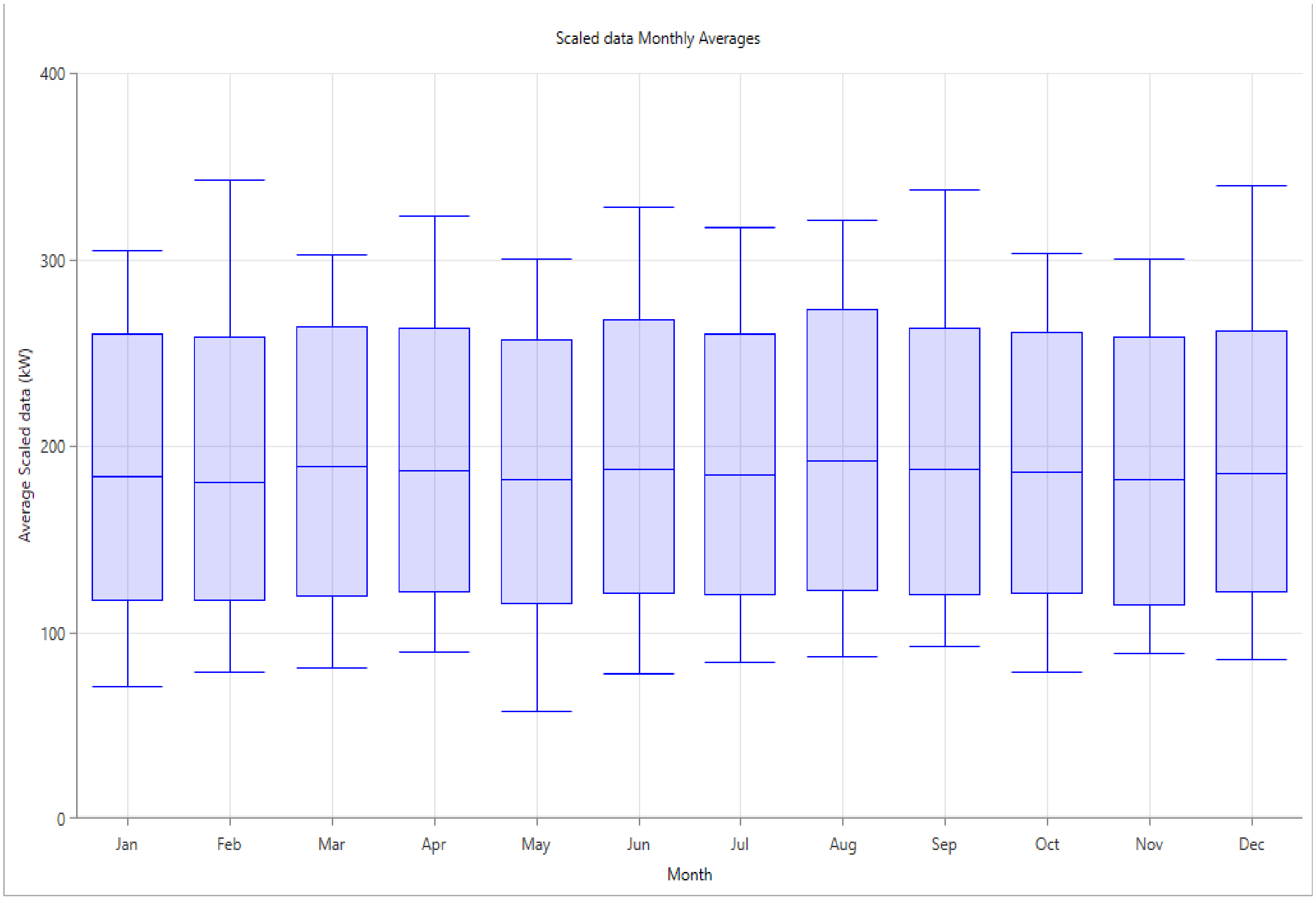

Fig.6. Monthly Load Profile

5.3.3 Yearly Load profile

Although the yearly load profile does not provide immediate significant data, it helps with the load increase assumption. The profile is provided in Fig.7.

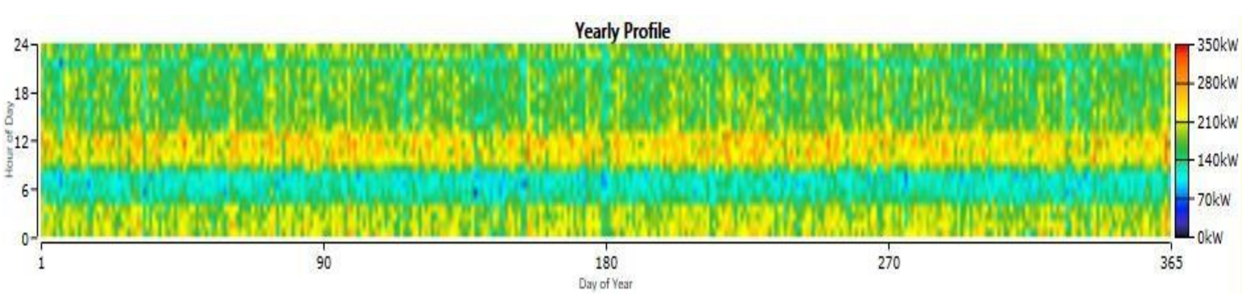

Fig.7. Yearly Load Profile

5.4 Solar Resources

The key solar resources data homer pro deals with are the monthly average solar global horizontal irradiance (GHI) data and the clearness index data. The required data was collected from NASA surface meteorology and Solar energy database. Average solar radiation is approximately 4.59 kWh/m^2 /day, where the peak values reaching from April to May during the summer season. The monthly irradiation and clearness index data are given in Table 3.

Table 3. Monthly Average Solar Global Horizontal Irradiance and Clearness Index Data

Month	**Clearness index**	**Daily radiation (kWh/m^2 /day)**
January	0.630	4.360
February	0.615	4.920
March	0.598	5.590
April	0.551	5.760
May	0.481	5.300
June	0.405	4.530
July	0.382	4.230
August	0.404	4.290
September	0.415	4.020
October	0.516	4.320
November	0.599	4.280
December	0.642	4.210

The clearness index indicates the clarity in the atmosphere. It is the ratio of the global horizontal irradiance and the extraterrestrial irradiance. Average solar radiation is calculated over a specific amount of area during a specific time; during this time, the total radiation is measured over that specific area to find the average solar radiation data. The graph of daily irradiance data and clearness data is given in Fig.8.

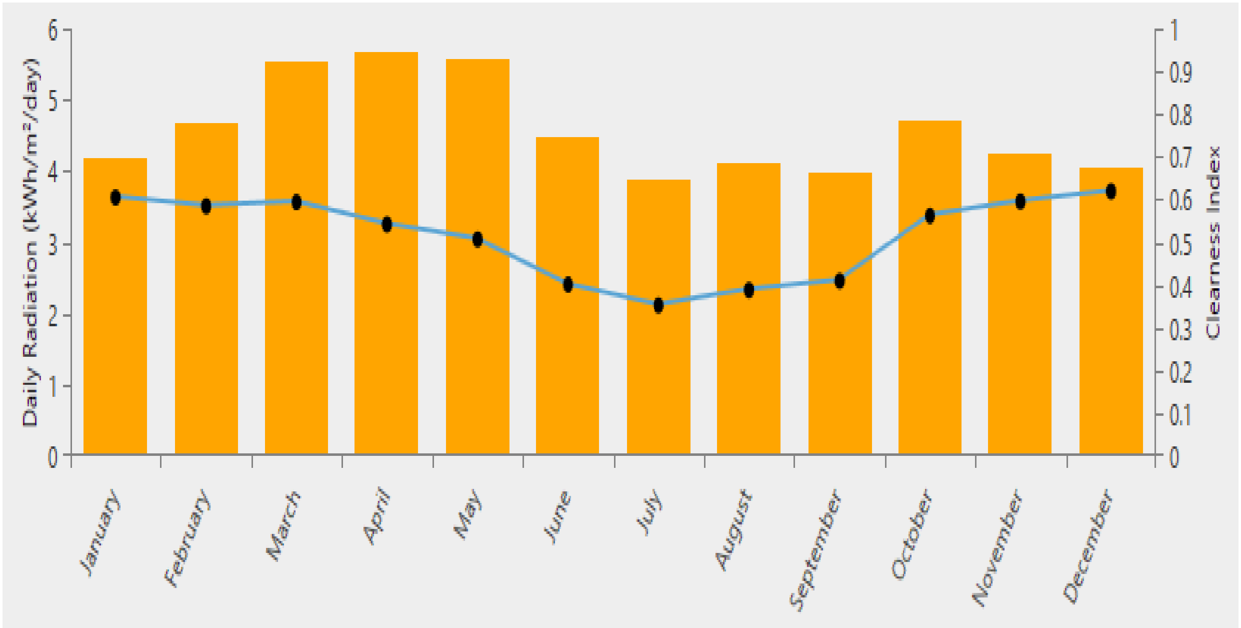

Fig.8. Solar Radiation Data and Clearness Index Data

5.5 Other Miscellaneous Parameters

There are some other parameters that need to be taken into consideration, like the diesel price, nominal discount rate and inflation rate. The diesel price in Bangladesh is 0.77 dollars/liter. In 2020, the inflation rate in Bangladesh has been found to be almost 5.65% [52].

HOMER Pro determines the annual real discount rate based [18] on the nominal discount rate and the inflation rate. The following equation is used for this calculation.

$$i = \frac{i' - f}{1 + f}$$

where:

i = real discount rate

i' = nominal discount rate

f = expected inflation rate

The latest information on the real interest rate in Bangladesh informs that the rate, as of 2019, is almost 4.88% [53]. Thus the nominal discount rate is calculated to be 10.81%. The interest rate data of 2020 could not be collected yet, so the latest rate of 2019 has been used.

5.6 Technical Components

The main components consist of PV modules, batteries, converters, diesel generator (For off-grid scheme). For the on-grid scheme, the grid is considered the secondary power source.

5.6.1 PV Modules

PV module also known as photovoltaic modules are the arrays of photovoltaic cells which absorb solar radiation and converts into direct electricity. PV cells use the photovoltaic effect to generate electricity. In this case, Peimar SG307M models are selected as they have moderately high electricity generation capacity, which is suitable for this application. The HOMER software already provides the specifications for this particular model, given in Table 4.

Table 4. PV module specifications

Model	Peimar SG370M
Power	370kW
Module efficiency	19.1%
Temperature Coefficient	-0.40% /°C
Operating Temperature	25 °C
Derating Factor	90%
Lifetime	30 years
Ground Reflectence	20%
Capital Cost	640 US dollars
Replacement Cost	640 US dollars

5.6.2 Diesel Generator

Diesel generator operates by burning fuel (in this case diesel) and converting mechanical energy to electrical energy. In this case the diesel generator is considered to be the secondary source of power. The PV panels will supply the electricity during the daytime, when the hospital demand is high, and also for the availability of sufficient solar radiation. During the night-time or in cloudy days, when solar radiation is less, the generator will supply the power. For this specific purpose, CAT-200kVA-50Hz-PP model diesel generator was selected for the secondary electricity source. Its specifications are given in Table 5. The fuel efficiency curve is given in Fig 9.

Table 5. Diesel Generator Specifications

Model	CAT-200kVA-50Hz-PP
Power	160 kW
Minimum Load Ratio	25%
Lifetime	60000 hours
Capital Cost	30665$
Replacement Cost	30665$
O&M Cost	8$/ hour

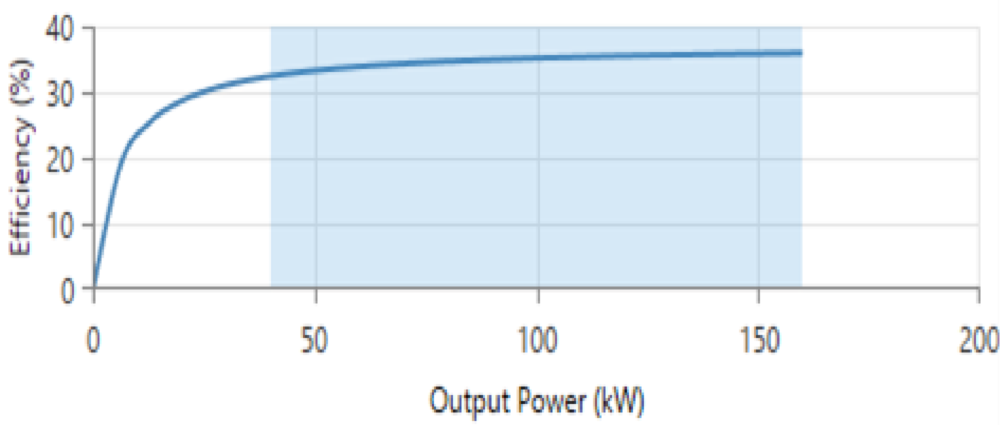

Fig.9. Fuel efficiency Curve for diesel generator

5.6.3 Converter

As stated above, PV cells convert solar energy to direct current, whereas the old hospital building and the medical equipment operate under alternating current. Thus, a converter is required to convert the solar-generated DC into AC. For this purpose, we have selected a generic converter with the specifications given in Table 6. The capital cost has been considered at 202 $ and the replacement cost at 152 $ per kW rating of the converter [54].

Table 6. Converter specifications

Model	Generic
Efficiency	25%
Lifetime	15 years
Capital Cost	202 US dollars/kW
Replacement Cost	152 US dollars/kW

5.6.4 Batteries

For storage purposes, batteries are required as the solar system will not be able to provide energy due to a lack of solar radiation at night time. We have selected the Surrette 4 KS 25P model batteries for our work, which are sufficient to store enough energy for this implementation. The capital cost, replacement cost and O&M cost for this model have been considered at 1150 US dollars, 900 US dollars and 40 US dollars/year, [55] respectively. The battery parameters are given in Table 7.

Table 7. Battery Specifications

Model	Surrette 4 KS 25P
Nominal Capacity	7.55 kWh
Nominal Voltage	4 Volts
Maximum Capacity	1900 Ah
Roundtrip Efficiency	80%
Max charge current	459 A
Minimum state of charge	40%
String size	6
Thoroughput	10,551.70 kWh
Lifetime	20 years
Capital Cost	1150 US dollars
Replacement Cost	900 US dollars
O&M Cost	40 US dollars/year

5.6.5 Grid Parameters

The grid will be in our considerations for the on-grid scheme with no generator backup. In the case of HFO (heavy fuel oil) systems, the grid power price is about 0.150 US dollars/kWh [56]. The grid sellback price, according to the tariff rate for hospitals in Bangladesh, is about 0.071 US dollars/kWh.

Chapter 6

Results

6.1 Optimization Results

The Optimization Results section gives us a list of all the suitable simulations for the selected model. The less feasible or profitable results are not shown. The optimized results are listed according to the type of system. The radio buttons above the Optimization Results table allow us to choose the list of suitable models according to system type [18].
In this part, our proposed energy models will be analyzed in terms of their technical and economic feasibility. Once the simulations are done, the most optimized systems will be recommended by HOMER, based on NPC.

6.1.1 Off-grid case

Here, the upper limit of PV size was set at 1000 kW and the lower limit at 0 kW in the HOMER Optimization field. The upper and lower limit of converter size were chosen at 500 kW and 0 kW, respectively. The upper limit and lower limit of battery strings were also set at 500 and 0, respectively. After the simulation, we found one suitable scenario in the optimization results. According to this result, the NPC, LCOE and operating cost of the system are 3,941,506.00 $, 0.1790 $/kWh and 192,367.90 $/yr, respectively, at a fuel price of 0.77 dollars per liter, a nominal discount rate of 10.81% and an expected inflation rate of 5.65%. The system architecture for this optimized scheme includes one 160 kW capacity CAT-200kVA-50Hz-PP generator, 67 strings of Surrette 4 KS 25P battery, a 324kW large generic converter and 1000 kW capacity of Peimar S370M PV panel. From [57], the area required for the PV modules is found to be 5000 square meters, which is sufficient in terms of the rooftop space available on the old medical building rooftop. The system generates 2,168,861 kWh electrical energy annually, out of which PV gives 1,619,195 kWh (74.7%), and the rest, 549,666 kWh (25.3%), is from the diesel generator. The renewable fraction is 64.4 percent. The monthly average electric production from PV and generator is given in Fig.10. Table 8 shows the optimization results.

Table 8. Optimization Results (Off-grid case)

PV (kW)	Generator (kW)	Converter (kW)	Battery (strings)	Dispatch	Capital Cost ($)	Operating cost ($/yr)	NPC ($)	LCOE ($/kWh)	Ren Fraction (%)
1000	160	324	67	Load following (LF)	1,200,000	192,367.90	3,941,506	0.179	64.4

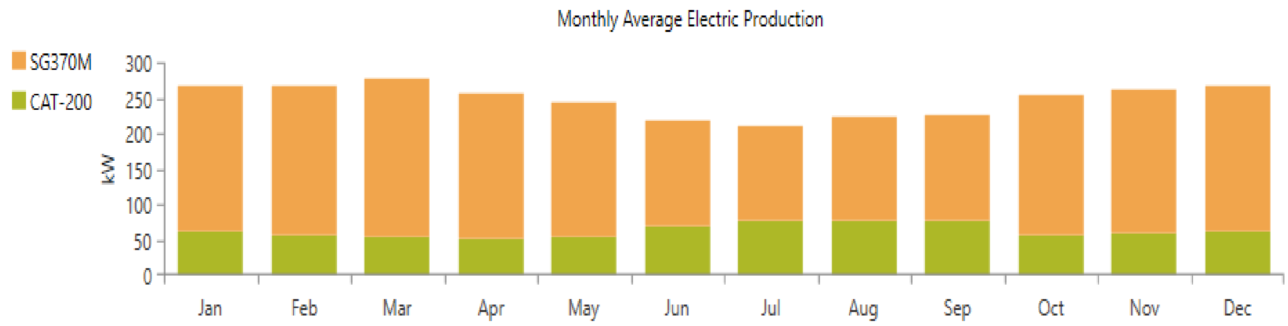

Fig. 10. Monthly average electricity production (Off-grid)

6.1.2 On-grid case

In this model, the upper and lower limits of the components in the HOMER Optimization field are the same. After the simulation, four feasible schemes were found, illustrated in Table 9. All these were obtained at a discount rate of 10.81% and an inflation rate of 5.65%.

Table 9. Optimization Results (On-grid case)

PV (kW)	Grid (kW)	Converter (kW)	Battery (strings)	Dispatch	Capital Cost ($)	Operating cost ($/year)	NPC ($)	LCOE ($/kWh)	Ren Fraction (%)
1000	999,999	500		Cycle Charging (CC)	741,000	96,460.62	2,127,556	0.0674	58.1
1000	999,999	499	6	Load following (LF)	747,774	97,400.65	2,136,629	0.0678	58.2
	999,999			Cycle Charging (CC)	0	243,890	3,477,676	0.150	0
	999,999	0.651	6	Load following (LF)	7,032	244,188.9	3,488,970	0.150	0.00142

The NPC, LCOE and operating cost of the most optimized system are 2,127,556 $, 0.0674 $/kWh and 96,460.62 $/year, respectively. The system for this scheme includes grid connection, a 500kW generic large converter and 1000 kW capacity of Peimar S370M PV panel. The PV capacity is the same as the off-grid case and hence the area required for the PV modules is also the same. This optimized model produces 2,548,458 kWh electrical energy annually, out of which PV supplies 1,619,799 kWh (63.6%), and the rest, 928,659 kWh (36.4%), is from grid. The renewable fraction is 58.1 percent. The monthly average electric production from PV and grid is given in Fig.11.

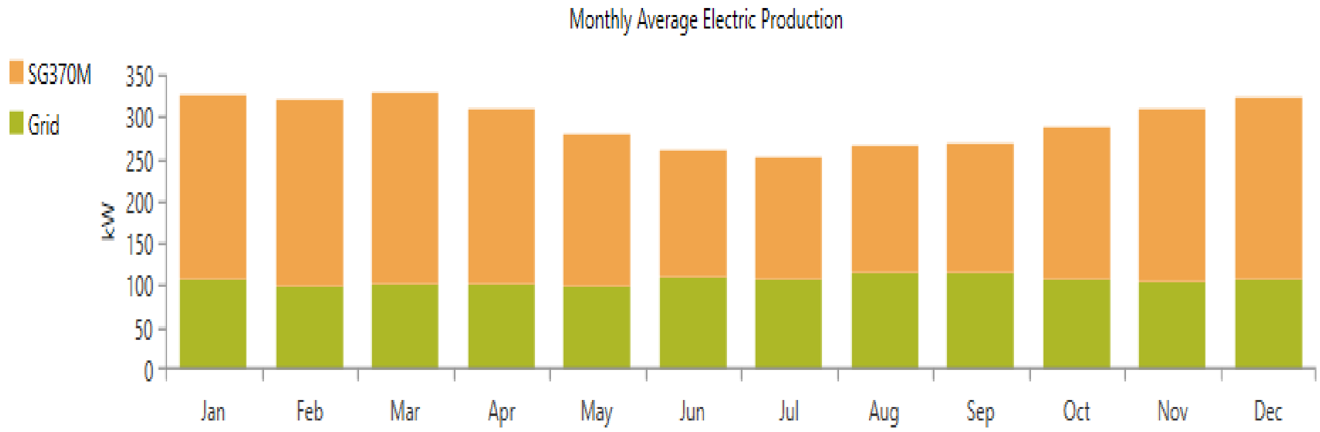

Fig.11. Monthly average electricity (On-grid)

6.1.3 Comparison between the two schemes

A comparison between our two proposed models is given in Table 10.

Table 10. Comparison between the two models

On-grid	Off-grid
NPC is 2,127,556 $.	NPC is 3,941,506 $.
LCOE is 0.0674 $/kWh.	LCOE is 0.179 $/kWh.
Operating cost is 96,460.62 $/year.	Operating cost is 192,367.90 $/year.
Capital cost is 741,000 $.	Capital cost is 1,200,000 $.
The renewable fraction is 58.1%.	The renewable fraction is 64.4%.

The comparison between the two schemes shows us that the on-grid model is economically much better than the off-grid one in terms of NPC, LCOE, operating cost and capital cost. However, if we think about renewable fraction, the off-grid scheme is better than the on-grid.

6.2 Cash Flow Analysis

The cash flow at any point in time is the difference between cash available at the beginning of the life time of a project and at the end [58]. The cash includes loan and capital cost, salvage cost, replacement cost and the sale of assets and goes out to pay for operating expenses, direct expenses, principal debt service, and the purchase of assets such as equipment. The cash that is spent is behind the project is considered as the cash outflow while the cash received is considered as the cash inflow.

The cash flow diagram for both the schemes are illustrated in Fig.12 and Fig.13, respectively.

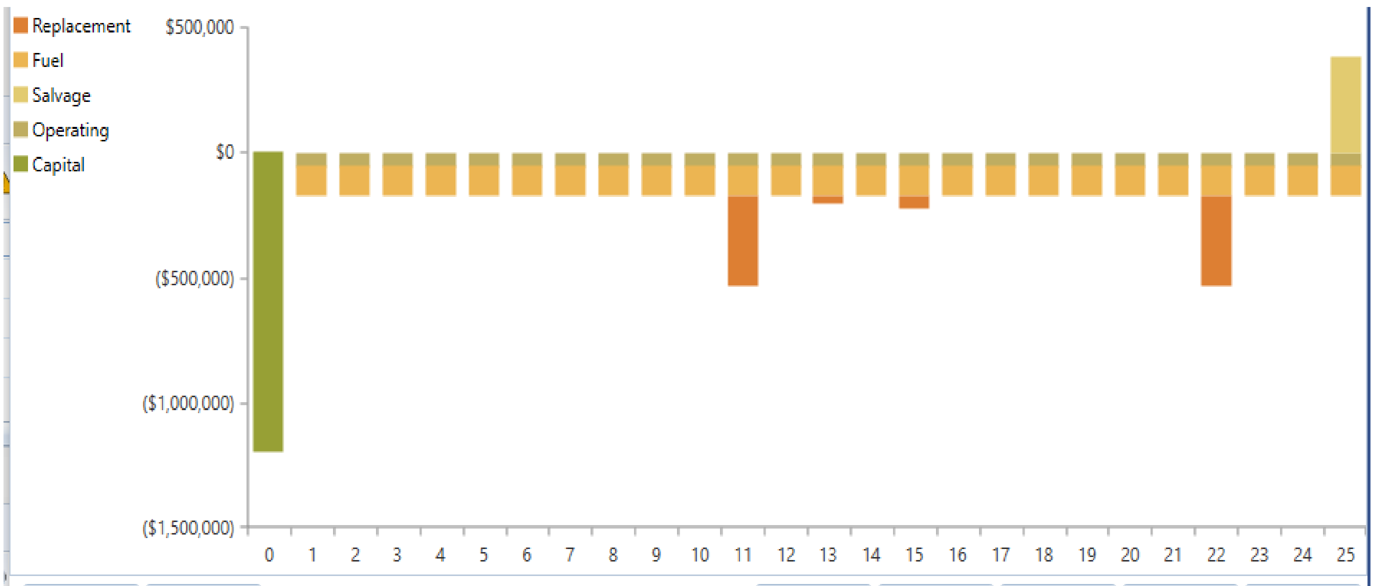

Fig.12. Cash flow diagram (off-grid)

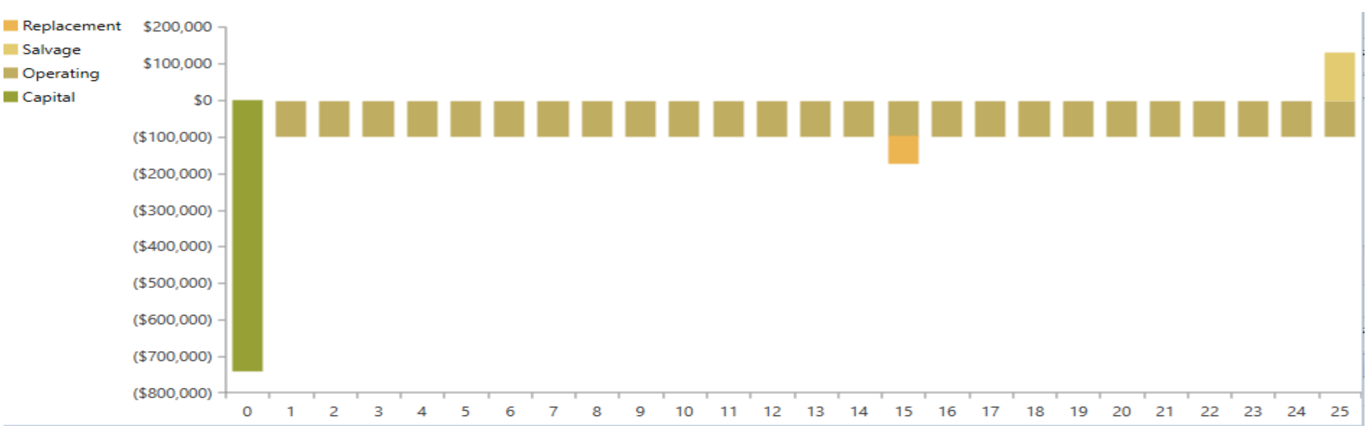

Fig.13. Cash flow diagram (on-grid)

As observed from the cash flow diagram in the off-grid model, a considerable amount of cash outflow occurs initially due to the installation and capital costs. The converter involves a replacement cost after 15 years. The batteries require to be replaced at an interval of 11 years. Also, there is a replacement cost for the PV modules after 13 years. At the end of the lifetime, a salvage cost is also observed since the equipment are depreciable.

For the on-grid case, a considerable amount is needed initially as the capital cost. A replacement cost is observed after 15 years since the lifetime of the converter is 15 years. Here also, a salvage cost is observed at the end of the lifetime of the project since the components are depreciable.

6.3 Sensitivity Analysis

Sensitivity analysis determines how different values of an independent variable influence a particular dependent variable under a given set of assumptions [59]. It studies how various sources of uncertainty in a mathematical model contribute to the model's overall uncertainty. This technique is used within specific boundaries dependent on one or more input variables.

Sensitivity analysis mainly deals with the change of some input variables and then observing the effect on some output parameters. At first, the sensitivity variables and their values need to be specified. The variables that have been considered for sensitivity analysis are as follows,

1. Nominal Discount Rate
2. Expected Inflation Rate
3. Average Solar Radiation
4. Diesel Price
5. Grid Power Price

The effect of these variables on NPC and LCOE will be observed and analyzed.

6.3.1 Effect of Nominal Discount Rate

A standard discount rate of 10.81% has been used for both models. By fluctuating the nominal discount rate from 9 to 12 %, we observed the corresponding response on NPC and LCOE and presented it graphically in Fig. 14 and 15.

As the nominal discount rate increases, an almost linear decrease in NPC and a linear increase in LCOE are visible. At the discount rate of 10%, the NPC for the on-grid scheme is 2.24 million dollars and at 11%, it is 2.10 million dollars. The LCOE at 10% and 11% are respectively around 0.0655 \$/kWh and 0.0678 \$/kWh. The same effect is visible in the off-grid case. In the off-grid case, the NPC at a discount rate of 10 and 11 percent is 4.17 million dollars and 3.89 million dollars, respectively. The LCOE at these two discount rates are 0.175 and 0.180 \$/kWh, respectively. Hence, we can conclude that NPC decreases and LCOE increases with the nominal discount rate, provided the other factors are kept at standard values.

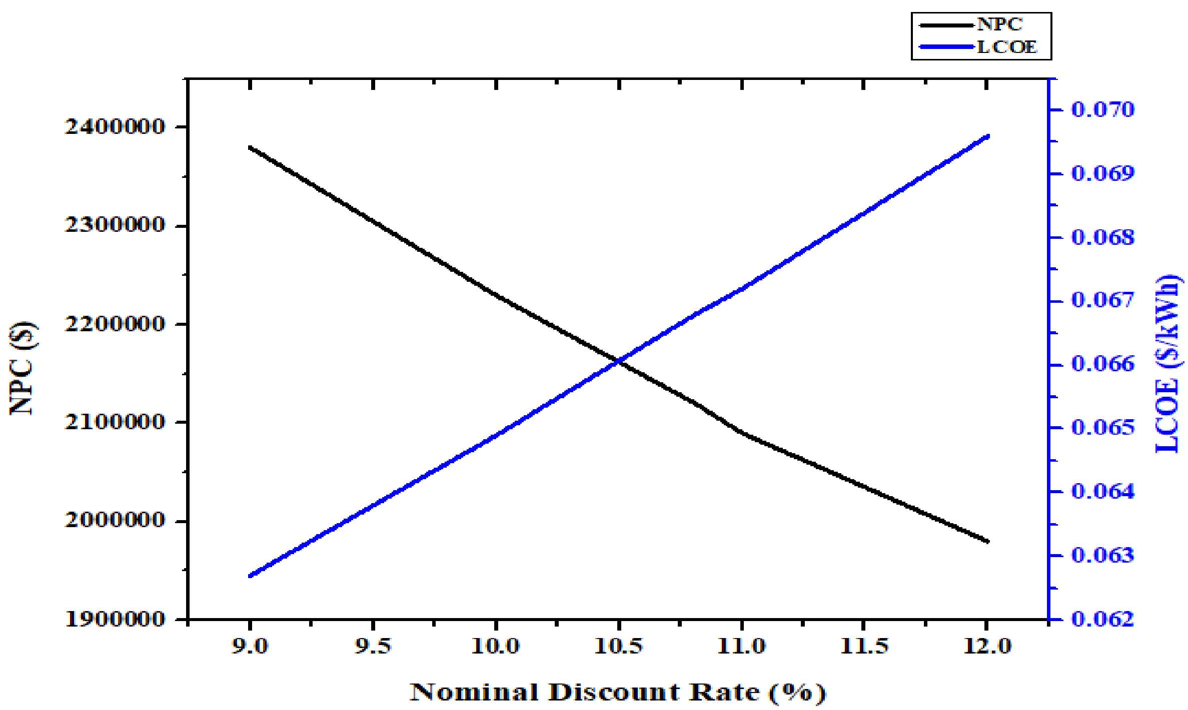

Fig.14. Effect of Nominal Discount Rate (on-grid)

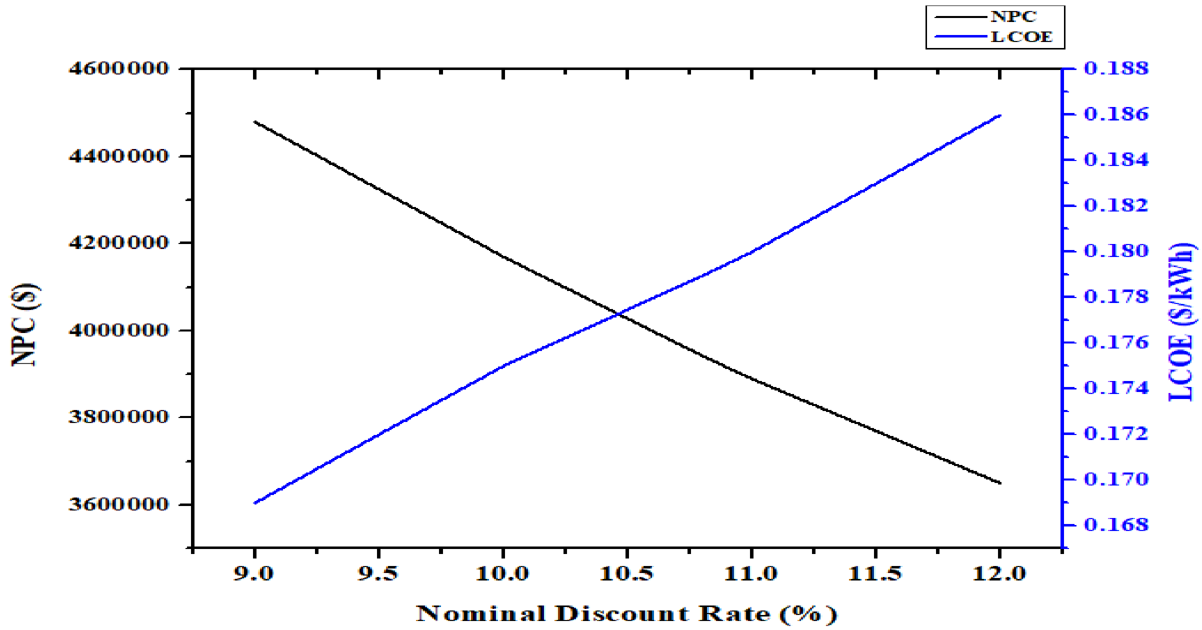

Fig.15. Effect of Nominal Discount Rate (off-grid)

6.3.2 Effect of Annual Average Radiation

A standard discount rate of 4.59 kWh/m^2/day has been used for both models. By fluctuating the nominal discount rate from 3-6 kWh/m^2/day, we observed the corresponding response on NPC and LCOE and presented it graphically in Fig. 16 and 17.

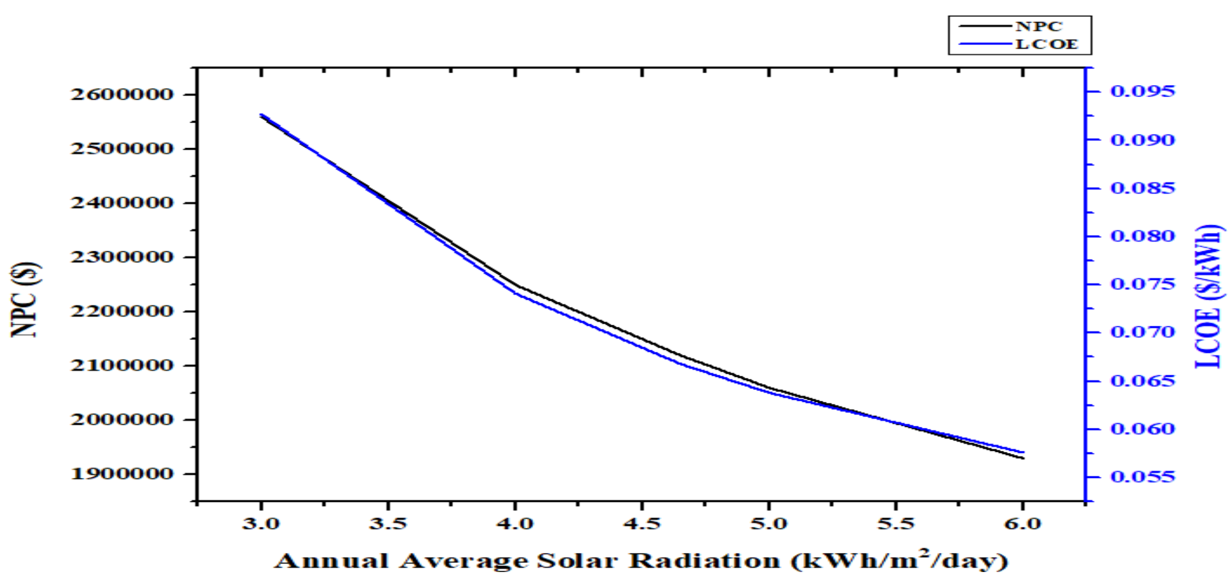

Fig.16. Effect of Annual Average Solar Radiation (on-grid)

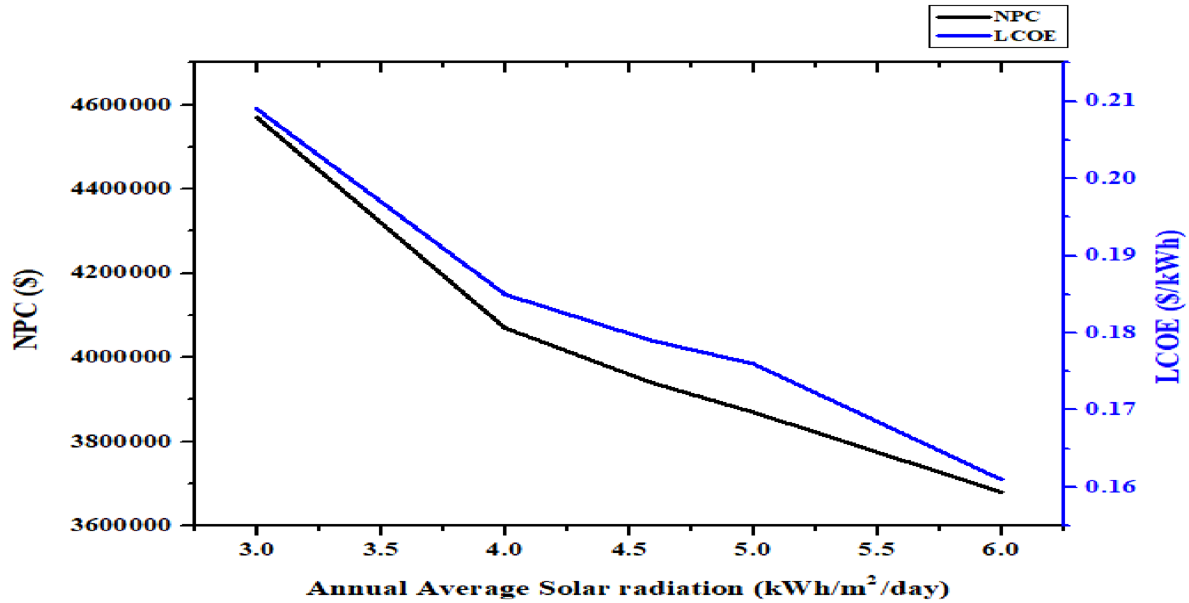

Fig.17. Effect of Annual Average Solar Radiation (off-grid)

As the average solar radiation increases, a decrease in both NPC and LCOE are visible. At the radiation of 3 kWh/m^2/day, the NPC for the on-grid scheme is 2.56 million dollars and at 4 kWh/m^2/day, it is 2.25 million dollars. The LCOE at 3 kWh/m^2/day and 4 kWh/m^2/day are respectively around 0.0927 $/kWh and 0.0741 $/kWh. The same effect is visible in the off-grid case. The NPC in the off-grid case at annual average radiation of 3 kWh/m^2/day and 4 kWh/m^2/day are 4.57 million dollars and 4.05 million dollars, respectively. The LCOE at these two radiations are 0.209 and 0.185 $/kWh, respectively. Hence, we can conclude that both NPC and LCOE decrease with the annual average solar radiation, provided the other factors are kept at standard values.

6.3.3 Effect of Inflation Rate

A standard discount rate of 5.65% has been used for both models. In 2021 and 2022, the rate is projected to be 5.88% and 5.49% [38] respectively. The sensitivity analysis has been conducted at these rates and then we observed the corresponding response on NPC and LCOE and presented it graphically in Fig. 18 and 19.

As the inflation rate increases, an increase in NPC and a decrease in LCOE are visible. At the inflation rate of 5.65%, the NPC for the on-grid scheme is 2.13 million dollars and at 5.88%, it is 2.16 million dollars. The LCOE at 5.65% and 5.88% are respectively around 0.0673 $/kWh and 0.0668 $/kWh. The same effect is visible in the off-grid case. The NPC in the off-grid case at an inflation rate of 5.65% and 5.88% are 3.94 million dollars and 4 million dollars, respectively. The LCOE at these two rates are 0.179 and 0.178 $/kWh, respectively. Hence, we can conclude that both NPC and LCOE decrease with the annual average solar radiation, provided the other factors are kept at standard values.

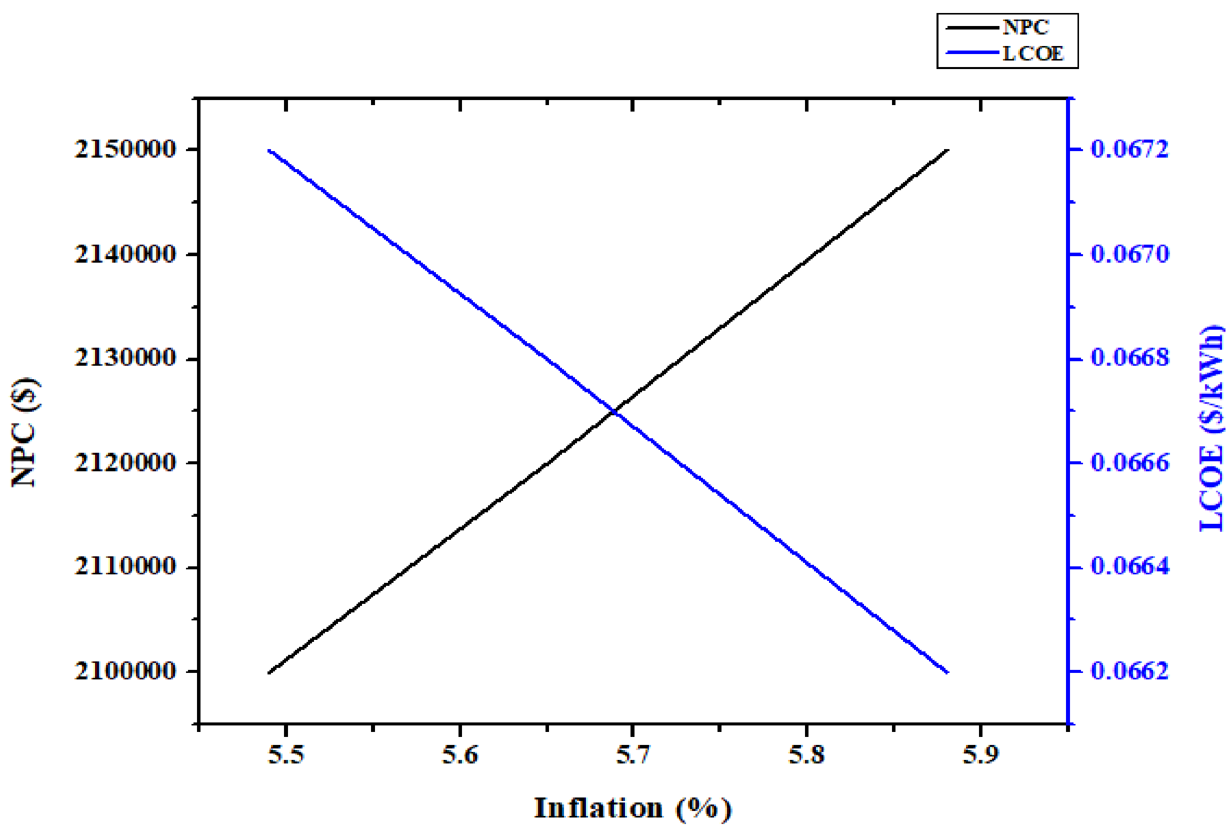

Fig.18. Effect of Inflation Rate (on-grid)

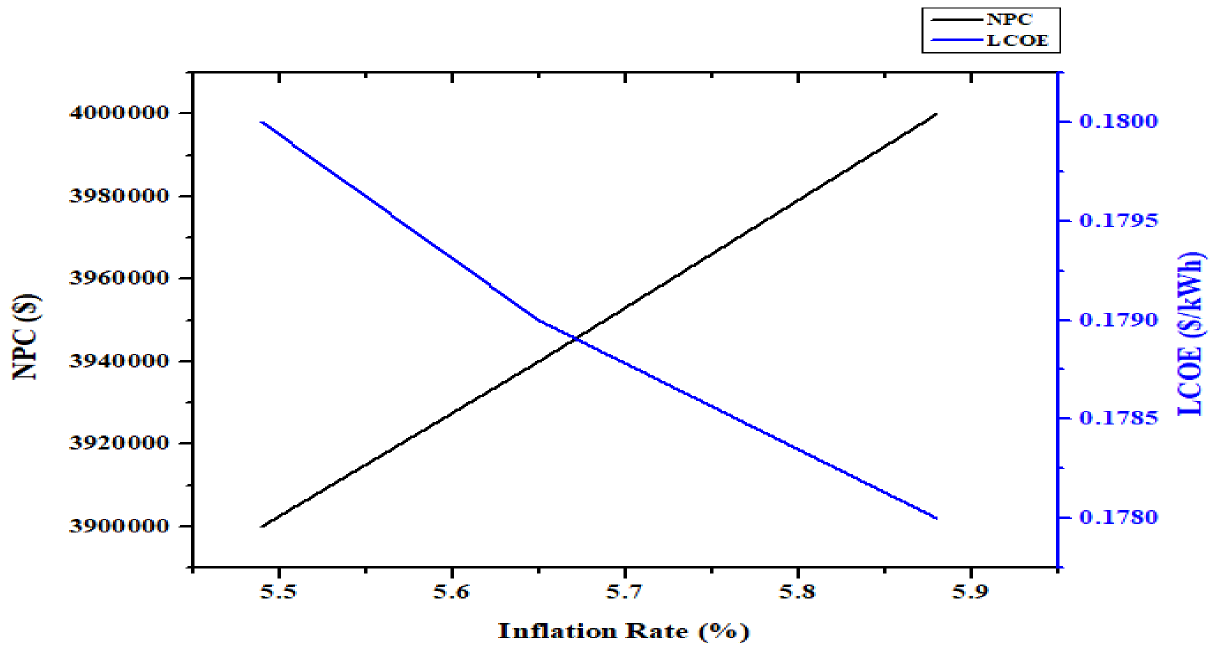

Fig.19. Effect of Inflation Rate (off-grid)

6.3.4 Effect of Diesel Price

A standard price of 0.77 dollars/litre has been used only in the off-grid model. Diesel price is not an issue in the on-grid case since no diesel generator has been used. By fluctuating the diesel price from 0.77 to 1 dollar/litre, we observed the corresponding response on NPC and LCOE and presented it graphically in Fig.20.

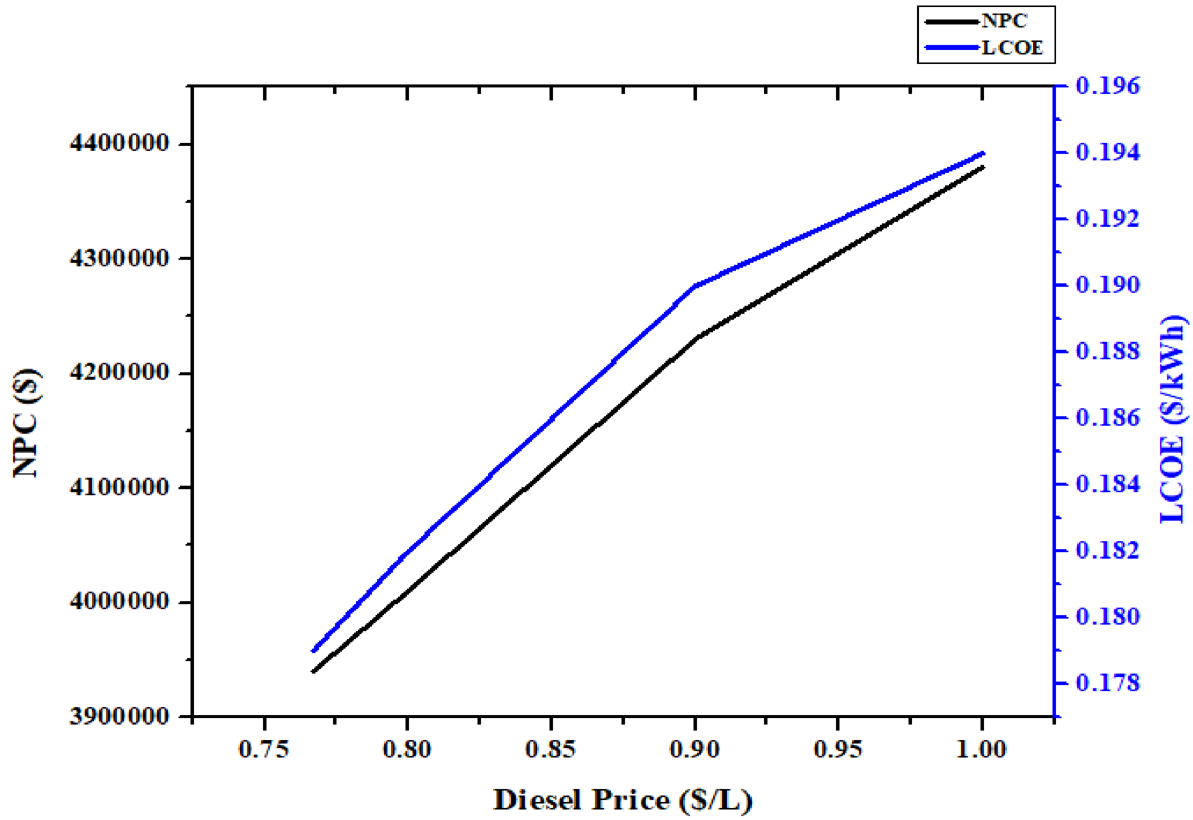

Fig.20. Effect of Diesel Price (off-grid)

As the diesel price increases, an increase in both NPC and LCOE are visible. At the diesel price of 0.8 $/litre, the NPC for the off-grid scheme is 4.01 million dollars and at 0.9 $/litre, it is 4.23 million dollars. The LCOE at 0.8 $/litre and 0.9 $/litre are respectively around 0.182 $/kWh and 0.190 $/kWh. Hence, we can conclude that both NPC and LCOE decrease with the annual average solar radiation, provided the other factors are kept at standard values.

6.3.5 Effect of Grid Power Price

A standard price of 0.15 dollar/kWh has been used only in the on-grid model. Grid power price is not an issue in the off-grid case. By fluctuating the power price from 0.15 to .17 $/kWh, we observed the corresponding response on NPC and LCOE and presented it graphically in Fig.21.

As the grid power price increases, a linear increase in both NPC and LCOE are visible. At the diesel price of 0.15 dollar/kWh, the NPC for the on-grid scheme is 2.13 million dollars and at 0.16 dollar/kWh, it is 2.26 million dollars. The LCOE at 0.15 and 0.16 $/kWh are respectively around 0.0632 $/kWh and 0.0715 $/kWh. Hence, we can conclude that both NPC and LCOE decrease with the annual average solar radiation, provided the other factors are kept at standard values.

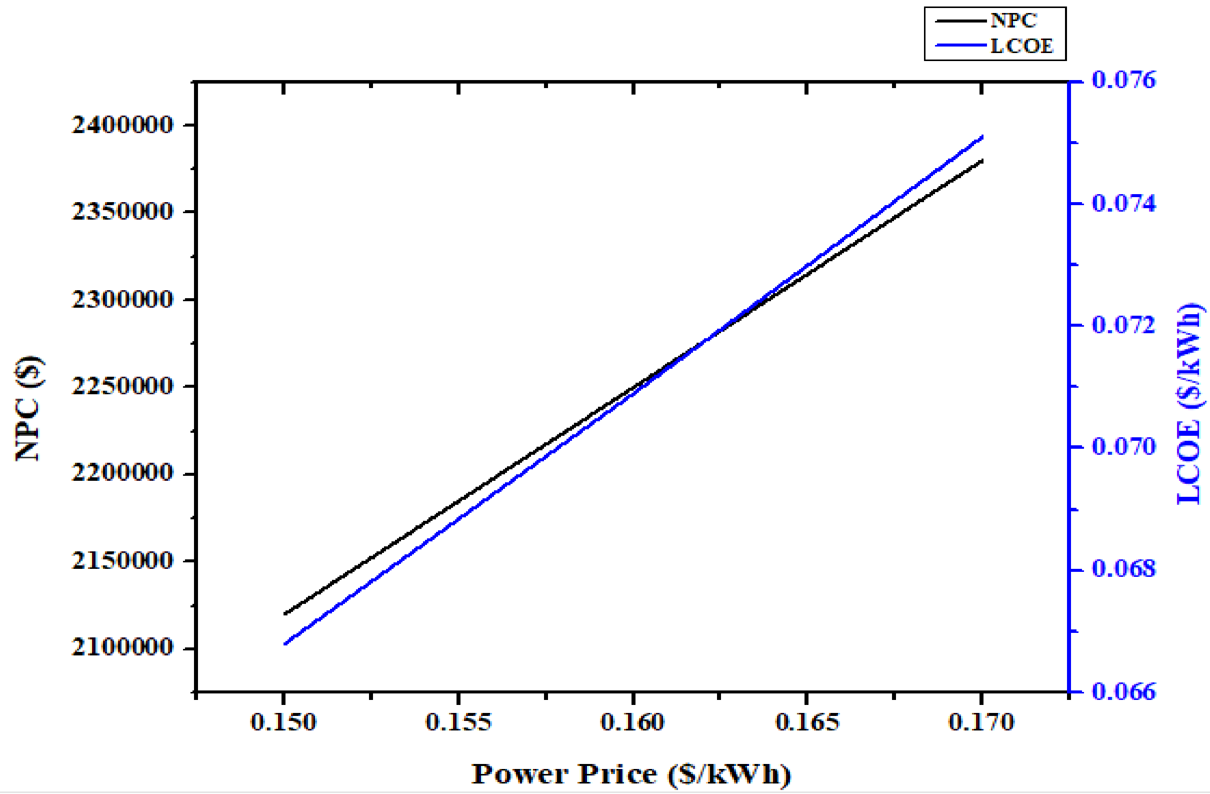

Fig.21. Effect of Grid Power Price (on-grid)

6.4 Electrical Summary

The electricity consumption and generation parameters will be discussed in this section. These parameters for both the on-grid and off-grid case are given in Table.11 and Table.12, respectively.

Table 11. Electrical Data (on-grid)

Quantity	Value (kWh/yr)
AC Primary Load	1,625,933
DC Primary Load	0
Grid Sales	589,520
Excess Electricity	265,279
Unmet Electric Load	0
Capacity Shortage	0

Table 12. Electrical Data (off-grid)

Quantity	Value (kWh/yr)
AC Primary Load	1,544,517
DC Primary Load	0
Excess Electricity	487,332
Unmet Electric Load	81,416
Capacity Shortage	132,668

6.5 Emission Summary

The emission of various gases and other substances will be discussed in this section. These parameters for both the on-grid and off-grid case are given in Table.13 and Table.14, respectively.

Table 13. Emission Data (on-grid)

Quantity	Value (kg/yr)
Carbon Dioxide	586,913
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0
Sulfur Dioxide	2,545
Nitrogen Oxides	1,244

Table 14. Emission Data (off-grid)

Quantity	Value (kg/yr)
Carbon Dioxide	416,270
Carbon Monoxide	0
Unburned Hydrocarbons	0
Particulate Matter	0
Sulfur Dioxide	1,032
Nitrogen Oxides	0

Chapter 7

Conclusion and Future Scope

In this thesis, two hybrid renewable energy models were designed and simulated. One was an on-grid model with PV, converter and grid connection. The other was an off-grid model with PV, generator, converter and batteries. These two models were modeled to meeting up the medical instrument and the electrical appliances of the old building of Dhaka Medical College. A rigorous software simulation and feasibility analysis had been conducted to get better insight into the operation and capacity of our propose models.

First, a load profile has been formulated, taking all the necessary data from relevant sources and online documents. Weather data for our site has been collected, like the solar resources. Considering the solar PV, generator, converter and the batteries as the key technical components of the proposed systems, extensive research was done in terms of technical and financial parameters. Then the necessary optimization and sensitivity analysis had been carried out. All these have been accomplished in the HOMER software. Cash-flow analysis and a summary of the electrical and emission results have also been presented.

After all the necessary simulations, we analyzed both models and looked for cost and renewable feasibility. As we have shown in the comparison between the two models, the on-grid model is cheaper and profitable than the off-grid one in terms of NPC, LCOE and operating costs. If our focus is on renewable benefits, then the off-grid is a better option since it gives a better renewable fraction.

HOMER software considers different permutations and combinations of the selected components and finally presents a set of feasible solutions. All the cost constraints and technical specifications of our selected components have been carefully chosen and only after that were our simulations carried out. The inflation rate, discount rate and fuel price also have been considered at their optimum standard rates. Thus, HOMER gave us the most optimized options with the least NPC and LCOE and satisfactory renewable fractions, capable of meeting up the consumption requirements of a busy and 24/7 operating hospital like the Dhaka Medical College Hospital.

In this work, we mainly focused on the software modelling and feasibility analysis of our systems. Detailed work on hardware implementation and wiring processes could not be carried out due to the COVID-19 pandemic. There is scope to work on the practical implementation of our models in the future. It may be possible to design an optimized energy model for the new hospital building of DMC as well.

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