TECHNO-ECONOMIC OPTIMIZATION OF STANDALONE MICROGRID HYBRID ENERGY SYSTEM IN ZERO ENERGY BUILDINGS FOR REMOTE COMMUNITY IN ANKARA

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OTHMAN JASIM MOHAMMED AL HAYALI

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Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

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Prof. Dr. Ali KARA
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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Electrical and electronic engineering department, Atilim University.

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This is to certify that we have read the thesis TECHNO-ECONOMIC OPTIMIZATION OF STANDALONE MICROGRID HYBRID ENERGY SYSTEM IN ZERO ENERGY BUILDINGS FOR REMOTE COMMUNITY IN ANKARA submitted by OTHMAN JASIM MOHAMMED AL HAYALI and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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Incremental consumption of electrical energy, fossil fuel reduction, high prices of transmission lines and environmental pollution problems drive the countries to develop zero energy buildings (ZEB) in which electricity is generated from renewable energy sources. Wind and solar are the promising energy sources. However, the intermittence nature of these resources reduces the system reliability. Hybrid renewable energy system (HRES) is considered a solution for this problem. To design a HRES, the investors need to consider the minimum configuration cost. In this study, installation of photovoltaic panel (PV) and wind turbine (WT) systems to electrify 30 households in a remote area in Ankara is simulated. Different scenarios have been considered to obtain the optimal hybrid system that can cover the load with the least costs. Hybrid Optimization Model for Multiple Energy Resources (HOMER) software and Particle Swarm Optimization (PSO) algorithm have been applied to obtain the optimal configuration. The HRES that consists of 107 kW PV, 3×10 kW WT, 10 kW diesel generator (DG) and 45×7.15 kWh units of batteries is chosen as the optimal choice to meet the electrical load demand. The cost of energy (COE) and net present cost (NPC) are found as 0.25 $/kWh and 568431 $, respectively. In sensitivity analysis, effects of PV and WT capital costs, fuel price and type of batteries on the system performance are examined to verify the results. As a result, doubling the fuel price has been observed to increase the COE and NPC around 14% and 13%, respectively. As the PV and WT capital costs halved, the COE

and NPC decreased by 20% and 12%, respectively. Utilizing a specific battery technology has been seen to reduce both the overall price and gas emissions.

Keywords: Off-grid ZEB, Renewable energy, PSO, HOMER, Ankara

ÖZ

ANKARA'DA UZAK KOMÜNİTE İÇİN SIFIR ENERJİ BİNALARINDA BAĞIMSIZ MİKROGRID HİBRİT ENERJİ SİSTEMİNİN TECHNO-EKONOMİK OPTİMİZASYONU

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Artan elektrik enerji tüketimi, fosil yakıtların azalması, iletim hatlarının yüksek fiyatları ve çevre kirliliği sorunları ülkeleri yenilenebilir enerji kaynaklarından elektriğin üretildiği sıfır enerji binaları (ZEB) geliştirmeye itmektedir. Rüzgar ve güneş enerjileri ümit verici kaynaklardır. Ancak, bu kaynakların kesintili doğası sistem güvenilirliğini azaltır. Hibrid yenilenebilir enerji sistemi (HRES), bu soruna bir çözüm olarak kabul edilir. Bir HRES tasarlamak için yatırımcıların minimum yapılandırma maliyetini göz önünde bulundurmaları gerekir. Bu çalışmada, Ankara'da uzak bir bölgede 30 evin elektriklendirmek için fotovoltaik (PV) ve rüzgar türbini (WT) sistemlerinin kurulması simüle edilmiştir.

Yükü en az maliyetle karşılayabilecek en uygun hibrit sistemi elde etmek için farklı senaryolar düşünülmüştür. Optimal konfigürasyon elde etmek için Çoklu Enerji Kaynakları için Hibrid Optimizasyon Modeli (HOMER) yazılımı ve Parçacık Sürüsü Optimizasyonu (PSO) algoritması uygulanmıştır. 107 kW PV, 3 × 10 kW WT, 10 kW dizel jeneratör (DG) ve 45 × 7.15 kWh pillerden oluşan HRES, elektrik yükü talebini karşılamak için en uygun seçim olarak seçilmiştir. Enerji maliyeti (COE) ve net yüzde maliyeti (NPC) sırasıyla 0.25 $/kWh ve 568431 $ olarak bulunmuştur. Duyarlılık analizinde sonuçları doğrulamak için PV ve WT sermaye maliyetlerinin, yakıt fiyatının ve pillerin türünün sistem performansı üzerindeki etkileri incelenmiştir. Sonuç olarak, yakıt fiyatını ikiye katlamak, COE ve NPC'yi sırasıyla 14% ve 13% oranında arttırdığı gözlenmiştir. PV ve WT sermaye maliyetleri yarıya

düştüğünde, COE ve NPC sırasıyla 20% ve 12% oranında azalmıştır. Belirli bir pil teknolojisinin kullanılmasının hem genel fiyatı hem de gaz emisyonlarını azalttığı görülmüştür.

Anahtar Kelimeler: Off-grid ZEB, Yenilenebilir Enerji, PSO, HOMER, Ankara

DEDICATION

TO THE CANDLE THAT HIGHLIGHTED MY WAY, MY GREAT … FATHER

TO THE SPRING OF KINDNESS, MY DEAREST … MOTHER

TO MY BROTHERS AND SISTERS, WITH LOVE AND GRATITUDE

TO MY LOYAL FRIENDS (OTHMAN, MOHAMMED, HASAN)

AND FOR EVERY PERSON WHOSE HEART THROBBED FOR ME

ACKNOWELEDGMENT

In the Name of Allah, the Most Gracious, the Most Merciful. Peace and blessings of Allah be upon the noblest of the Prophets and Messengers, our Prophet Mohammed and upon his family, companions and who follows.

I would like to express my gratitude to all, who during the past two years have supported me in some way or another. To my supervisor Asst. Prof. Dr. Mehdi Mehrtash, a special thanks for giving me the opportunity to work with him and for his patience, tolerance, understanding, and encouragement. It has been a great pleasure working with him. I really appreciate the time and efforts he devoted for the completion of my dissertation. I'd like to express my gratitude to my co-advisor and the head of electrical and electronic department represented by Assoc. Prof. Dr. Kemal Efe Eseller for the ethics and knowledge he has offered me. Also, I'd like to express my gratitude to the head of institute represented by the director Prof. Dr. Ali Kara for helping by providing facilities, advice and support. I also thank the staff members of Atilim University for providing facilities. A special thanks to my friends and colleagues the engineers Dr. Ahmed Eid, Khalid, Ayaa, Yosif, Burnsrdo, Omar, Nofal, Mustafa, Zaid, Ahmed and Ali for providing help and support. I am grateful to my parents for being my support and guide during most difficult times of my life. They are source of inspiration to me all the time. Without them it would not have been possible for me to become what I am today.

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LIST OF ABBREVIATIONS

PV	-	Photovoltaic panel
WT	-	Wind turbine
DG	-	Diesel generator
ZEB	-	Zero energy buildings
HRES	-	Hybrid renewable energy system
REPA	-	Turkey Wind Energy Potential Atlas
GEPA	-	Turkey Solar Energy Potential Atlas
EIE	-	Electricity Affairs Survey Administration
DC	-	Direct current
AC	-	Alternative current
COE	-	Cost of energy
NPC	-	Net present cost
SoC	-	State of charge
DOD	-	Depth of discharge
O&M	-	Operation and maintenance
LPSP	-	Loss of power supply probability
HOMER	-	Hybrid Optimization Model for Multiple Energy Resources
PSO	-	Particle swarm optimization
LA	-	Lead acid battery
ZF	-	Zinc flow battery
VF	-	Vanadium flow battery
LI		Lithium ion battery

CHAPTER 1

1 INTRODUCTION

1.1 Study Background

At present, the ever-increasing demand for energy has become one of the major problems in the world that must be addressed. It is directly linked to the environmental, economic and social development of the countries. The functions of productions, trade and economies of any country cannot be completed without energy [1].

In most countries, buildings occupy a large proportion of the annual energy consumption. According to the European environmental data, the buildings consume around 40% of the total energy consumption and responsible for around 36% of the total carbon emissions. In Turkey, buildings account for 35% of primary energy consumption [2]. The other study indicated that the buildings produce around one – third of the global greenhouse gas emissions [3].

There are several forms of energy such as electrical, mechanical, hydraulic, solar, nuclear, wind, geothermal and chemical energy. These energy forms can be converted into other forms using advanced technologies. However, the methods of converting energy from its real form to another can make a huge negative impact on the people and the environment.

The world relies mainly on fossil fuels in energy production [4]. In electrical energy, most of the generating stations at present depend on fossil fuels by converting them to electrical energy. The gases resulting from the combustion of fuel in electrical stations such as a chlorofluorocarbon, carbon dioxide, nitrous oxide and methane harm the environment [5]. These gasses increase the surface temperature of the earth and cause climate change including the problems of global warming, seasonal deviations, natural disasters, glacier meltdown and environmental pollution [6].

Electrical energy goes through several stages namely, generation stations, transport stations and finally the distribution stations until it reaches the recipient.

Generally, it is not feasible to install stations and transmission lines to deliver electricity to small and remote areas, which consist of a limited number of houses with small load. Initial costs, the cost of maintenance, as well as in some cases, difficulties in reaching these specific regions because of the terrain or the presence of trees are the reasons for this matter [7].

There are still around 1.5 billion people in some countries living in isolated or remote communities with no or low proper access to electricity, and often these places have large resources of renewable energy [8]. Diesel generator (DG) is commonly used to meet the electrical energy demand for these isolated areas, which gives off high pollutant gases to the environment and result in large uncertainties for fuel cost [9].

To solve these problems, designing zero energy building (ZEB) and investing in renewable sources of energy must be considered as a priority. As they are clean, reliable and do not harm the living organisms, nor do they pollute the environment.

1.2 Research Objectives

The main objectives of this study are:

1. To study the opportunity of implementing ZEB and investing renewable energy sources in Ankara.
2. To study the components of the off-grid hybrid renewable energy system (HRES).
3. Optimize and design a hybrid energy sources in different scenarios of systems to select the optimal hybrid renewable energy system components to achieve the ZEB from electrical load demand side.
4. Simulate the optimal system to perform the economic effect and power supply quality.
5. To inform investors about the power quality and feasibility of the selected area in Ankara which will help them to make a plan for investment.

1.3 Problem Statement

In any place, the existence of renewable sources such as solar radiation and wind speed are different. The designing of HRES depends on the meteorological data of the selected area because it affects the reliability and economy of the system. Meteorological data of Ankara is used in this study to design, simulate and optimize

a HRES in order to give a better explanation in construction of ZEBs. The study deals with the following questions: Is it possible to install a HRES for the selected location? How is the feasibility of HRES in Ankara? How to find out the sizes of a system components that lead to the optimal HRES? Does the system work properly? How about the costs and electrical power sources quality?

1.4 Motivation

In general, there are two types of HRES which are on-grid and off-grid systems. In remote and rural places, the off-grid system is more promising to provide electricity to cover the load demand due to its efficiency, reliability and low cost because there is no long transmission between the source and consumption. Since there are good renewable sources presented in Ankara and the combination of wind turbine (WT) and photovoltaic panel (PV) are the most common renewable sources in ZEB off-grid systems, the combination of PV and WT as renewable energy sources with DG and battery as a backup will be investigated in this study.

1.5 Outline

Chapter 1 covers the introduction of the thesis including the overall view of energy, the problem that could be faced in electrifying the remote areas. Besides, the objectives of the study and problem statement are included in this chapter. Chapter 2 covers the literature review on different types of renewable energy systems in detail. In addition, various types of hybrid energy system configurations, optimization techniques and software tools for optimum sizing of hybrid systems are discussed. Chapter 3 indicates the methodology including the case study and the techniques that are used. Chapter 4 shows the results of the study including the comparison between the outputs of different configurations. The conclusion and future work are in chapter 5.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Zero Energy Buildings

Buildings consume large amounts of energy and considered one of the main reasons for the increase in energy demand [10]. The trend of green architecture in accessing zero energy building has evolved, as it contributes to tackling the problem of significant increase in energy demand. The ZEB is known as the building in which its annual energy consumption is equal to its annual energy generation. This building has evolved from building that can rationalize energy consumption to building that produces the energy they consume [11]. Access to ZEB not only solves the energy crisis, but also preserves the environment and protects the people from the risk of diseases they are exposed to due to the pollutants caused by the buildings. It depends on renewable energy in large percentage of its energy instead of fossil energy. In addition to its self-sufficiency, it does not have a large negative impact on the environment. The most renewable sources that ZEB use are solar energy, wind energy, solar thermal and heat pump [12]. The challenging factors for the ZEB are reducing the cost of energy (COE) and carbon dioxide (CO_2) emission. Different countries put a target that all the new buildings shall be ZEB. UK indicated that the new houses should be zero carbon emission by the year of 2016. Hong Kong put a target to reduce the carbon emission from buildings by around 50%-60% by the year of 2020 comparing with 2015 [13-15]. California put a target to make all the new residential buildings as a ZEB by 2020 and all commercial building by 2030. Similarly, China, Australia and Japan try to convert their buildings to ZEBs.

2.2 Renewable Energy

Renewable energy is fundamentally different from non-renewable energy. In non-renewable energy, oil, coal, or natural gas are burned to produce electrical energy, releasing many harmful gases. However, in renewable energy, electrical energy production depends on solar radiation, wind speed, tidal wave movements and

geothermal energy with no harmful greenhouse gases released during the conversion [17].

There are some characteristics that renewable energy source enjoys, and these make it a unique source of energy. Renewable energy is well and permanently present in all parts of the world. It is considered clean source and environmentally friendly. It is easy to use by applying simple mechanisms and techniques. It is characterized by being very economical and considered as an important factor in environmental and social development. It also helps in creating new job opportunities and reducing the damages of gases and thermal emissions [18].

The use of renewable energy has become widespread at the present time, as electrical energy is produced in large proportions by hydroelectric stations, where large dams are built on rivers and waterfalls to store water for energy generation. Also, wind and solar energy are used for electricity generation. These modern technologies are widespread in developing countries, where plans are put in place to reduce fossil fuel consumption and increase the dependence on renewable energy. At the present time, many renewable energy systems are installed in homes, hospitals, schools, and universities due to their cleanliness, technical benefits, as well as the constant decrease in their prices, which helps reduce the electricity bill [19].

2.3 Renewable Sources

Renewable energy sources are a natural source that people does not interfere with its production. The most important advantages of renewable energy sources are that they are clean, continuously available and non-emitting sources of toxic gases that pollute the natural, environment and cause global warming [20].

Wind energy is one of the promising renewable sources. WT use air energy to generate electricity. They can be installed in different places, such as agricultural land, forestry or sea because of the high wind speed generally found at places close to the sea. The wind is considered as a clean and low-cost source like other renewable sources [21].

Solar energy is the energy emitted by the sun in the form of light and heat, which is the most important energy source for humans and all living organisms. Currently,

with technological development, utilizing concave mirror or PV, solar energy can easily be exploit and converted into electrical energy [22].

Hydroelectric energy is used in electrical energy production. Water flows through controlled channels placed into the dam. Water stream rotates the turbine which itself is connected to an electrical generator that produces electricity. The advantages of this source are that it is clean and do not causes gas emissions despite the large amount of electric power it supplies. On the other hand, the disadvantage is the construction of the dam that may change the geographical terrain and cause the sinking of many land areas. Likewise, the possibility of dam collapsing may lead to catastrophic incidents such as floods [23].

Tidal energy is one of the renewable energy forms. It stored in the currents resulting from the tides due to the gravity of the sun, moon and the rotation of the earth around its axis. There are many countries started to invest this kinetic energy to generate electrical energy [24].

2.4 Energy in Turkey

The demand for energy in Turkey has escalated dramatically since 2002. Installed capacity and electricity generation have increased with average rates of 6.2 and 6.3 percent, respectively and the total generation of electricity in Turkey reached 297,278 GWh in 2017. Turkey relies mainly on fossil fuels for energy production. Natural gas with a large proportion of electrical energy estimated by 37%. Coal covers 32.5%, wind energy 6.1%, hydropower 20% and the others including solar energy 4.4% [25]. Figure 2.1 shows the percentage of each energy sources in Turkey.

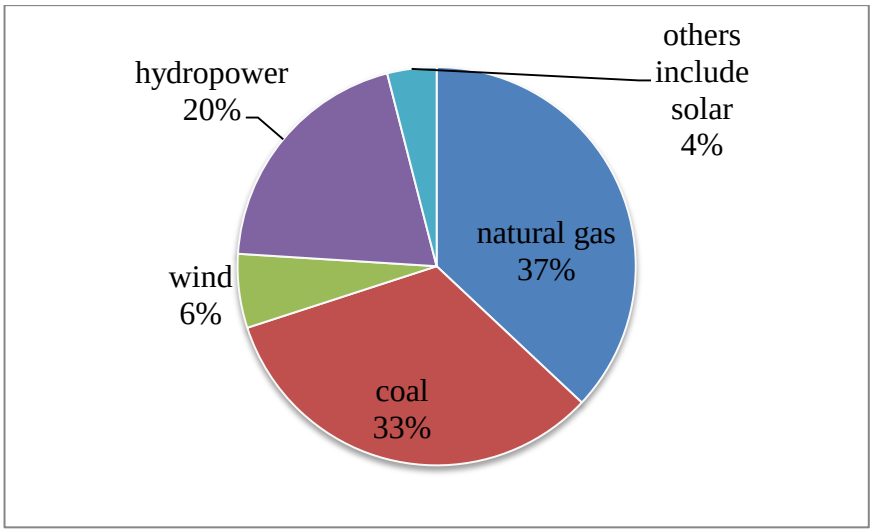


Figure 2.1 Percentage of each energy sources in Turkey.

2.5 Renewable Energy in Turkey

Turkey imports a huge amount of natural gas and coal to meet the increasing demand for energy. In 2017, the bill imports stood at 234 billion US dollars in Turkey while energy imports cost around 37.2 billion US dollar. Furthermore, the emission of CO_2 from electricity generation was 144.6 million tons in 2016 [26].

Turkey is located at 26º – 45º eastern longitudes and 36º – 42º northern latitudes, so it has a good prospect to get high benefit from renewable sources [27]. Turkey has the potential to benefits from different types of alternative energy sources such as wind, hydro, biomass, solar, and geothermal. These sources are indicated as the key factor to meet the problem of growing energy in Turkey. Turkey has a distinguished position in the solar energy market compared to some other European countries because of its geographic location. In order to expose Turkey's wind and solar energy potential, Turkey Wind Energy Potential Atlas (REPA) and Turkey Solar Energy Potential Atlas (GEPA) have been created by Electricity Affairs Survey Administration (EIE). REPA was organized in 2002 based on the General Directorate of State Meteorology Affairs (DMI) and the data from the EIE, the annual solar energy in Turkey yield as 1,527 kWh/m² (average 4.18 kWh/m^2 per day) and the annual period sunshine in Turkey identified as 2,741 h (daily average 7.5 h) [28].

Turkey is eager to use all forms of renewable energy sources. It laid down a plan that must be reached by the year 2030, limiting the use of traditional sources that Turkey imports in large and costly quantities, and reducing the emissions emanates from the conversion of fuel to electrical energy. Table 2.1 shows the renewable energy targets for electricity generation [29].

Table 2.1 Renewable energy targets of Turkey for electricity generation in MW [29].

Type	2017	2019	2023	2030
Biomass	27,700	32,000	1000	1000
Wind	9500	10.000	5000	20,000
Geothermal	420	700	1000	1000
Solar	540	3000	20,000	5000
Hydro	1800	700	34,000	34,000

2.6 Hybrid Energy System

Different renewable and non-renewable systems are used to generate electricity to meet the electrical load demand in buildings. The challenge of using renewable energy is the intermittency of the sources. Wind speed is not constant all times and the solar radiation change between day and night. Thus, the electric system that uses a single source is deemed as an unreliable system.

The integration of different energy sources such as WT, PV, conventional source, and energy storages is the key to solve this issue and make the system more reliable, which could help in overcoming the intermittency and make the system more reliable. This integration is called HRES [30].

The size of HRES depends on the load demand that the system should meet. The system with capacity between 0 and 5 kW is called small system. The system with capacity between 5 kW and 100 kW is called medium system and the system with capacity more than 100 kW is called large system. Table 2.2 explains the sizes with their general typical load [31,32].

Table 2.2 Types of HRES sizes.

Type	Size	Typical Load
Small	System < 5 kW	Telecommunication
Medium	5 kW < System < 100 kW	Small Remote Place
Large	System > 100 kW	Regional Load

There are standard procedures to connect different energy resources to produce a HRES. In general, there are three types of HRES which are AC-based system, DC-based system and AC-DC based system.

2.6.1 AC-based system

In this category, all energy sources are connected to the alternative current (AC) bus via either Power Electronics circuit or directly. Direct current (DC) sources such as PV is connected to the AC bus through converters because it generates DC voltage and should be converted to AC voltage while the AC sources such as WT are connected directly to the AC bus or to the power electronic circuit to control the energy flow. The load is then connected to the AC bus as shown in Figure 2.2.

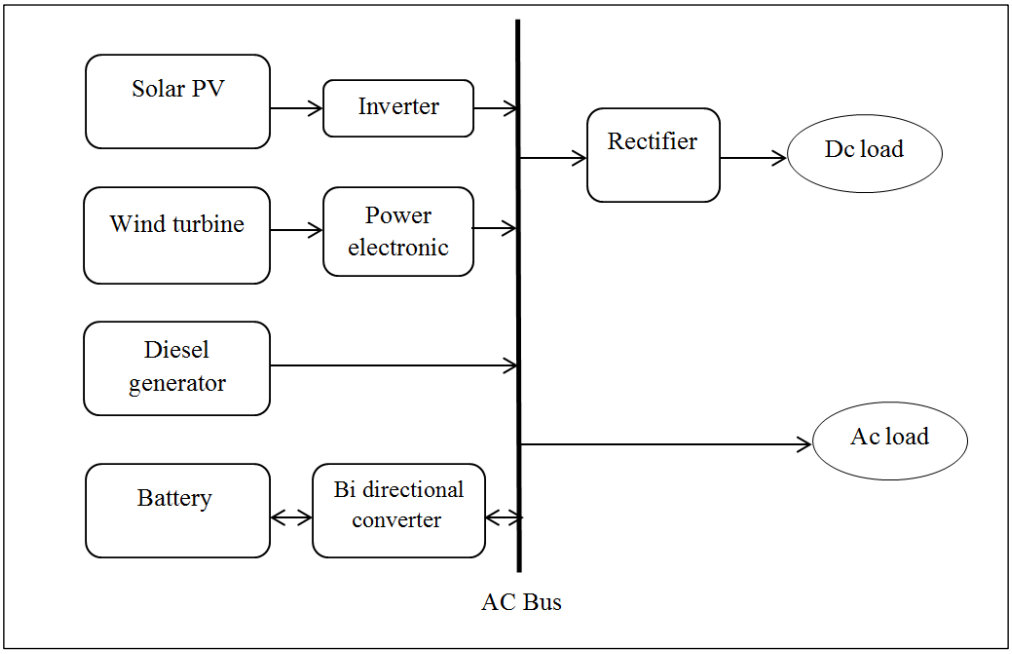


Figure 2.2 AC-based system.

2.6.2 DC-based system

In this category, all energy sources are connected to the DC bus. The AC sources are connected to the rectifier to convert the generated AC voltage into DC voltage. The DC sources are connected to the power electronic circuits to control the energy flow then connected to the DC bus. The load is connected to the DC bus through inverter because generally it works on AC voltage as shown in Figure 2.3.

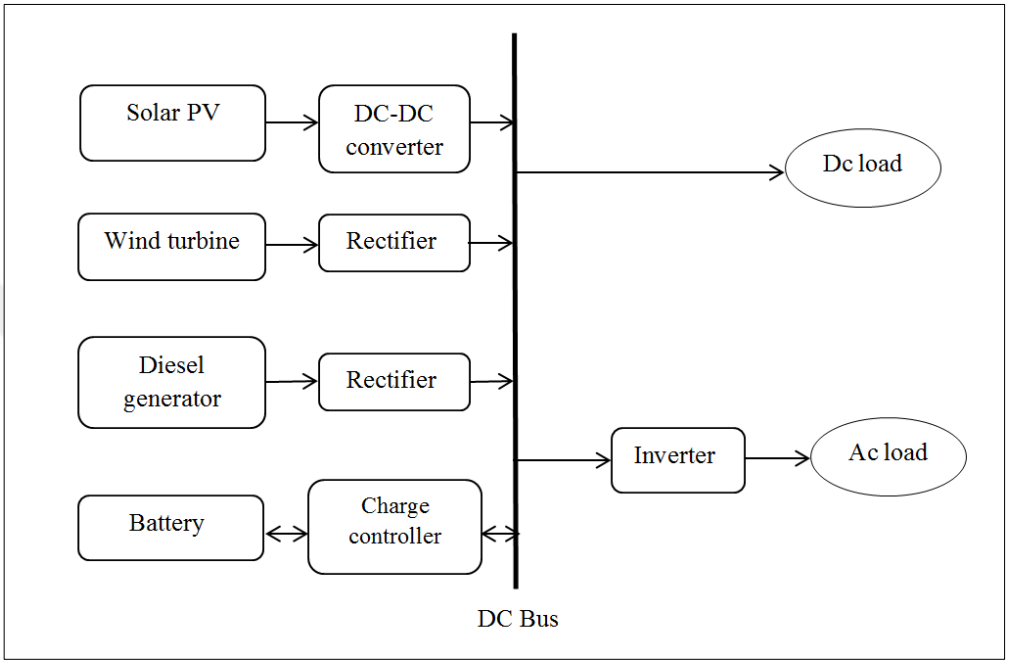


Figure 2.3 DC-based system.

2.6.3 AC-DC integrated system

In this type, both AC and DC buses are available. AC energy sources are connected to the AC bus and DC energy source are connected to the DC bus. The efficiency of this system is better than the single bus because some energy resources will be connected directly without power electronic device so there will not be any losses associated with these devices. The cost also will be reduced for the same reason. Figure 2.4 shows an AC-DC integrated system.

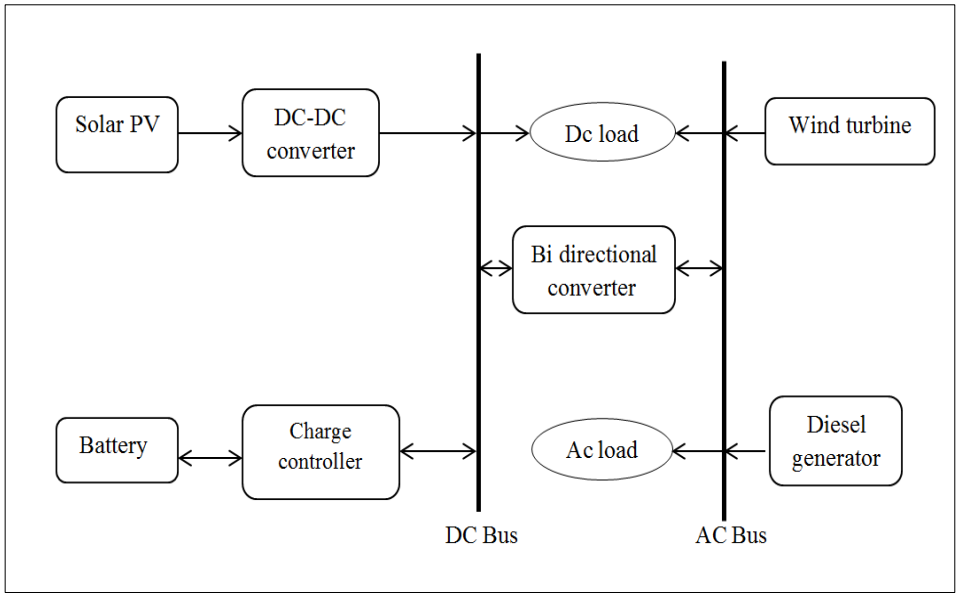


Figure 2.4 AC-DC integrated system.

2.7 Solar Energy

Solar energy is the main source of all energies in the universe, and unlike fossil fuels, it is widely available in all parts of the world. Solar energy is involved in many sectors that require the production of heat and electricity. It is considered as a clean source and does not cause any environmental pollution, so countries are seeking to exploit it appropriately to meet the growing demand for energy. With continuous technological development, the use of solar energy to generate electricity has become continuously increasing. The intensity of the solar radiation varies from one place to another as it depends on the geographical location of the region, the length of the day and the nature of the climate for the selected region [33]. There are many advantages and disadvantages regarding the solar energy that will be explained below [34].

2.7.1 Solar energy advantages

1. The sunlight is inexhaustible and always available all over the world.

2. It is easy to acquire and can be used for many applications such as electricity and heat production, and desalination especially in places where there is no clean water.

3. Low costs of maintenance. Despite the high costs of construction, the maintenance is available and cheap.

4. The continuous development in the field of nanotechnology and quantum physics will improve the efficiency and effectiveness of solar energy generation systems in the future.

2.7.2 Solar energy disadvantages

Although solar energy has many advantages, there are some unfavorable aspects associated with it, including:

1. Not being able to take advantage of it in the evening, so there must be a device to store the energy like battery.

2. It is necessary to provide vast area to collect the large amount of solar energy to make full use of this energy.

2.7.3 Photovoltaic technology

PV is a device that converts the sunlight into electricity. It consists of several small parts called solar cells or photovoltaic cell. Solar cells are an essential energy provider as they do not need chemical reactions or fuel to produce electrical energy, and unlike generators, they do not have any moving parts. Solar cells may exist in the form of small designs called a solar model that is used in homes to replace the traditional energy source. These panels are used in many remote geographical locations that are difficult to provide traditional energy sources for them. Usually, the PV provides around 12 or 24 Volt in DC form. Solar cells may be in the form of large groups called array so that it consists of several thousand individual cells [35]. Figure 2.5 shows the exploded view of a PV array which consists of several individual cells.

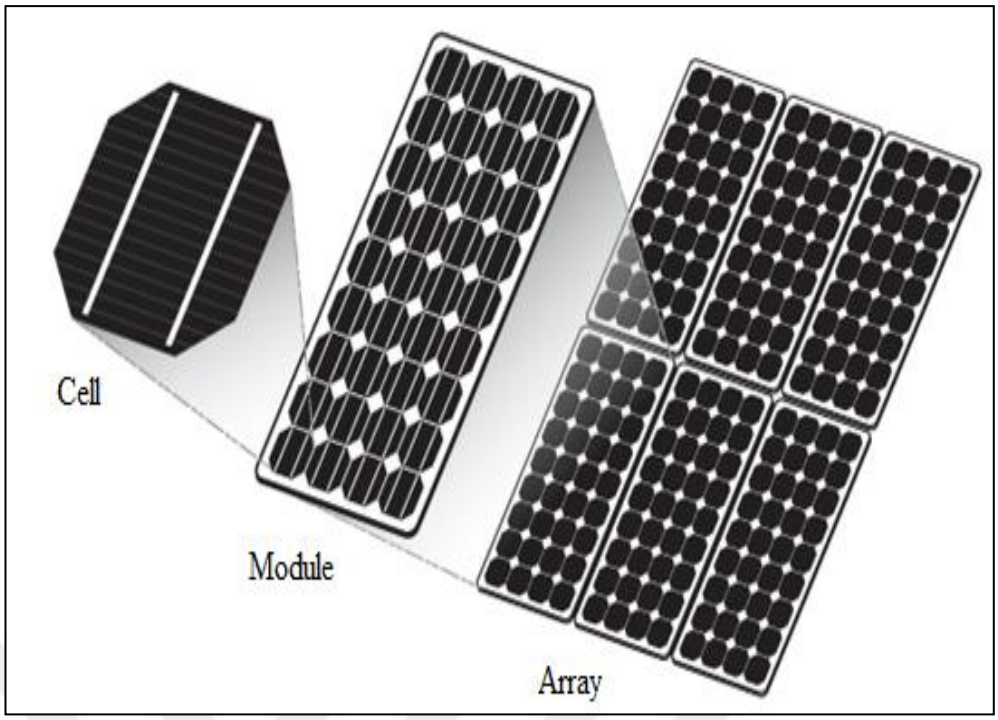


Figure 2.5 Cell to PV array [36]

Solar cells are used to supply solar energy for industrial, residential, and commercial complexes. Either they are connected to the network, or they are separated, especially in remote areas. Solar cells contain semiconducting materials that have the ability to convert light into electrical energy, such as silicon. It also contains two electric layers, positive and negative. The positive electrode is located on the front layer of the cell, while the negative electrode is located on the posterior side of the cell. These two layers transfer the electrical charges generated in the cell. There is also an anti-reflective layer added to the cell to reduce light reflection and take advantage of incident light as much as possible. Figure 2.6 shows the cross-section of a solar cell [37].

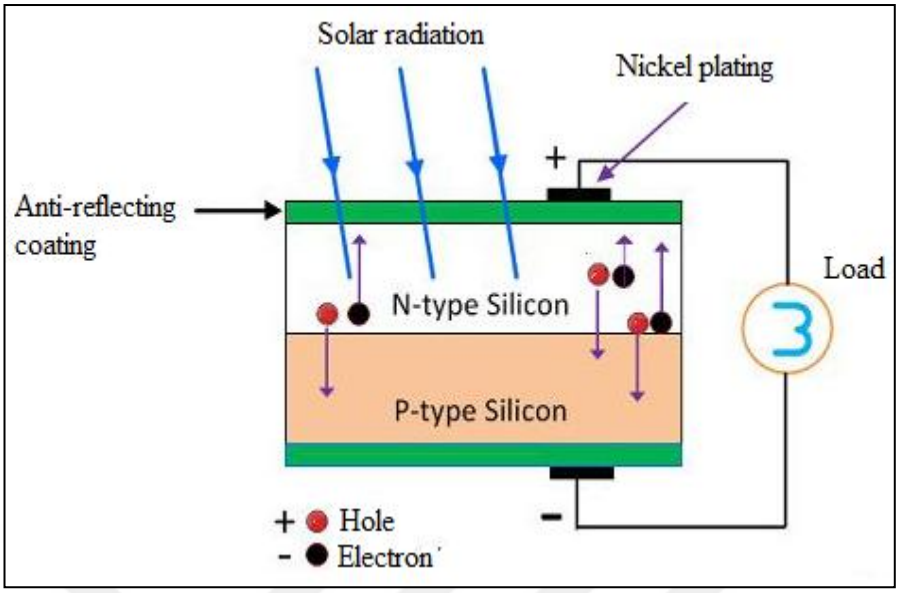


Figure 2.6 Cross section of a solar cell [37]

In general, PV panels are used in ground-mounted and roof-top. Installation tracking system with panels gives maximum energy by tracking the sun, and this increases the direct exposure of solar panels. The major types of tracking systems are zero-axis fixed tilted, one-axis south-north tilted tracking, one-axis (north-south or east-west) horizontal tracking, one-axis vertical tilted tracking and two-axes tracking as shown in Figure 2.7. Due to the existence of extra movable electronic parts in the tracking system, the initial cost of the project as well as cost of maintenance is high [38].

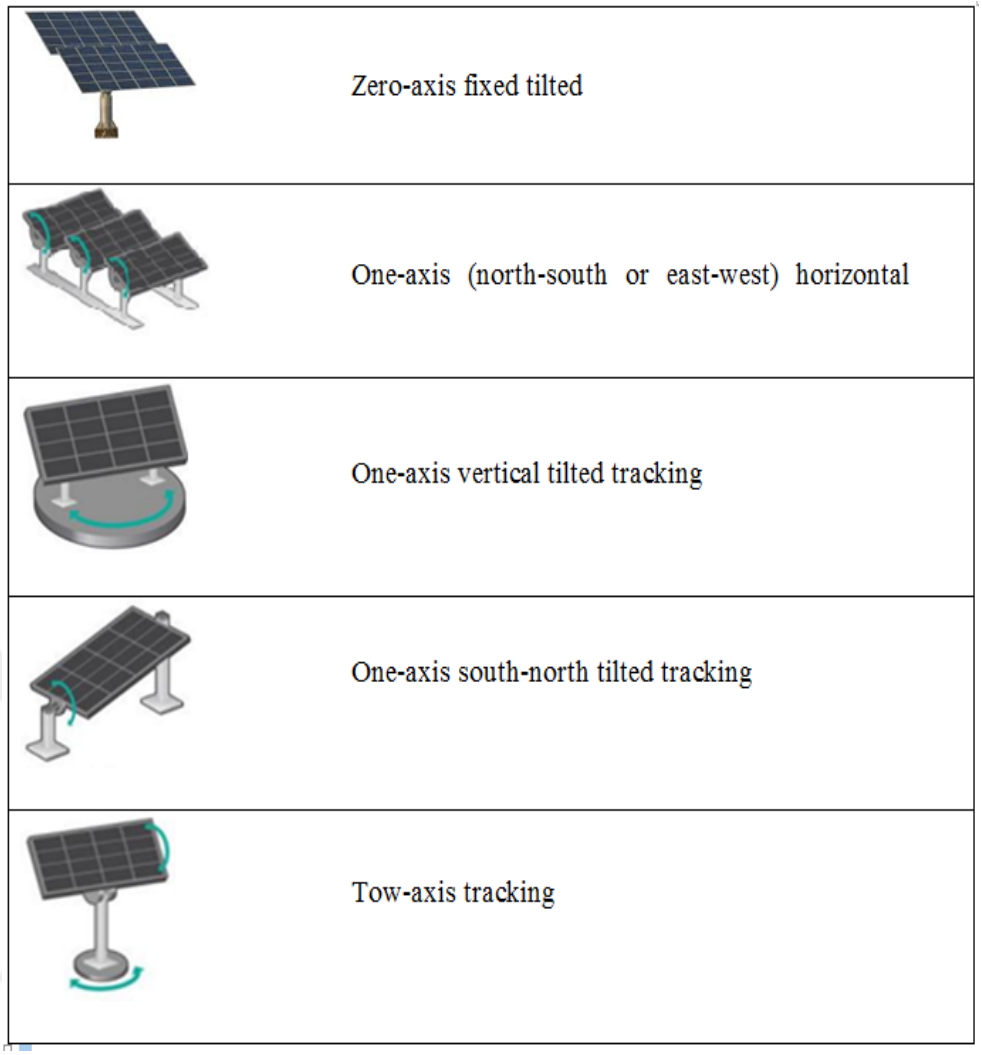


Figure 2.7 Major types of tracking systems [38].

2.8 Wind Energy

Wind energy is a kind of renewable energy in which the turbine converts the wind kinetic energy into mechanical energy and then to electrical energy through electrical generators. It is an indirect form of solar energy resulting from a group of factors that include asymmetric heating of the atmosphere, which causes the air in the atmosphere to move in a certain direction. Its speed depends on the amount of pressure difference between the two points. Wind energy is a form of renewable energy, which can be used to provide electricity for homes, schools, and large cities [39].

Wind energy has a set of properties, divided between positive and negative [40].

2.8.1 Advantages of wind energy

- Wind energy is free energy that is not subject to restrictions. This energy does not need special methods to extract.
- Once WT are installed, the energy generated does not emit pollutants or greenhouse gases.
- The area used from the land is very small, and this means that the land under the WT can be used for other functions especially for agricultural purposes.
- In remote areas where there is no electricity supplier, WT can be built to provide electricity, as it is an easy source for generating electricity.
- WTs are available in several sizes and this means that they can be used in many fields and businesses such as in homes and villages.

2.8.2 Disadvantages of wind energy

- The wind speed is not fixed, it changes from time to time, and this means that WTs do not generate or produce the same amount of electricity all of the time.
- It causes inconvenience due to its loud sound while spinning.

2.8.3 Wind turbine

WT is a device that converts wind energy into mechanical energy, which can be used for specific tasks such as grinding grains, pumping water and the generator can convert this mechanical energy into electricity [41].

The most important components of WT are as follows [42,43]:

- Fan blades.
- An electrical generator that converts kinetic energy into electrical energy.
- Brake that stops the fan when very strong wind or storm occurs.
- The hanging room contains a power transformer and other devices, including a transmission.
- An electric motor that directs the WT.

- Control electronic that changes the placement of the blades axially and turn the suspended compartment through the electric motor, so that the suspended compartment takes the optimal direction to benefit from the wind.

Basically, air collides with the turbine blades and rotates them. Consequently, this rotational movement revolves the connected engine, generating a quantity of electrical energy commensurate with the speed and strength of the wind. There are devices to measure the wind speed and direction and an electric motor that moves the fins to make the most of the wind according to its direction. The resulting electrical energy is saved in batteries. The stronger the wind, the more electrical energy is generated. However, the turbine contains a brake, which controls the movement of the fins and stops them completely when the wind intensifies greatly [44, 45].

WT can be built on land or in the sea in large water bodies such as oceans and lakes. It requires varying areas depending on the size of the station and the type of towers used; thus, it is not recommended to place WT in urban areas due to the presence of obstacles that prevent taking advantage of good wind speeds. Large fields of electrical energy production by WT are spread around the world in countries such as Denmark, USA, Germany, Spain, China and India. These and other countries are also planning to establish offshore fields.

There are two general types of WT in the world they are horizontal and vertical axis WTs as shown in Figure 2.8. The horizontal one has two or three blades facing the wind and is considered the most common type today, while the unpopular one is the vertical WT with blades that extend from the top to down. The size of these WTs varies between large and small according to their production capacity. The small turbines are used to generate electricity for homes or companies. The large turbines are put together on a large place to form wind farms [46].

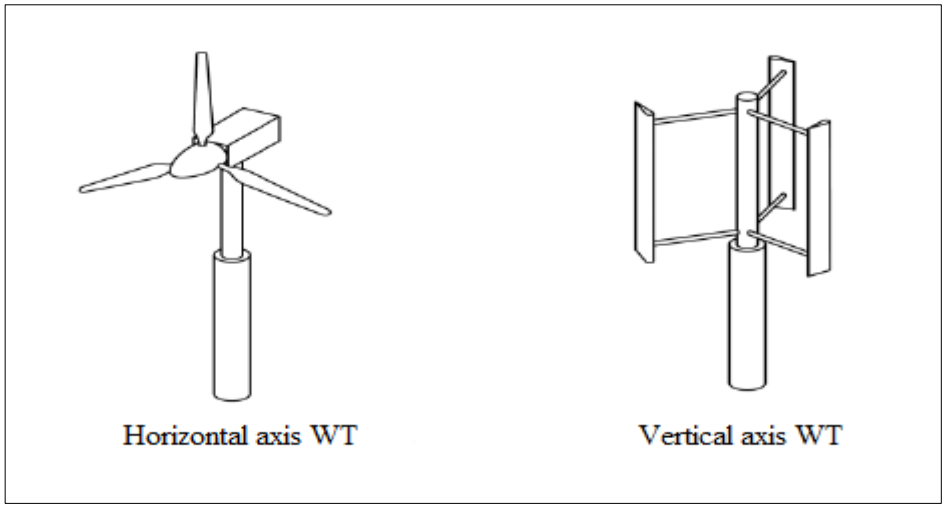


Figure 2.8 Horizontal and vertical axis WTs [47]

2.9 Energy Storage

It is well known that the search for energy storage methods is a matter that worries scientists in the modern era more than anything. Energy storage means to save energy produced at a specific time and utilize it in another time. Energy storage device is used to save the excess power during low load demand period to another peak period. For example, the solar irradiation and wind speed vary from time to time during the day. Thus, in HRES, both the load and generation change throughout the day. These changes may affect the power distribution, the frequency and the voltage. The distribution of power can be assisted by increasing the storage element. The energy storage can be a generator or load depending on the demand to supply [48]. In energy storage, the first step is to convert it into a storable energy form, then transform it to the desired energy as shown in Figure 2.9 [49].

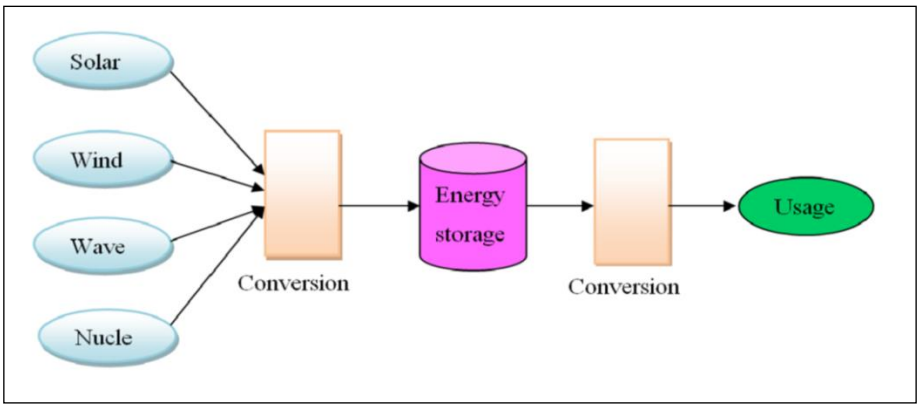


Figure 2.9 Electric storage scenarios**.**

Generally, there are four main categories of storage technologies which are electrochemical process, mechanical process, thermal processes and electromagnetic process. Some of them are used for short-term such as the electric battery and some of them for long-term such as water dams. Figure 2.10 shows some of the main storage technologies currently being used in different applications.

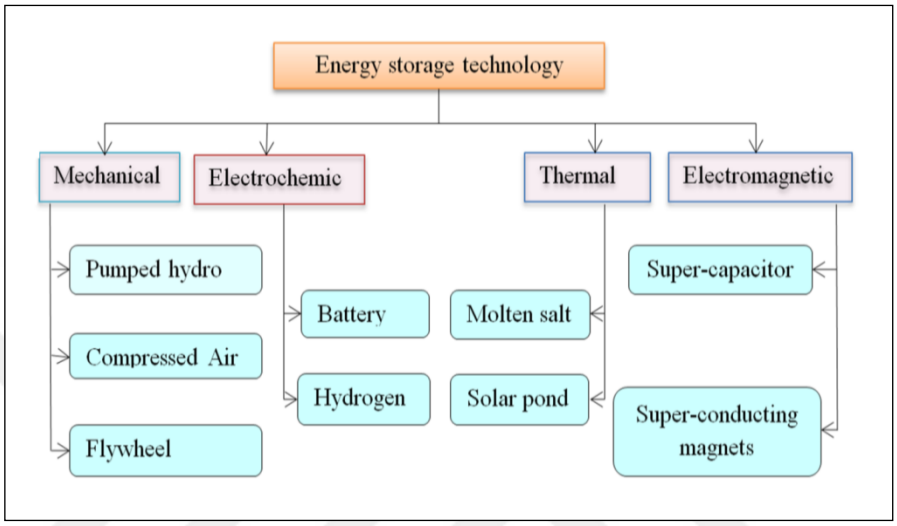


Figure 2.10 Main storage technologies.

Some of the available energy storage technologies are also explained below.

2.9.1 Hydrogen

Hydrogen is one of the newest methods of energy storage; nonetheless, it is flawed by the high cost of its use in storage. The strategy of using it in energy storage depends on electrolyzing water electrically to its primary chemical elements and store it as a primary chemical carrying energy. It is characterized by its ability to produce high energy and lightweight. It can also be stored in the form of liquid hydrogen such as that is used in the space shuttle. However, it needs high energy for Liquefaction process, as well as well-insulated containers for storage, which increases the overall cost of the system. Hydrogen can also be stored in a compressed form in light tanks. But it is more dangerous compared to the case where the hydrogen is stored in liquid form [50].

2.9.2 Air storage

One of the old ways for storing energy is to use excess energy to compress the air and pumps it into the underground caves (tanks). This compressed air is being

released again to generate electricity when the demand for electricity increases. This method still needs to overcome some of its drawbacks. First, the energy generated is less than the energy consumed in the storage process. Second, storing air underground is complex and costly process that requires to heat the air before it is compressed [51].

2.9.3 Hydroelectric stations

Currently, hydroelectric plants are one of the newest and best methods of energy storage in the world. They depend on kinetic energy by converting them into electrical energy. Storing energy in hydroelectric stations depends on the use of surplus electrical energy produced in the stations to raise water to large tanks that are created on mountain slopes or high plateaus, which are retrieved when they are needed to generate electricity through its slope to fill the deficit in electricity. This method remains the newest, cleanest and best energy storage method, characterized by high storage efficiency of about 80% [51].

2.9.4 Fuel cells

It is a method that has an excellent capacity to generate electrical energy. It mainly depends on generating electricity from the interaction between oxygen and hydrogen gases. It was used in space vehicles and can be used in cars but it is still not very widespread method due to its high cost [51].

2.9.5 Electric batteries

The battery is one of the best possible solutions in energy storage as it refers to the process of converting energy from one form (mainly electrical energy) to another form that can be stored and then converted to electrical energy when needed. The basis of storing electrical energy in the battery is the recharging of the battery after its exhaustion, which is the reason for its distinctiveness and use in several applications. The battery is generally a group of similar electrochemical cells. The oxidation and reduction reactions that occur within them lead to the conversion of energy from electrical to chemical energy, or from chemical to electrical energy (charging and discharging). The batteries have a high energy efficiency approximately in the range of 60-95% [52]. This method contains many benefits, including:

- Helping electrical energy sources in supplying electricity for the required load at peak time.
- Reducing the problem of fluctuation in renewable energy sources.
- Using them in electric vehicles and meet their need for long distances.
- It is included in the smart electrical networks that researchers seek to develop.

Deep charge batteries are used in on-grid and off-grid HRESs, as well as multiple industrial and marine applications. These batteries are designed to be charged in the full sun period and high wind speed and then discharge them overnight. Deep charging batteries can charge or discharge in a long time and low current [53]. Most commonly used rechargeable batteries in hybrid systems include [54]:

- Lead acid battery (LA)
- Nickel cadmium (NiCad) battery
- Nickel metal hydride (NiMH) battery
- Lithium ion battery (LI)
- Lithium-polymer battery
- Zinc flow battery (ZF)
- Vanadium flow battery (VF)

Brief overview about different batteries and their unique properties are described below.

2.9.5.1 Lead acid battery

It is one of the most famous batteries used in renewable energy systems. It was invented by the French scientist Gastone Plate in the year of 1859. It is considered to be simple and in most cases produces the cheapest COE per kW in electrical systems compared to other storage systems. It also has the advantage of being able to charge and discharge, but cannot be fully discharged because that affects its lifetime. It is used in various applications because of its flexibility and ease of handling [55].

There are two technologies used in the LA battery which are Gel version and Absorbed Glass Mat. Both of them have achieved success in developing the battery efficiency and lifespan [56].

2.9.5.2 Lithium ion battery

The lithium battery is considered one of the most used batteries, especially in electronic devices such as headphones, smartphones, computers, and hand watches duo to its small size and high energy density. This battery is excellent in the field of energy storage, so it is being developed greatly for the use in hybrid cars as well as it can be used in modern electric systems. Researchers strive to reduce manufacturing maintenance costs and they try to increase its safety [57].

2.9.5.3 Nickel-Cadmium (NiCad / Ni-Cd)

This battery is a rechargeable battery and utilizes nickel oxide hydroxide, cadmium and metallic cadmium as electrodes. This type of battery is characterized by its long lifetime and light weight. Nickel-Cadmium battery also has a constant voltage potential throughout its lifetime and has the ability to adapt with variable temperatures. Therefore, it is used in different applications and in renewable energy technology [55,58].

2.9.5.4 Flow Batteries

In flow batteries, the electrolyte is usually stored externally in tanks and then flows either by pumping or gravity. The chemical energy is converted directly to electrical energy by the electrochemical cell in the reactor. These batteries have low energy density and have a high self-discharge rate. Since there are several parts in these types of batteries, they are more sophisticated and require advanced controls, precise sensors, and appropriate pumps [59].

Two types of flow batteries are explained here,

- Redox Flow Batteries
- Hybrid Flow Batteries

2.9.5.4.1 Vanadium Redox-Flow

The Vanadium Redox Flow is an important new generation of power storage units as it is an example of a redox flow battery. Typically, the cell in the redox flow battery

contains two electrolytic fluids, one is negative and the other is positive. During the charge or discharge, they flow through the cell from the outside, separating them by a permeable membrane of ions. The electrolytic fluids are kept in two separate reservoirs outside the cell. Therefore, they are less exposed to combustion and high temperature. When the two fluids are pumped into the cell, the ion exchange between the anode and the cathode through the membrane causes circulation of current and the flow of electrical power. The capacity of the battery is directly related to the size of tanks. This type of battery is included in the grid energy storage and renewable energy applications [60-62]

2.9.5.4.2 Zinc bromine battery

The ZB battery is a hybrid battery as it is a kind of flow battery with one fuel cell electrode and one battery electrode. One or more electroactive components are placed on the electrode of the battery during its operation. In redox flow battery, the power and energy are fully decoupled, while this is not possible in hybrid flow battery. The size of the electrode can affect the energy of these batteries. These batteries consist of two tanks, one for the negative electrode reactions and the other for the electrolyte for the positive electrode reactions. They have some advantages, for example, they have high energy density, can be operated up to 100% SoC, and have more than 2000 cycles [55,63].

2.9.5.5 Battery specifications

In order to choose batteries that are suitable as energy storage for the system, battery specifications must be known. Among those specifications, some important ones will be explained below[64-66].

2.9.5.5.1 Battery voltage

The voltage is the difference in the magnitude of electrical energy (electric potential) between the poles of the battery. It is also known as the driving force of electrons from the negative electrode to the positive electrode. The unit used to measure the electrical voltage is the volt.

2.9.5.5.2 Charge voltage

It represents the lowest value of voltage required to charge the battery. It depends on the properties of the battery. For example, the battery with a voltage of 12 volts requires a charging voltage between 13.2 and 14.4 volts to charge them well.

2.9.5.5.3 Battery capacity

Capacity is one of the most important specifications of batteries. It is the value that we look for when calculating solar batteries. It represents the amount of energy that can be stored in the battery. The unit of measurement for the battery capacity is Ampere hour (Ah or amp hr), which is the product of the current used (in amps) and the time required to discharge the battery (in hours).

We should also know that the temperature affects the capacity of the battery. Battery capacity is better in summer than in winter. This is because chemical reactions are usually faster at higher temperatures. We can know the battery's capacity as its ability to transfer a specific value of current within an hour.

2.9.5.5.4 Depth of discharge

Most batteries need to maintain a certain percentage of energy all the time due to the chemical elements that are installed in it. When using 100% of the capacity of the battery, this will cause a remarkable decrease in its operating life.

2.9.5.5.5 Battery life

Like all rechargeable batteries, the batteries used in hybrid systems charge and discharge almost daily. The more batteries are used, the lower their ability to maintain electricity. The battery life is estimated by the number of charge and discharge cycles that the battery can go through before its ability to conserve electricity is diminished.

2.9.5.5.6 Battery efficiency

The battery efficiency represents the amount of energy that can be used as a percentage of the energy that was stored. For example, if the battery is fed with 10-kilowatt hours of electric energy and produced 9-kilowatt hours of useful energy, it means that the battery efficiency is 90%.

2.10 Bidirectional Inverter

A bidirectional inverter is one of the most essential parts in the HRES system which the system cannot work without it. It works in two ways between the generation sources and batteries. It can be used to transfer the electrical power energy in two directions. It can work as a rectifier when it charges the battery by converting the AC voltage to DC voltage while it can work as an inverter to supply the electricity to the load by converting the DC voltage to AC voltage [67].

2.11 Existing Studies on Different Systems

Several researches were conducted to optimize and design of different generation systems in buildings. Some researchers focus on on-grid systems while the other studies are concerned with off-grid standalone systems. There are several studies concerned on internal structure of the building, while the other studies focus just on the aspect of electrical energy required. Since this study is concerned with meeting the energy needs of buildings, studies related to this aspect will be taken into consideration.

Interconnection of different non-renewable and renewable energy systems such as PV power, fuel cell, wind power and DG to meet energy load demand decreases the use of fossil fuels. HRES will be the best option for modern electrical systems in ZEB The advantages. include environmental, economic and social advantage [68]. Many types of research are focused on HRES by combining two or more sources around the world.

Prasad, Reddy and Saibabu [69] analyzed the buildings energy consumption and how these building can be a ZEB with the combination of different renewable energy sources. The results indicated that the renewable energy technology is the best option for ZEB.

Nag and Sarkar [70] studied the economic feasibility of a single source and different sources to provide electricity for a remote area in India. The result indicated that the combination of different sources is more reliable than single-source renewable energy.

Mohammed, Amirat, and Benbouzid [71] optimized off-grid WT/Tidal/PV/Storage HRES using Genetic Algorithm (GA) in Brittany/France. The objective function was

to reduce the cost of HRES model. The load demand was suggested to be covered under different climate conditions with the total life of the project which is 25 years interval with different solutions and cases respecting many constraints. As a result, WT/Battery system was the optimum system in the studied area. The optimal system was seen to be sensitive to many variables such as load data, weather data and location.

The same authors [72] used Particle Swarm Optimization (PSO) algorithm to find out the optimal standalone system from a combination of PV/WT/Tidal/Battery to satisfy the load demand of Brittany/France. The PSO was improved to minimize the cost and get high reliability of the system optimally with less time. Results showed that the optimal system in the studied area was consisted of WT/Battery due to the high wind speed in that place. Furthermore, the improved PSO algorithm was able to solve any complex or non-linear problem to find out the most suitable solution.

Ghafoor and Munir [73] studied off-grid PV/Battery system to supply electricity for a single household in Faisalabad/Pakistan. The load profile and solar energy availability were considered for system design. The result indicated that the cost of energy (COE) that proposed by PV/Battery system is less than the COE of the conventional grid in the studied area. This model can be used in any geographical location in the world to assess the economic feasibility of PV/Battery system. The result also showed that off-grid PV electricity is economically and technically viable technology for supplying electricity for residential application under the weather conditions of Pakistan.

Kharrich, Mohammed, and Akherraz [74] studied the techno-economic analysis of PV/WT as renewable sources and DG/Battery as a backup to supply electricity for a house. The case study has been done in Baghdad and Rabat to find out the optimal economic system. The results showed that the using of the micro-grid hybrid system in Rabat is less economic than the one used in Baghdad with the same load due to the high renewable sources in Rabat. In their study, temperature effect that reduces the PV output was not considered.

Movahediyan and Askarzadeh [75] designed PV/DG system to supply electricity for isolated communities by using multi-objective framework. The operating reserve was used to ensure the reliability of the system despite variability in PV power supply

and load. To have a clean, reliable and cost-effective power generation system, three objective functions were considered which were CO_2, net present cost (NPC) and loss of power supply probability (LPSP). The sizing was done by using multi objectives crow search algorithm and validated the result with multi objectives particle swarm optimization algorithm. The result indicated that PV/DG system is a clean, reliable and cost-effective system. It also showed that the price of fuel for the generator is very important and can affect the sizing of the system.

Mohammed Kharrich, Mohammed, and Akherraz [76] Studied the chance of using the renewable energy sources to install renewable energy technology in different places in Morocco by addressing the economic assessment of the sources. The study aimed to find out the economic cost and optimum size of HRES at six sites in Morocco by using PSO. Depending on the results, the tidal energy is not suitable in all studied regions because of the low speed of tidal. The WT/PV system was the best combination comparing with the others because it was a cost-effective system, especially in Dakhla. Because of the high solar radiation, a PV panel was a promising component to use in the electricity production in Morocco.

Shezan et al. [77] compared between conventional and renewable energy power system in terms of NPC and CO_2 emission. Hybrid Optimization Model for Multiple Energy Resources (HOMER) software was used to analyze the off-Grid WT/PV/DG/Battery HRES. The result indicated that the optimized system can reduce the CO_2 emission and NPC by 16 tons and 29.65%, respectively.

Haratian et al. [78] designed an off-grid PV/WT/Battery system to supply electricity to renewable laboratory in KhshU site/Iran. Data for wind speed and solar radiation of that place were used. The result pointed out that the configuration of the PV/Battery was more economic than WT/ PV/ Battery.

Vendoti, Muralidhar, and Kiranmayi [79] optimized WT/PV/DG HRES to electrify a rural village in India. The study aimed to minimize the COE and NPC of the system using HOMER software. Results indicate that PV/DG system gave a good solution for that area.

Chouaib, Messaoud, and Salim [80] designed and simulated PV/WT/DG HRES to electrify a village of Timimoun/Algeria by using Matlab/Simulink. The results showed that the DG production was less than the PV and WT production. The

fraction of renewable energy was 68% and all the load of the village was covered properly.

Shahzad et al. [81] analyzed techno-economic study of standalone PV/Biomass system for a residential community and farm in Punjab/Pakistan. The result showed that the use of the proposed system is a cost-effective and reliable option for the studied area.

Iemsomboon, Pati, and Bhumkittipich [82] studied the feasibility of WT/PV/Hydropower system to meet the load of a rural school in Thailand. The researchers found that the proposed system was economically and technically suitable.

Aziz et al. [83] optimized off-grid hybrid energy system to electrify a safari camp in the United Arab Emirates (UAE) by using HOMER software. After trying many different HRESs, the result indicated that the PV/battery is the best choice to provide electricity on that site.

Aziz et al. [84] studied the environmental and economic feasibility analysis of the off-grid HRES in Iraq. HOMER was used to find out the optimum system among five cases. The cases are proposed based on hydro, PV, DG, and battery. The optimal system that was consist of 13 kW PV, 5 kW DG, 14.7 kW Hydropower, 9 kW converter and 8 unites of batteries. The renewable fraction was 91.3%, NPC was 113201 $ and fuel consumption was 6444 L.

Ciez and Whitacre [85] performed techno-economic analysis of PV/DG/Battery HRES with three different batteries. The result showed that the LI batteries were able to provide lower power cost with a high discount rate, while the LA batteries were useful with lower discount rate.

Bhakta, Mukherjee, and Shaw [86] used HOMER software to analyze the techno-economic performance of PV/WT/ Battery HRES for the island of Lakshad weep/India. Three scenarios were used which were PV/Battery, WT/ Battery and PV/WT/Battery. It was concluded that the standalone PV/WT/Battery HRES was more economical than WT/Battery and PV/Battery Systems.

Lozano et al [87] performed the techno-economic analysis of PV/DG and solar only to find out the optimal system to provide electricity for Gilutongan Island by using HOMER software. Results indicated that the PV/DG hybrid system could reduce the COE to 0.3556 $/kWh. Solar only and PV/DG systems could reduce the COE by around 68–70%. The payback period was about 1.7 years.

Mamaghani et al [88] studied the probability of using renewable energy systems in three independent villages in Columbia. Techno-economic feasibility of PV/WT/DG/Battery HRES was studied. The input data was the climatic characteristics of the studied villages. The results indicated that the PV/WT/DG HRES was the best selection with COE of 0.473 $/kWh and NPC of 836,210 $ in Puerto.

Aghajani, Shayanfar, and Shayeghi [89] optimized and planed different micro-grid systems to supply electricity for a residential building, remote village and business building in Chhattisgarh and Palari/India. PV/WT/Biodiesel generators are used in the proposed system. HOMER software was used to find out the optimal system configuration which can meet the load with the least cost. LA battery was used as backup storage for the system. The result indicated that the price of electricity of a system that includes DG is less than the price of electricity with full renewable sources. They pointed out that that the availability and type of resources can affect the COE.

Dhundhara, Verma, and Williams [90] performed techno-economic study for different configurations of micro-grid system with two types of batteries which were LA battery and LI battery. Real meteorological data, real price of components and real load were used to compare between the two types of batteries. Load profile of a business organization, urban building and two rural villages were used. Different scenarios of micro-grid were done to get the performance of batteries. The result indicated that the LI and LA batteries are very important to be used in the electrical power systems in the future.

Baneshi and Hadianfard [91] performed the techno-economic analysis of PV/WT/DG/Battery HRES for a big city in Iran. The average daily consumption of the city was 9900 kWh and peak load was 725 kW. Based on economic, environmental and technical analysis, HOMER software has been used to design the

system and find out the optimal configuration that can cover the load demand. Both on-grid and off-grid systems were designed. The governmental policies like low interest for the renewable project, annual growth of load, carbon tax and grid prices were taken into account. From the results, PV/WT/Battery was suitable configuration to supply electricity for the studied area.

Ramli, Hiendro, and Al-Turki [92] discussed the feasibility of different off-grid systems to find out the optimal system to supply electricity for Yanbu/Saudi Arabia. HOMER software was used for simulation. Due to the high solar radiation of the selected place, results pointed out that the solar energy cost is less expensive than the wind energy cost.

Kalinci [93] used HOMER software to design HRES to electrify the island of Bozcaada /Turkey. The study considered an on-grid and off-grid connection. The system consisted of PV/WT/electrolyzer/hydrogen storage/fuel-cell and converter. Many configurations were simulated to find out the optimum system according to COE and NPC. As a result, in the off-grid scenario, PV/WT/FC was the optimum system with 0.836 $/kW, while in the on-grid scenario, grid/wind with 0.103 $/kW was the optimum system.

Grande et al. [94] introduced the techno-economic analysis of PV/Battery off-grid system to supply electricity for electric vehicle charging stations. The load shifting principle and the meteorological data of Madrid/Spain were applied using HOMER software. In order to verify the reliability and the effectiveness of the studied system, the efficiency of the result has compared with grid-connected charging stations from both environmental and economic aspects. The obtained results demonstrated that the PV/Battery off-grid system is technically and economically viable option. Moreover, it is profitable and could reduce air pollution.

Ajlan, Tan, and Abdilahi [95] investigated the optimization and sensitivity analysis of off-grid HRES to meet the load demand of a small village in Yemen. Five different combinations of energy sources were used with a key objective to find out the optimal system that achieves the minimal cost of the system and environmental population. The results indicate that the combination of PV/WT system could reduce the CO_2 emission with 100% and COE with 30%. Comparatively, the combination of

PV/WT/DG system could only reduce the CO_2 emission with 70% but the COE with 45%.

Khan et al. [96] performed a techno-economic analysis of many combinations of HRES to supply electricity for telecommunication applications in many cities of Punjab, India. The peak load was 1.3 kW and the combinations of the systems were studied in all cites. The optimal system has been obtained with WT/PV/DG/Battery systems with 0.162 $/kWh energy cost.

Das et al. [97] analyzed the potentiality of using the renewable energy system to electrify remote village consisting of 50 houses in the east of Malaysia. Both systems, PV/Battery and PV/Battery/FC were analyzed and then compared with the DG-based system. The result indicated that the PV/Battery system is more economical and environmentally friendly than the others with the COE of 0.323 $/kWh. It can be an appropriate replacement system for the DG-based ones.

Mohammed, Amirat, and Benbouzid

[98] studied a multi-optimal combination of standalone HRES to meet the load demand in Tioman Island/Malaysia. This place had been studied by Ashourian et al [99]. In both studies, similar cases (large resort centre and island resorts) were investigated which are affected by tourism flows, and WT/PV/DG/Battery hybrid system was selected as the optimal system.

Al-Sharafi et al [100] performed different off-grid renewable energy technologies to meet the load demand of a typical house in five different locations with different climatic parameter in Saudi Arabia. The study aimed to identify cost-effective configurations. The optimal system in Yanbu was found to be PV/WT/Battery generation system with a minimum COE of 0.609 $/kWh. Replacing the battery bank by a combination of fuel cell, electrolyzer and hydrogen tank storage system is possible, but the cost would increase due to the cost of the system components.

Bentouba and Bourouis [101] studied the opportunity of replacing the DG-only system with hybrid generation system to reduce the COE and carbon emissions. The study was done to meet the load of 200 houses in Timiaouine town/Algeria. This town is not connected to the grid. The optimization results showed that the system consists of PV/WT/DG/Battery configuration can supply 100% of the electric

demand with 0.176 $/kWh COE and carbon emissions was reduced by 593.125 tons/year.

Fazelpour, Soltani, and Rosen [102] investigated the techno-economic feasibility of using HRES systems to satisfy the energy required for a household in Tehran/Iran. The average load that should have met was 17 kWh/d and the peak demand was 1.5 kW for the considered house. Among five different combination systems (PV/WT/Battery, PV/WT/FC/H_2, WT/FC/H_2, WT/FC/Battery+H_2, WT/Battery), WT/Battery/H_2 system was the optimal system that can meet the load demand.

Chade, Miklis, and Dvorak [103] compared DG-only systems with the same system but supported with WT and hydrogen energy storage to cover the load demand of 40 buildings in Grimsey island/Iceland. The wind resources and electrical load consumption are used to size the system components. The optimization result showed that the infrastructure of the proposed system might be suitable, and the period of payback was below 4 years for the system.

Kim et al. [104] investigated the feasibility of HRES from the environmental, economic and technological sides to discover the optimal standalone and grid connected systems in Jeju Island/South Korea. The simulated system composed of an existing grid system, renewable energy and DG. The simulation analysis found that on-grid PV/WT/Battery and off-grid PV/WT/DG/Battery systems have the lowest COEs.

Different studies of HES with various energy sources, configurations and batteries have been done by various researchers. Table 2.3 outlines the type of configurations, COE, battery types, location and the technique of some studies which were done in recent years. PV, WT, DG and biogas are commonly used in these studies.

Table 2.3 Different types of configurations, COE, battery types, location and the technique used in the literature.

Ref.	Year	Technique	Location	System	Battery	Load	COE ($/kWh)
[105]	2016	HOMER	Tamil Nadu/ India	WT/PV/Hydro	LA	Household load	0.11
[106]	2015	HOMER	Tehran/Iran	PV/WT	BULL-BLOC-Battery	Office building	1.54
[107]	2018	HOMER & PSO	Barwani/ India.	(WT/PV /Bio/DG)	LA	Residential/Village	0.289
[108]	2017	HOMER	New Delhi/India	On-grid PV	LA	time of day (ToD) tariff	-
[109]	2017	HOMER	New Delhi/India	WT/PV/DG	LA	Engineering faculty	0.104
[110]	2017	RET-Screen	Bisha/Saudi Arabia	PV	With/ without battery	Grid	-
[111]	2017	HOMER	Bangladesh	Biogas generator (BG)/PV/	DG/ LA	Village	0.28

				DG			
[112]	2017	HOMER	Kohmak /Thailand	PV/DG	LA	Off-grid Hotel,	0.374
[113]	2017	HOMER	Jhawani /India	PV/DG/BG	LA	Jhawani village	0.145–0.064
[114]	2017	HOMER	Sabah/Malaysia	PV/DG Off-grid	Fiamm type Battery	Two islands	1.22-1.36
[115]	2016	HOMER	Chamoli/ India	Mini Hydro Power-Biomass/BG/WT/PV Off- grid	LA	Village household load	0.092
[116]	2016	ABC, PSO Algo. & HOMER	Punjab/India	WT/PV/Biomass	LA	village, India	0.017–0.181
[117]	2016	ABC Algo. & HOMER	Patiala, Punjab/India	PV-Biomass	Without battery	Village load	0.11
[118]	2015	NPSP vs GA and HOMER	Saudi Arabia	WT/PV/DG	Flooded battery	Saudi Arabia	0.33

CHAPTER 3

3 METHODOLOGY

In this study, a case study has been conducted in Ankara/Turkey and the target is to optimize an off-grid HRES for 30 houses which can be ZEBs. To design a HRES for a specific place, the meteorological data of the selected place and the properties of the component of the system should be studied carefully. In this chapter, the selected site, load demand for the selected site, meteorological data (solar radiation, wind speed and temperature), system component, HRES configurations and mathematical calculations are analyzed to have an optimal system to meet the load demand to achieve ZEBs in a specific region in Ankara.

3.1 Selected Site

The hybrid energy system is designed to electrify 30 houses in a remote rural place in Ankara, the capital city of Turkey, with a Latitude: 39° 55' 11.53" N and Longitude: 32° 51' 15.37" E [119]. Since Turkey wants to reduce the using of fossil fuel and increase the using of renewable energy, the target in this study is to investigate the renewable energy to supply electricity for houses as much as possible. The picture of the selected region is shown in Figure 3.1. The climate of south and central Ankara is considered as continental climate since its winters are cold with rain and snow. As for the summer, it is hot and dry. There are important differences in temperature at night, day, summer and winter in the regions. July and August are the hottest months of the year while January is the coldest month of the year.

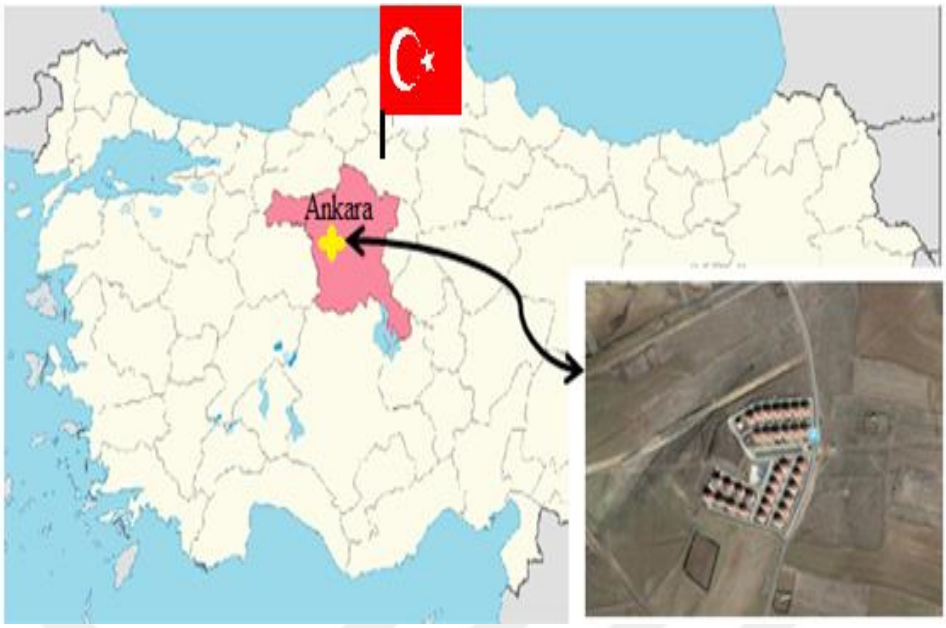


Figure 3.1 Location under study

3.1.1 Load profile

The modelling and sizing of the HRES depend on the electrical load demand of the selected region. HRES is considered to cover the load demand of basic components in any house such as lights, TV, kettle, water pump, refrigerator, air cooler, fluorescent tube, water pump, iron, a small geyser and a microwave as shown in Table 3.1. These devices are used at different times and some of them are used just at the weekend.

Table 3.1 Energy consumption by devices.

Item	Power (watts)	Number in use	Operating hours	Total load (watt-hour)
lamps	24	4	16	1536
Living room lamp	40	1	9	360
Room fans	50	3	13	1950
TV	250	1	3	750
Water pump	750	1	1	750
refrigerator	350	1	24	8400
Kettle	400	1	1	400
Air cooler	350	1	12	4200
geyser	1500	1	1	1500

The typical hourly load demand of one house is shown in Figure 3.2 and for the whole region in Figure 3.3, respectively. The load was considered in the summer season; however, the optimal system for this load is suitable for other seasons because the load profile will be lower during the remaining months. The daily average energy consumption is 597 kWh/day. The average and peak loads are 24.8 kW and 30 kW, respectively.

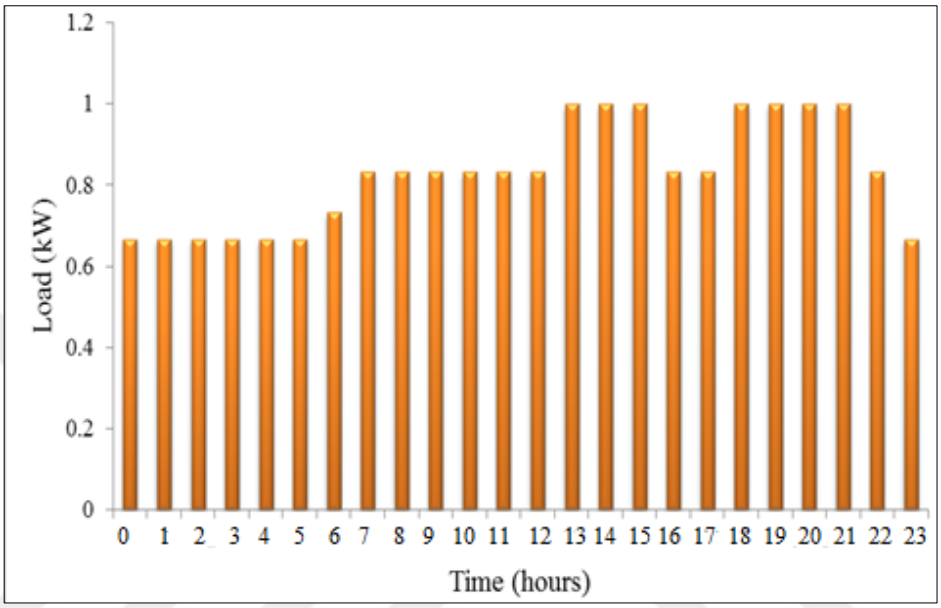


Figure 3.2 Daily load profile for one house

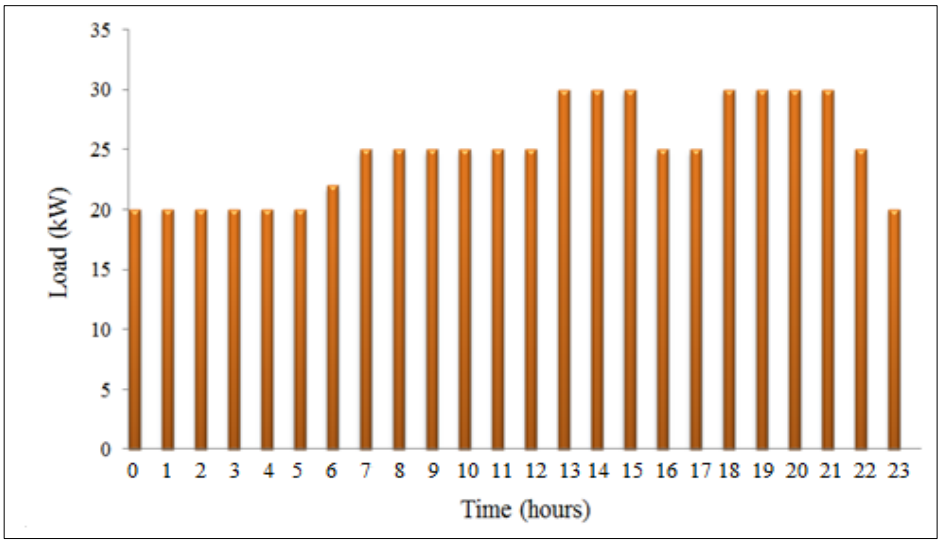


Figure 3.3 Daily load profile for 30 houses

3.1.2 Solar radiation

The mathematical calculation of the solar radiation effect is explained in the modelling part. Figure 3.4 shows the solar radiation obtained from National Aeronautics and Space Administration (NASA) for the selected place. The average annual and maximum solar radiation received in that place are 4.4 kWh/m^2/day and 7.164.4 kWh/m^2/day, respectively. The lower level of solar radiation is obtained from October to February while the higher level is from March to September.

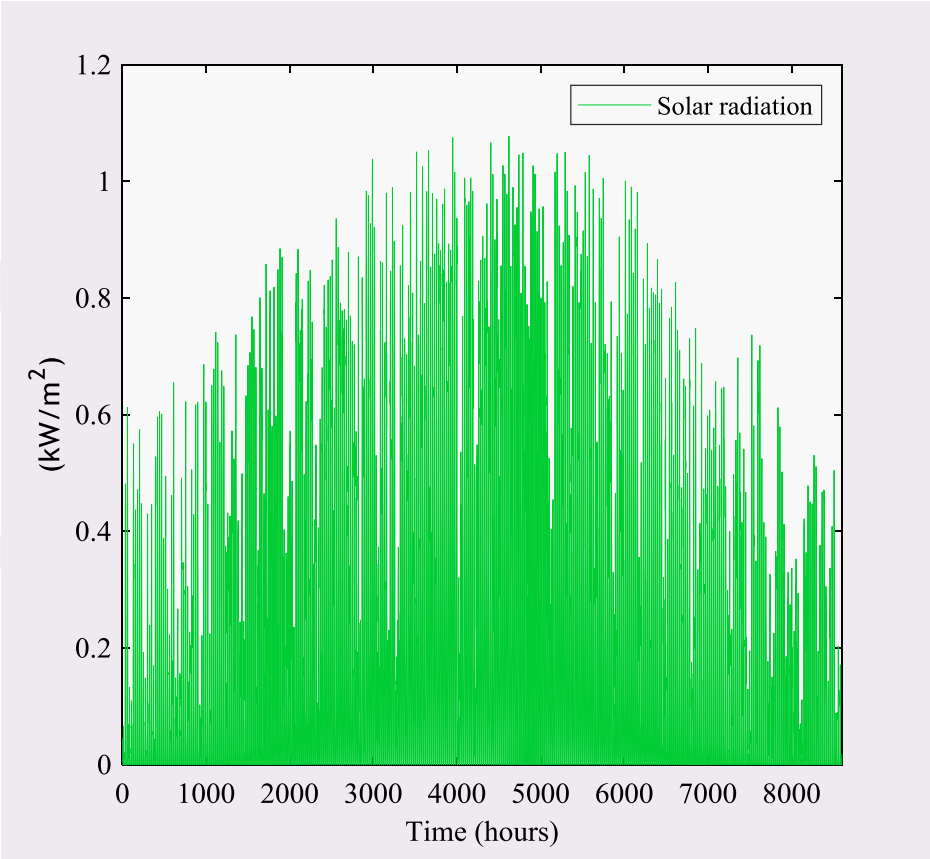


Figure 3.4 Solar radiation.

3.1.3 Ambient temperature

Temperature also affects the performance of the PV and influences the air density, so it affects the power output of both PV and WT. Figure 3.5 shows the hourly ambient temperature of the selected site. The annual average ambient temperature obtained for the selected region is 11.99°C.

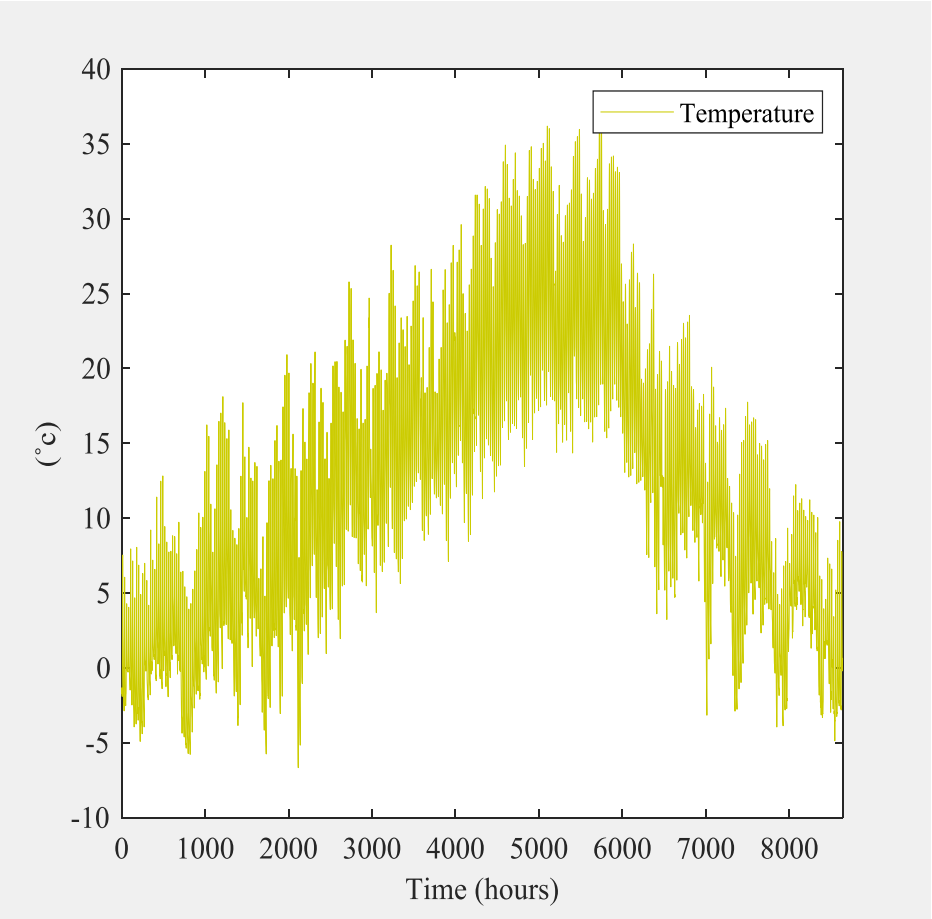


Figure 3.5 Hourly ambient temperatures.

3.1.4 Wind speed

WT depends on the wind speed in the production of electricity as mentioned in the modelling part. The average wind speed can determine if the turbine will work and produce energy or stop for safety reasons. The hourly wind speed is shown in Figure 3.6. The annual average of wind speed in the selected location is 4.6 m/s.

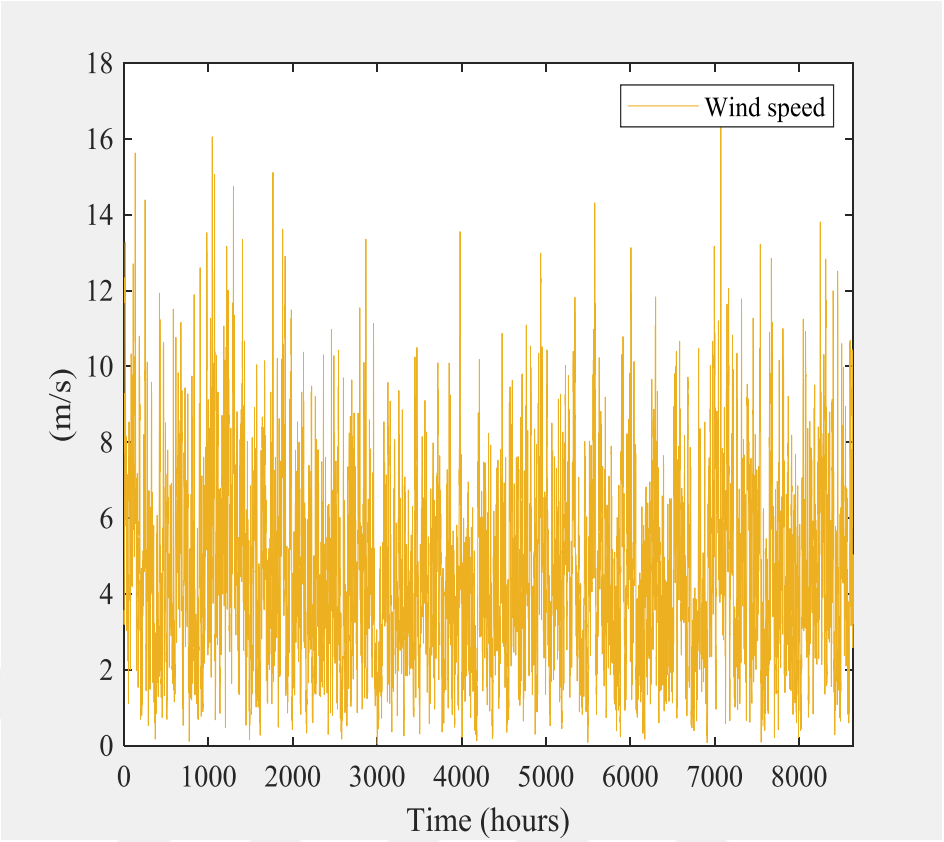


Figure 3.6 Hourly wind speed.

3.2 Hybrid System Components

Two types of the hybrid system are usually used which are on-grid and standalone systems. The major resources of renewable energy used in standalone systems are PV and WT. Because of intermittent energy of wind and solar, the storage resources should be used to overcome this problem.

Standalone systems are very important, and they are being used to electrify the rural and remote areas because of its reliability, efficiency and lower cost. Five major components are used in the proposed system, which are WT and PV as electricity sources in addition to DG and battery as a backup when renewable energy is not enough. An inverter is used to convert the current from AC to DC and vice versa depending on charging or discharging cycle of the batteries. The schematic diagram of the proposed system is shown in Figure 3.7.

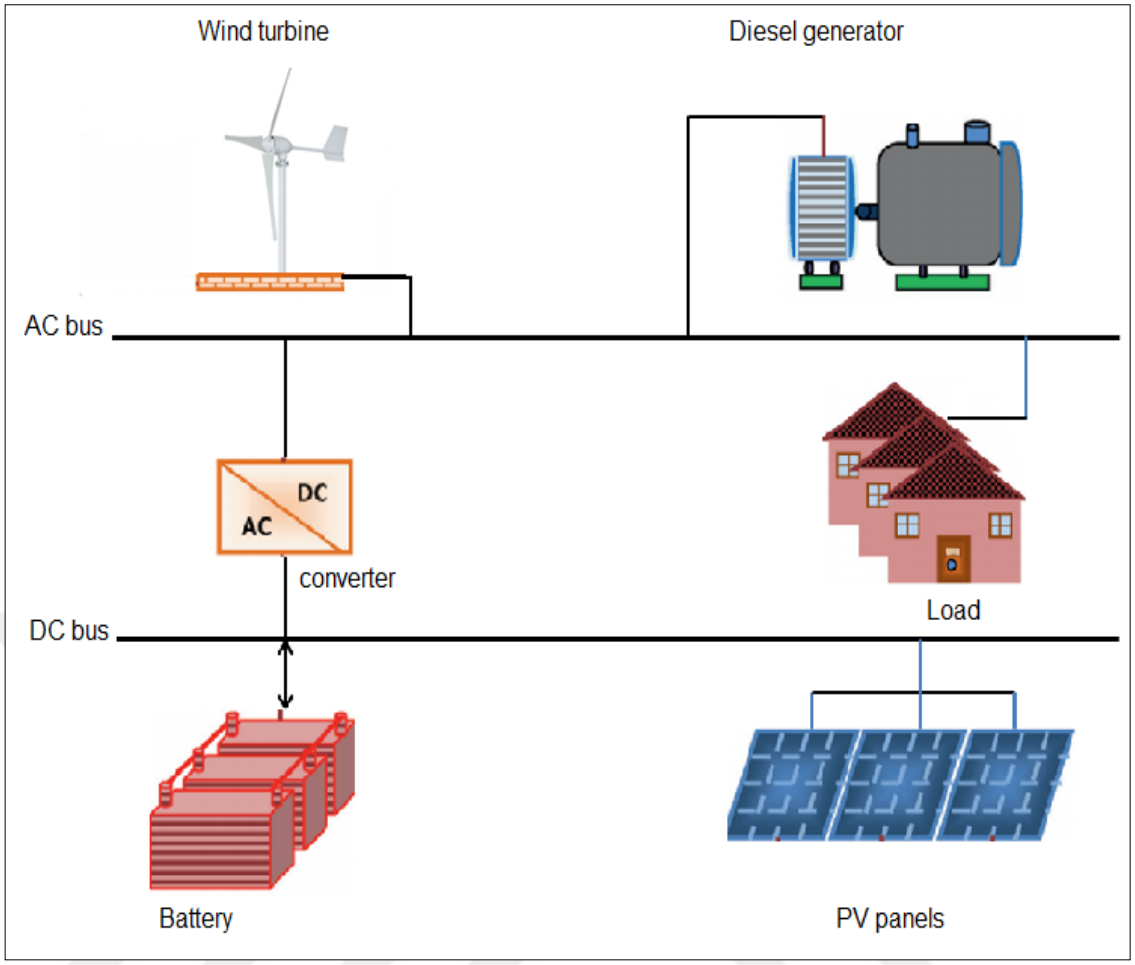


Figure 3.7 Proposed system configuration.

3.2.1 System component properties

In every system, different components with different prices and properties are used. The input parameters, sizes and costs of the proposed system components are presented below.

3.2.1.1 PV panel model

Polycrystalline panels with rated power of 325 W are used in this study. The capital and operation and maintenance (O&M) costs are set as 1500 $/kW and 5 $/kW/year, respectively. Table 3.2 shows the technical characteristics of the selected PV:

Table 3.2 Technical characteristics of the selected PV [40,84].

Description	Specification
Tracking system	Fixed
Efficiency (%)	16.97
Temperature coefficient (%/˚c)	-0.41
Operating temperature (˚c)	45
Capital cost ($/kW)	1500
O&M ($/kW/year)	5
Replacement cost ($/kW)	1000
Lifetime (year)	25

3.2.1.2 Wind turbine

There are different sizes of WT in the market. Selecting a size for a specific place depends on the available wind speed of that place because every WT has cut-in and cut-off speed which the WT work just between these values. The selected rated power of WT is 10 kW in this study, due to its low cut-in speed so the low wind speed is harnessed efficiently. Table 3.3 illustrates the technical characteristics of the selected WT.

Table 3.3 Technical characteristics of the selected WT [33].

Description	Specification
Nominal capacity (kW)	10
Cut-in wind speed (m/s)	2.75
Cut-off wind speed (m/s)	20
Capital cost ($)	30000
Replacement cost ($)	25000
O&M ($/year)	1000
Lifetime (year)	25

3.2.1.3 Diesel generator

A DG with a capacity of 10 kW and lifetime of 15000 hours is used in this study. The capital, replacement and O&M costs are taken as 5500 $, 5000 $, 0.3 $/hour, respectively. The price of fuel taken as 0.75 L which is the price of fuel in April in Turkey. Table 3.4 shows the technical characteristics of the selected DG.

Table 3.4 Technical characteristics of the selected DG [106].

Description	Specification
Capacity (kW)	10
Capital cost ($)	5500
Replacement cost ($)	5000
O & M cost ($/hour)	0.3
Lifetime (hours)	15000

3.2.1.4 Battery and converter

Most of the PV systems installed today use LA batteries as storage. This is due to the fact that the LA battery is a mature technology and its initial investment cost is lower

than the cost for the other technologies [120,121]. Duman and Guler [33] claimed that the LA battery is suitable to be used in the renewable systems**.**

LA battery with a maximum capacity of 3570 Ah is used in this study. Many researchers used LA batteries in their study as mentioned in Table 2.3. Table 3.5 demonstrates the technical characteristics of the LA battery [122]. The power converter is located among the battery, load and sources. The capital, replacement, O&M and lifetime are 550 $/kW, 450 $/kW, 5 $/kW, 15 years, respectively as shown in Table 3.6.

Table 3.5 Technical characteristics of the selected LA battery.

Description	Specification
Name	Hoppecke 24 OPzS 3000
Type	Vented LA
Nominal voltage (V)	2
Nominal capacity (kWh)	7.15
Maximum capacity (Ah)	3570
Maximum battery charge current (A)	610
Maximum battery discharge current (A)	610
Capital cost ($)	722
Replacement cost ($)	665
O&M cost ($/year)	180
Lifetime (year)	10

Table 3.6 Technical characteristics of the selected converter [84].

Description	Specification
Capital cost ($/kW)	550
Replacement cost ($/kW)	450
O&M cost ($/kW/year)	5
Lifetime (year)	15

3.3 Mathematical Representation

3.3.1 PV models

Parameters that can significantly affect the performance of a PV are the intensity of solar radiation and module temperature [123]. The solar cell is considered as a single diode. A current source and $R_{sh}$are connected in parallel with an ideal diode under positive bias. A series resistance R_s is connected between the source and the load. The circuit voltage (v_{oc}) and short circuit current (I_{sc}) are the basic parameters of this model. These can be affected by solar radiation, used material and PV cell temperature. Figure 3.8 shows the equivalent circuit of the solar cell.

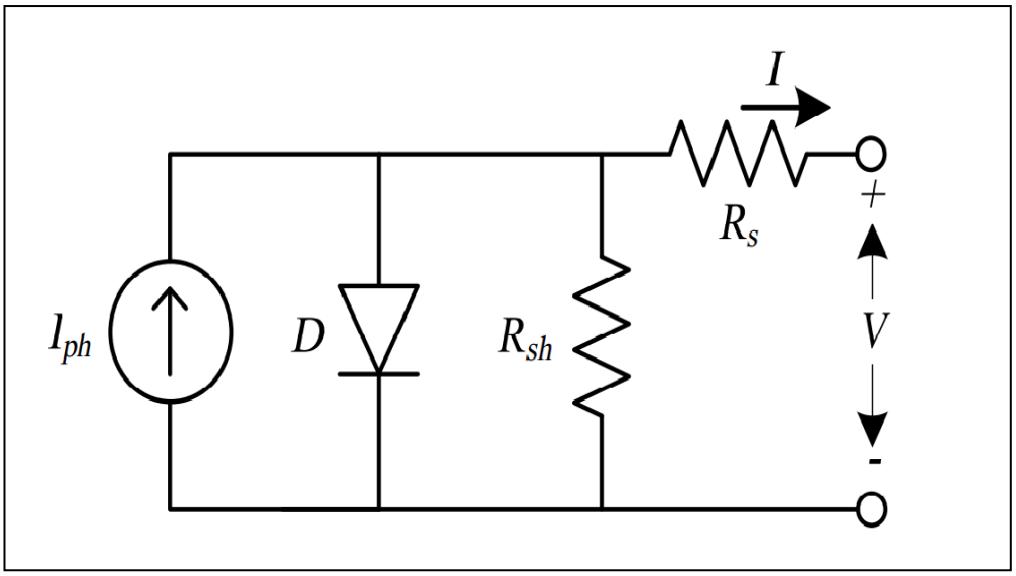


Figure 3.8 Equivalent circuit of solar cell [124].

The fill factor (FF) and maximum power output (P_{MAX}) are another important parts of PV module. It can be calculated by:

$$P_{MAX} = V_{MP} \times I_{MP} \quad (1)$$

Where, I_{MP} is the maximum current, and V_{MP} is the maximum voltage.

P_{MAX} can also be calculated by using the I-V curve as shown in Figure 3.9 [125]. FF is used to find out the quality of different solar cells with the same natural conditions. The quality of the module increases with the increasing of FF until it reaches 1. The range of it is from 0.5 to 0.85, and it can be calculated by [126]:

$$FF = \frac{P_{MAX}}{V_{OC} I_{SC}} = \frac{I_{MAX} V_{MAX}}{V_{OC}\, I_{SC}} \quad (2)$$

$$FF = \frac{P_{MAX}}{P_T} = \frac{I_{MP}.V_{MP}}{V_{OC}.I_{SC}} \quad (3)$$

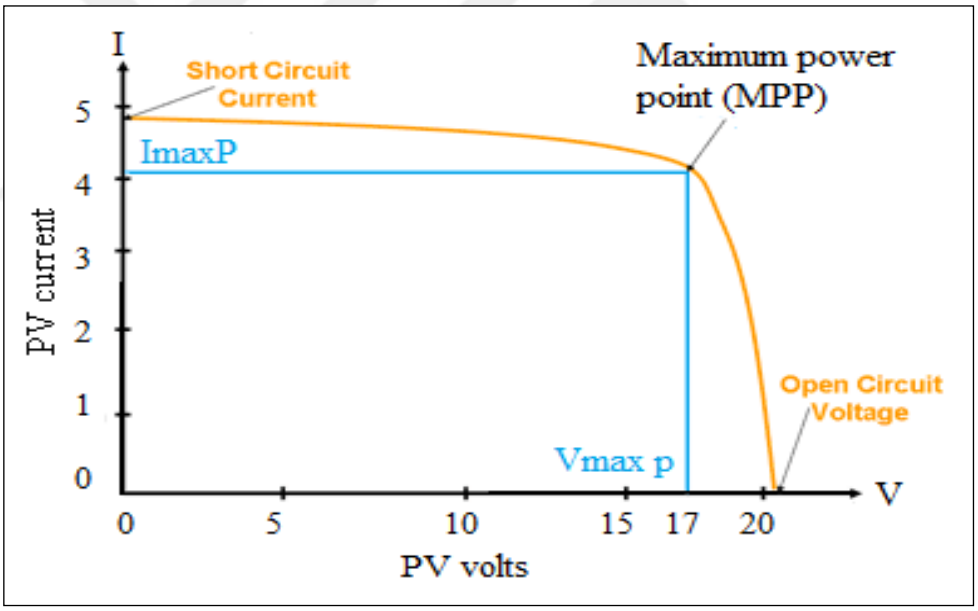


Figure 3.9 Fill factor in I-V curve [127].

Efficiency is another important parameter, which is derived from equation below [128]:

$$\eta = \frac{FF \times V_{OC} \times I_{SC}}{P_{IN}} \quad (4)$$

Where, P_{IN} is input power and η is power conversion efficiency.

The power of PV array with N_P modules in parallel and N_S modules is calculated by [129]:

$$P_A = N_P . N_S . P_{M.} \eta_{MPPT} . \eta_{OTHER} \quad (5)$$

Where, η_{MPPT} is the efficiency of the maximum power point tracking and η_{OTHER} is the factor that indicates other losses (cable resistance, dust)

Weather conditions such as solar radiation and temperature affect the power of PV. The output power of the panels can be calculated by [130]:

$$P_{P_{OUT}} = P_{N_{PV}} \times \frac{G}{G_{REF}} \times [1 + K_t \left(\left(T_{AMB} + (0.0256 \times G) \right) - T_{REF} \right)] \quad (6)$$

Where, $P_{P_{OUT}}$ is the output power of PV, $P_{N_{PV}}$ is the rated power used under reference conditions, G is the solar radiation (W/m^2), G_{REF} is the reference radiation (1000 W/m^2) T_{REF} is the reference temperature (25°C), Kt is -3.7×10^3 (1/°C), and T_{AMB} is the ambient temperature.

3.3.2 WT modelling

The WT can be cost-effective and provide promising electricity if the average wind speed is high and reaches to 3-4 m/s monthly. WT should be installed far from trees and buildings and should not be installed very far from the load because of losses.

3.3.2.1 Wind speed distribution

The performance of WT can be determined by Wind speed distribution for any location by predicting the electric energy produced from WT [131]. Different methods are used to find out the wind distribution such as Gamma, Burr, Erlang, Inverse Gamma and Weibull. The acceptable method is the Weibull distribution function because of its simplicity and flexibility [132].

3.3.2.2 Height of tower

The wind speed is not fixed and affected by several factors that change its direction and speed. These factors occur in an area called the boundary layer, which is defined as the layer near the surface that extends to a height of approximately (1000 m) or more, and responds to the changes of the surface of the earth. Turbulence and surface

roughness, friction clouds, evaporation and heat transfer occur within this layer. Furthermore, it includes the influence of the terrain, which plays a major role in changing the speed and direction of the wind. The wind speed increase as the surface roughness is low and therefore friction decreases because it is considered an obstacle to winds. WTs have different heights exceeding 10 m. The turbulence and surface roughness will decrease with the height; therefore, the wind speed will increase with height. The wind changes exponentially with the height and the law of the logarithmic equation used to find the velocity of the wind at different heights and the wind section can be represented by [133]:

$$U_2 = U_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \tag{7}$$

Whereas, U_2 is the wind speed at height Z_2, U_1 is the wind speed at height Z_1, Z_2 is the calculated height and Z_1 is the known height.

α is the surface friction coefficient, which is a function of surface roughness and stability, and has agreed-upon ideal values and the best-calculated value for this parameter is 0.14. This coefficient can be calculated by [134]:

$$\alpha = \frac{\log(\frac{U_2}{U_1})}{\log(\frac{Z_2}{Z_1})} \tag{8}$$

3.3.2.3 Wind power

Many studies were done to determine the output power of the WT. Every study depends on the wind speed, WT characteristics and WT application. The energy primarily in wind is the kinetic energy of large air masses moving above ground. Blades of WT receive this kinetic energy and convert it into mechanical energy and then to electricity. The efficiency of converting wind energy into other forms depends largely on the efficiency of the reaction of the rotor to the wind flow. Power equation is given by [135]:

$$P = \frac{1}{2}\rho A v^3 \tag{9}$$

Where, P is the mechanical power (watt), v is the upstream wind speed at the entrance of the rotor blades (m/s), A is the area swept by the rotor blades (m^2).

The second approach is based on the power curve. The power curve of a WT is indicated in Figure 3.10.

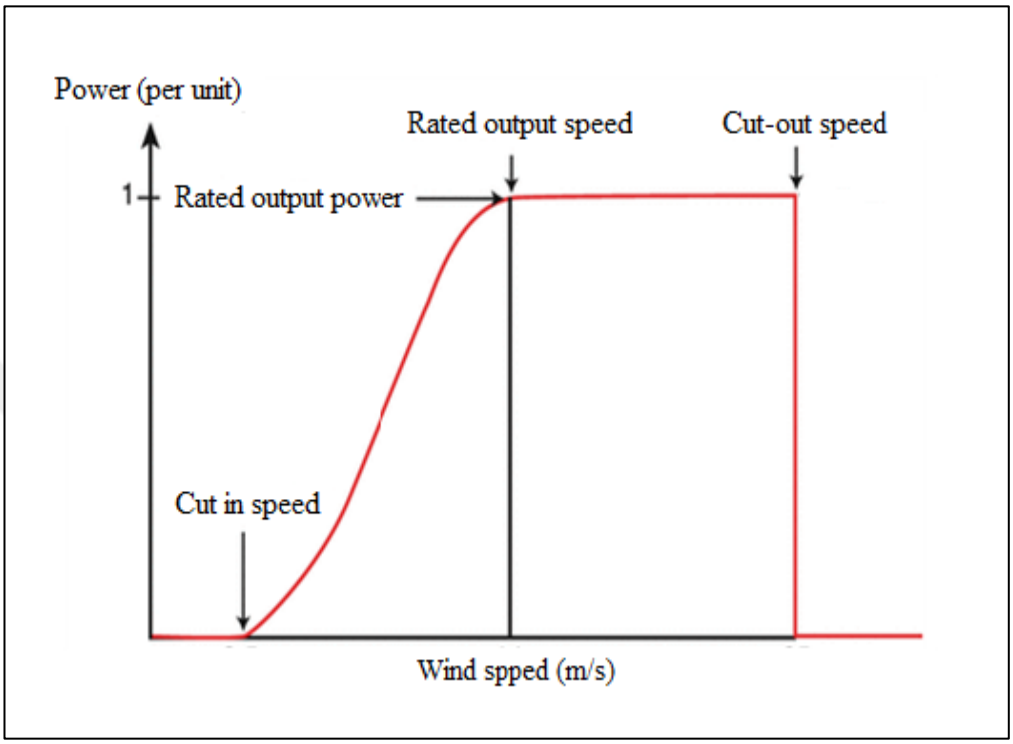


Figure 3.10 Power curve of WT [136]

Power output of WT can be calculated by [137]:

$$\begin{cases} 0 & V < V_{cut-in}, V > V_{cut-out} \\ V^3\left(\frac{P_r}{V_r^3 - V_{cut_{in}}^3}\right) - P_r\left(\frac{V_{cut-in}^3}{V_r^3 - V_{cut-in}^3}\right) & V_{cut-in} \le V < V_{rated} \\ P_r & V_{rated} \le V \le V_{cut-out} \end{cases} \quad (10)$$

Where, P_r is the rated power, V is the wind speed in the current time step, $V_{cut\text{-}out}$ is the cut out wind speed, V_{rated} is the nominal wind speed, $V_{cut\text{-}in}$ is the cut in wind speed.

The efficiency of WT is calculated by [138]:

$$E = E_r \times E_g \times E_t \tag{11}$$

Where, E is the wind efficiency, E_r is the rotor efficiency, E_g is the generator efficiency and E_t is the efficiency of the transmission.

3.3.3 Battery

The capacity of a battery is calculated by [139]:

$$C_B = \frac{AD.E_L}{V_B.DOD_{MAX}.T_{CF}.\eta_B} \tag{12}$$

Where, E_L is the load demand in kWh, AD is the days of autonomy, DOD_{MAX} is the maximum depth of discharge, V_B is the battery operating voltage, η_B is the charging/discharging efficiency, and T_{CF} is the temperature correction factor.

Overcharge and deep discharge can damage the battery, so the control of the battery is a very important point. State of charge (SoC) of the battery is a significant point in managing and controlling the hybrid system. It represents the percentage of the existing capacity in the battery to the rated capacity in AH and can be calculated by:

$$SoC = \frac{\text{Available capacity (AH)}}{\text{Rated capacity (AH)}} \times 100 \tag{13}$$

Iteration techniques are used in optimizing the hybrid system, so it needs the value of SoC of the battery in every moment during a specific load profile or a specific period. It can be calculated by [140]:

$$SoC(t) = SoC(t-1).(1-\sigma) + \left[\frac{E_L(T)}{\eta_{INV}} - E_{GEN}(t)\right] \tag{14}$$

And

$$SoC(t) = SoC(t-1).(1-\sigma) + \left[E_{GEN}(t) - \frac{E_L(T)}{\eta_{INV}}\right].\eta_B \tag{15}$$

Where, $E_L$is the electric load demand, σ is the self-discharge rate, and E_{GEN} is the generated energy.

Eq. (14) is applied for battery discharge cycle and Eq. (15) is applied for battery charge cycle. From the upper equations, it can be understood that the SoC of the battery related to the previous step in each moment during the work. However, in

each moment the SoC should not become less than SoC_{MIN} or exceed 1, which is calculated by [141]:

$$SoC_{MIN} = 1 - DOD \tag{16}$$

3.3.4 Diesel generator

The DG generator is an important part in designing a HRES because it is used as a second backup when the battery reaches to its minimum SoC or during the peak load to increase the reliability and the stability of the system. The generator should work within a normal operating range when the load increases suddenly in order to avoid high shortage.

Two characteristics in any DG should be taken into account during designing a HRES, which are hourly fuel consumption and efficiency [142]. They can be expressed by:

$$Q(t) = a.P(t) + b.P_r \tag{17}$$

Where, $Q(t)$ is the fuel consumption in L/h, P (t) is the generated power in kWand P_r is the rated power of the generator,

a and b represent the coefficients of fuel consumption. They are constant and can be approximated to 0.246 and 0.08415, respectively [143].

The DG efficiency is calculated by [15]:

$$\eta_{overal} = \eta_{brakethermal} \times \eta_{generator} \tag{18}$$

Where, $\eta_{brakethermal} \times \eta_{generator}$ represent the overall efficiency and the brake thermal efficiency of DG, respectively.

3.3.5 Bidirectional inverter

Inverter plays an important role in the HRES as the system does not work without it. It converts the electrical current from DC into AC and vice versa with the desired load. The efficiency could be calculated by {Formatting Citation}

$$\eta = \frac{P}{P + P_O + KP^2} \tag{19}$$

P_O, P and k could be found by using the equations below:

$$P_O = 1 - 99\left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9\right)^2 \quad (20)$$

$$K = \frac{1}{\eta\_100} - P_O - 1 \quad (21)$$

$$P = \frac{P_{OUT}}{P_N} \quad (22)$$

$\eta_{10} and\ \eta_{100}$ are the inverter efficiency at 10% and 100% of its nominal power provided by manufacturers. The efficiency of the inverter is assumed to be constant.

3.4 Economic Criteria of Hybrid Energy Systems

3.4.1 Net present cost

The NPC is one of the most important parameter of the HRES design. The NPC indicates the capital, replacement, O&M costs, plus the cost of fuel for the DG over project lifetime. The NPC can be calculated by [87]:

NPC = capital cost + replacement cost + O&M cost + fuel price (23)

3.4.2 Cost of energy

The average cost per kWh of useful electrical energy produced by the system. It is calculated by [146-148]:

$$\mathrm{COE} = \frac{\mathrm{NPC}}{\sum_{h=1}^{h=8760} \mathrm{P_{load}}} \times \mathrm{CRF} \quad (24)$$

Where, $\mathrm{P_{load}}$ is the total power consumption. CRF is used to calculate the component value in a specific time with taking the interest rate into account:

$$\mathrm{CRF} = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}} - 1} \quad (25)$$

Where, i is the interest rate and n is the lifetime of the system.

The lifetime of the system usually takes the same PV life because it has a longer life period among the other components in HES.

3.4.3 Reliability

Studying the reliability of a hybrid system is very necessary to have a system without failure during working because the production of electricity depends on the wind speed and solar radiation which are changing during the day. Consequently, the amount of electricity changes also, which directly affect the reliability of the system [149,150].

Different methods of reliable evaluation are used such as loss of power supply probability (LPSP), loss of energy expected, loss of load expected and equivalent loss factor. LPSP method is mostly used in the hybrid system. It can be found by:

$$\mathrm{LPSP} = \frac{\sum(\mathrm{P_{PV}} - \mathrm{P_{LOAD}} - \mathrm{P_{WT}} + \mathrm{P_{SoC_{MIN}}} + \mathrm{P_{DG}})}{\sum \mathrm{P_{LOAD}}} \quad (26)$$

3.5 The scenarios used in this study

In this study, five scenarios are analyzed to find out the optimum system that can meet the load demand with an acceptable price of electricity and reliability. The lifetime of the project is taken as 25 years. The lifetime of PV and WT is considered as the same lifetime of the project in all scenarios so there is no replacement needed. The different scenarios studies are conducted below.

3.5.1 Scenario 1: PV/Battery

The first scenario is done by combining only PV as an energy source with a battery as energy storage. The PV operates to meet the load demand in the day due to the availability of solar radiation and the excess electricity is used to charge the batteries to use them during the night.

3.5.2 Scenario 2: WT/Battery

In the second scenario, the load demand supplied with a system consisting of WT and battery. The WT production depends on the wind speed of the selected area, so it works at any time when the wind speed is higher than cut-in speed and less than cut-out speed. The storage system is important to save the electricity because the wind speed is interrupted and not constant all time, so in this case, the load should be met by a battery.

3.5.3 Scenario 3: PV/DG/Battery

In the third scenario, a new electric generator is added to the system which is the DG. The DG may reduce the COE and NPC, but at the same time, it releases different gasses which affect the environment.

3.5.4 Scenario 4: WT/DG/Battery

In the fourth scenario, WT and DG are used to cover the load demand with the assist of battery to increase the reliability.

3.5.5 Scenario 5: PV/WT/DG/Battery

The fifth scenario is done by considering all components used in previous scenarios which are PV/wind/DG/Battery.

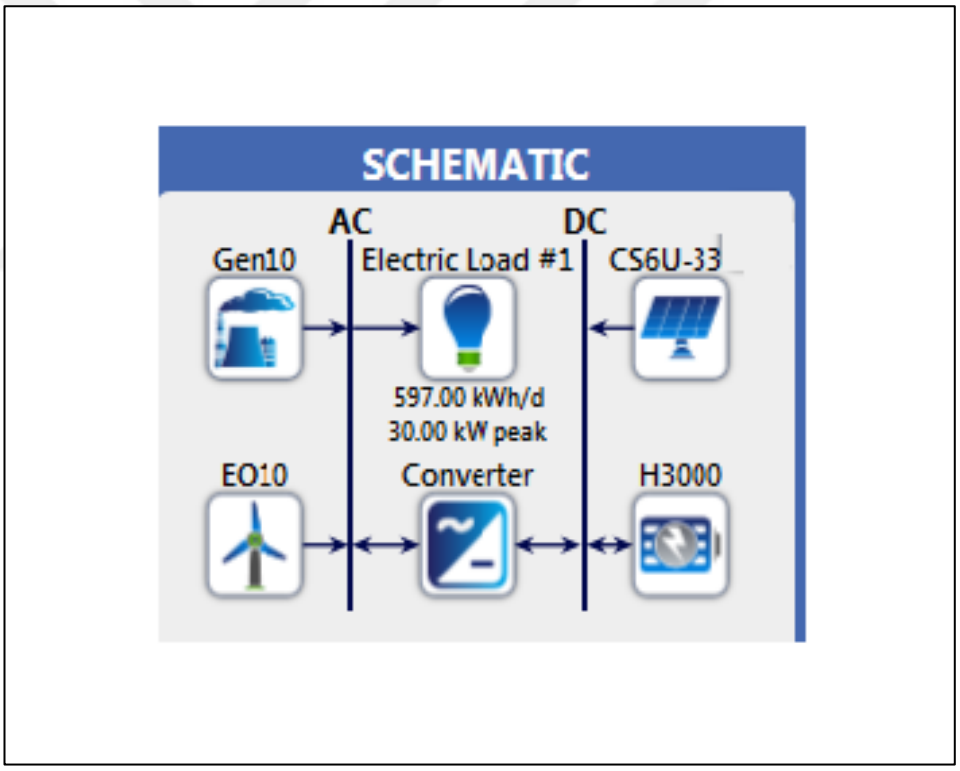


Figure 3.11 Hybrid renewable energy system configuration in HOMER software.

3.6 Power Management

The power management of HRES is slightly critical because the system consists of renewable and traditional sources with a battery as a backup so managing the power supplied from renewable energy and charge/discharge of the battery with the

working of the DG during the need of it should be taken into account and chosen properly. The strategy of controlling the power is summarized in four points:

- The renewable sources cover the load demand and the extra energy is used to charge the battery.
- The renewable sources cover the load demand and charge the battery and still, there is extra energy. This energy goes to the dump load.
- The renewable sources are not able to cover the load and there is a shortage. In this case, the battery will discharge to meet the shortfall.
- The renewable resources are not able to cover the load and the battery reached to its minimum SoC. The DG is turned on to meet the load and charge the battery.

The flow chart of different modes is shown in Figure 3.12.

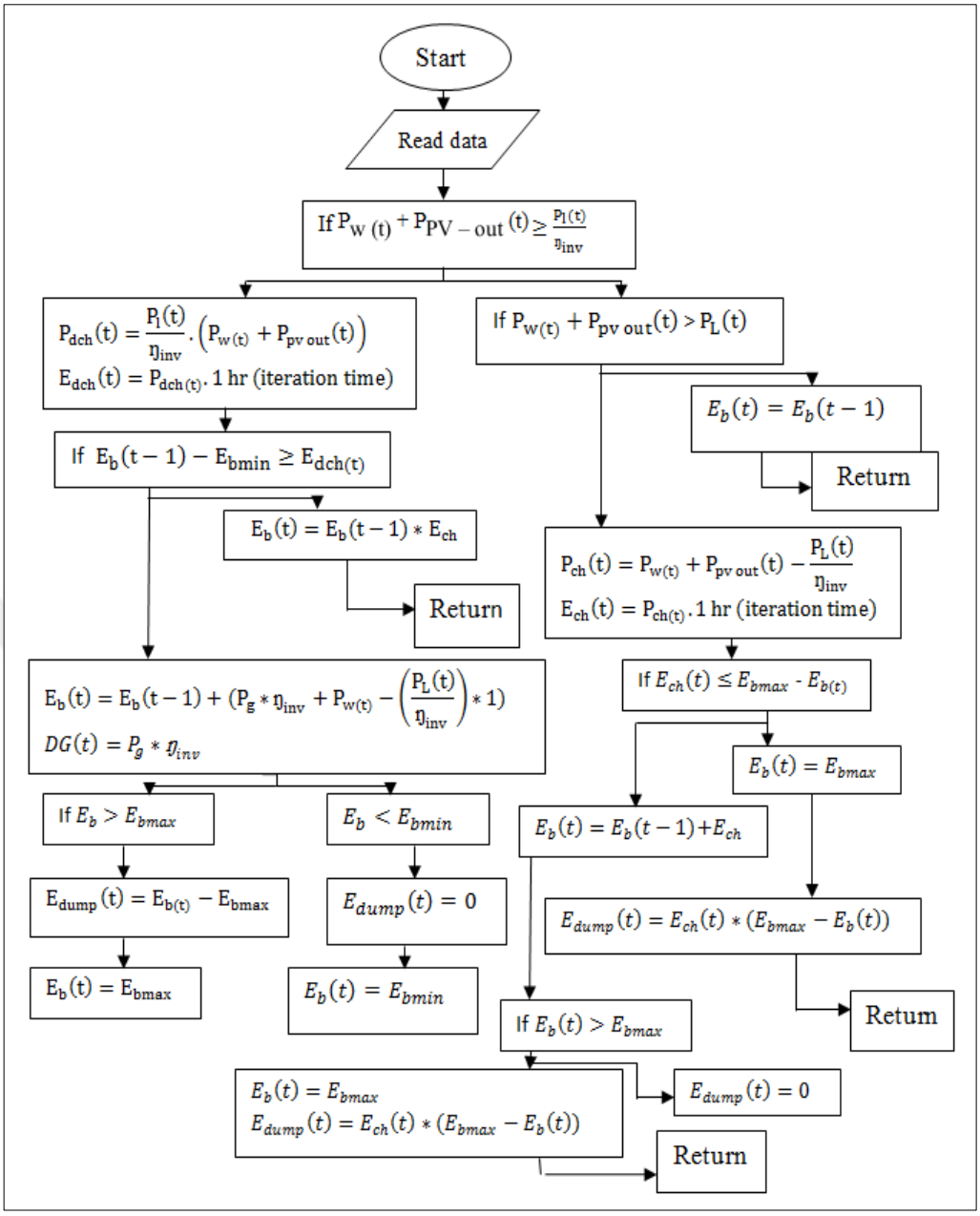


Figure 3.12 Power management flow chart [151].

3.7 Technic Used

There are many tools and technics to optimize a HRES for buildings. The examples of tools are LEAP, iHOGA. TRNSYS, HYBRID and HOMER. There are also well-known algorithms such as Genetic algorithm, Ant colony, and PSO. Lu et.al [16] conducted a study on the recent researches of optimization of ZEB. The results indicated that the HOMER is the best tool in this regard. Mohammed, Amirat and Benbouzid [72] indicated in their study that PSO is one of the most important algorithms in the renewable optimization field.

3.7.1 HOMER

HOMER software is a tool that is used to design a HRES by combining different renewable and non-renewable sources such as WT, PV, DG, hydro generator, fuel cells, inverter and energy battery for all sector such as villages, islands and campuses. It was created by National Renewable Energy Laboratory/USA. The input data that the HOMER needs to optimize the system are the system variables, which are the types and sizes of the component with the prices of them and the meteorological data which are wind speed, solar irradiance and ambient temperature. It can model on-grid and off-grid systems and provide different configuration to get the optimal system with the least COE. HOMER can handle three tasks which are simulation, optimization and sensitivity analysis [152-154].

In simulation, HOMER performs calculations on all the proposed options for the system based on the type of loads required and renewable sources such as solar energy and available wind energy. It compares the energy that the system can provide to the electrical load demand in every hour of the year and calculate the direction of generated energy between the components. The number of these possibilities may be hundreds or even thousands.

In optimization, optimal solution or optimal design of the system is found among all the available design options that the program reached, and the optimal here is to express the economic aspect because HOMER is essentially an economic model for choosing the best model. For example, the program offers the option that achieves the largest savings of spent fuel for DG if it was approved as a source to cover the load that the system was designed for.

HOMER is also considered the best option in the sensitivity analysis. The word sensitivity here is related to economic operations. It analyses the effect of changing one factor on the performance of the system. For example, it performs the changing of solar radiation or wind speed on the amount of fuel consumed with keeping constant the rest of the factors. Figure 3.13 shows the HOMER flowchart.

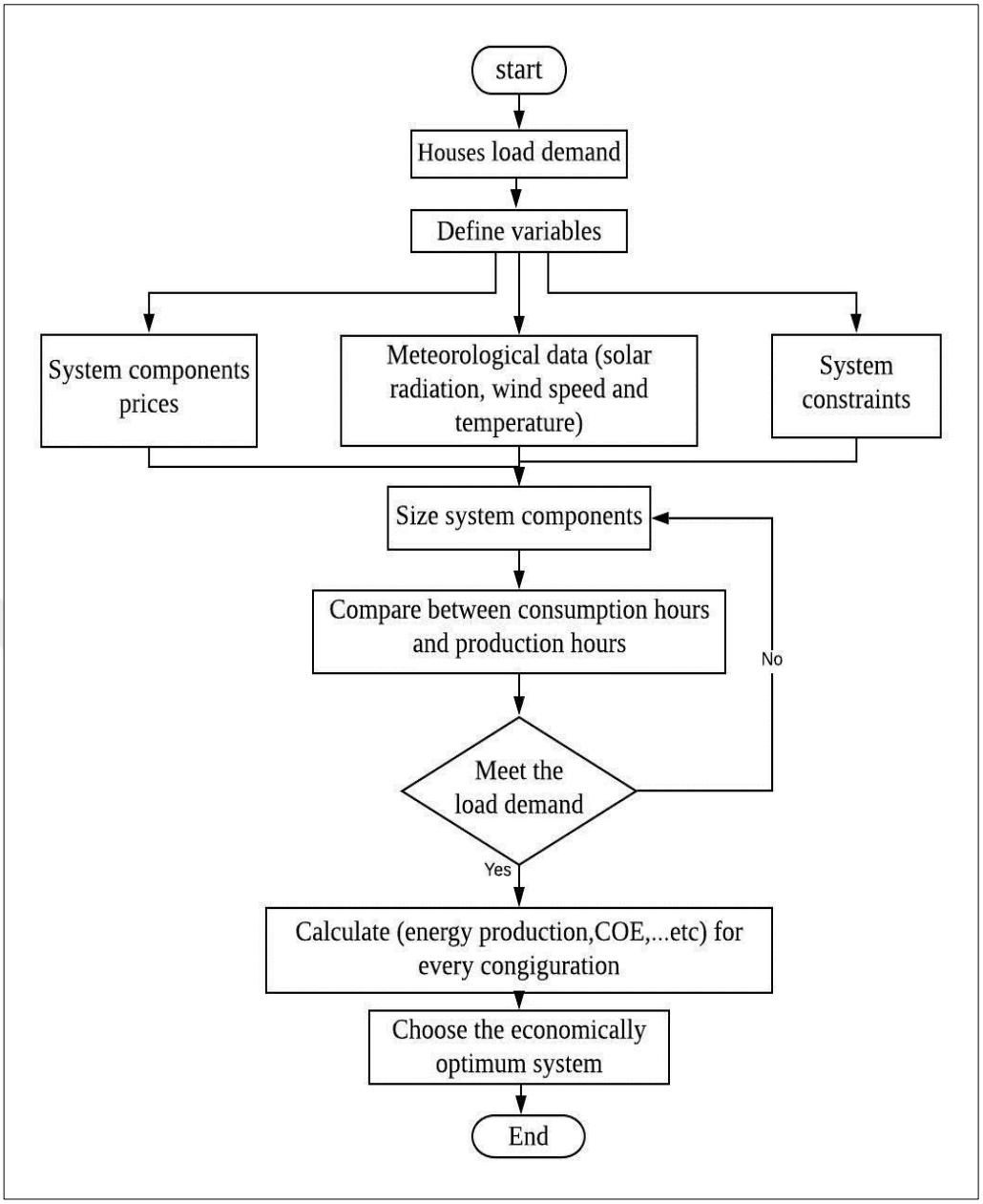


Figure 3.13 HOMER flowchart

3.7.2 Particle swarm algorithm

This algorithm is one of the most advanced areas of artificial intelligence. It was discovered by Dr. Eberhart and Dr. Kennedy in the year 1995. This technology was developed to tackle a problem and get the best solution among many solutions available for that specific problem. The idea of this technique is based on the methods used by birds in the search for food. For example, if there is a swarm of birds spread in a specific place for the purpose of searching for food and this food is found in a specific place in addition to the fact that birds do not know where the food is, the best way to find it is by spreading all the birds in the area, starting with

searching for the place of food and telling the birds each time about the place of it. Once the birds figure out a good place for food, they will use it to get the best food. This is also the similar work of the algorithm, where the idea of the algorithm is based on a group of elements called particles, where these particles are randomly distributed in a limited area, with the aim of searching for the optimum solution within this region [155-158].

Each of these elements possesses an appropriate value called fitness value and this value represents the suitability of the solution of this component compared to the rest of the particles in the region. This process is performed with the help of a fitness function. These elements have speeds that lead them to search for food and address problems by using some variables, including:

P_{best} : Appropriate value that the particle has recorded.

g_{best} : Most favorable value recorded in the swarm.

I_{best} : Better localization of an element compared to locally adjacent elements.

After knowing the values of these elements, the elements change their velocity and positioning in each repetition with the help of the following equations:

$$X_{s+1}^{i} = X_{s}^{i} + V_{k+1}^{i} \tag{27}$$

Where, x is the particle position and V is the particle velocity in iteration s

The equation below describes the velocity calculation:

$$V_{s+1}^{i} = s\ x\ [V_{k}^{i} + c_1 r_1 \left(P_{s}^{i} - X_{s}^{i}\right) + c_2 r_2 (P_{s}^{q} - X_{s}^{i})] \tag{28}$$

$$K = \frac{2}{\left|2 - \emptyset - \sqrt{\emptyset^2 - 4\emptyset}\right|} \tag{29}$$

Where $\emptyset = c_1 - c_2$, P^i is the best individual particle position and P^q is the best global position. c_1 is cognitive parameter and c_2 is a social parameter. r_1 and r_2 are taken as random values between 0 and 1. V_s^i makes all particles shift in the same velocity to the same position. $c_1 r_1 \left(P_s^i - X_s^i\right)$ makes the particle in the swarm return back to the former location when it experienced high individual fitness. $c_2 r_2 (P_s^q - X_s^i)$ makes the particle in the swarm tend to return back to the best place that the

swarm has found in the area and to track the best path of the neighbor. If $c_2 >> c_1$, the particles in the region are more attracted to the global best positions. If $c_1 >> c_2$, here each particle in the region is more attracted to individual best positions. Figure 3.14 shows the PSO algorithm flowchart.

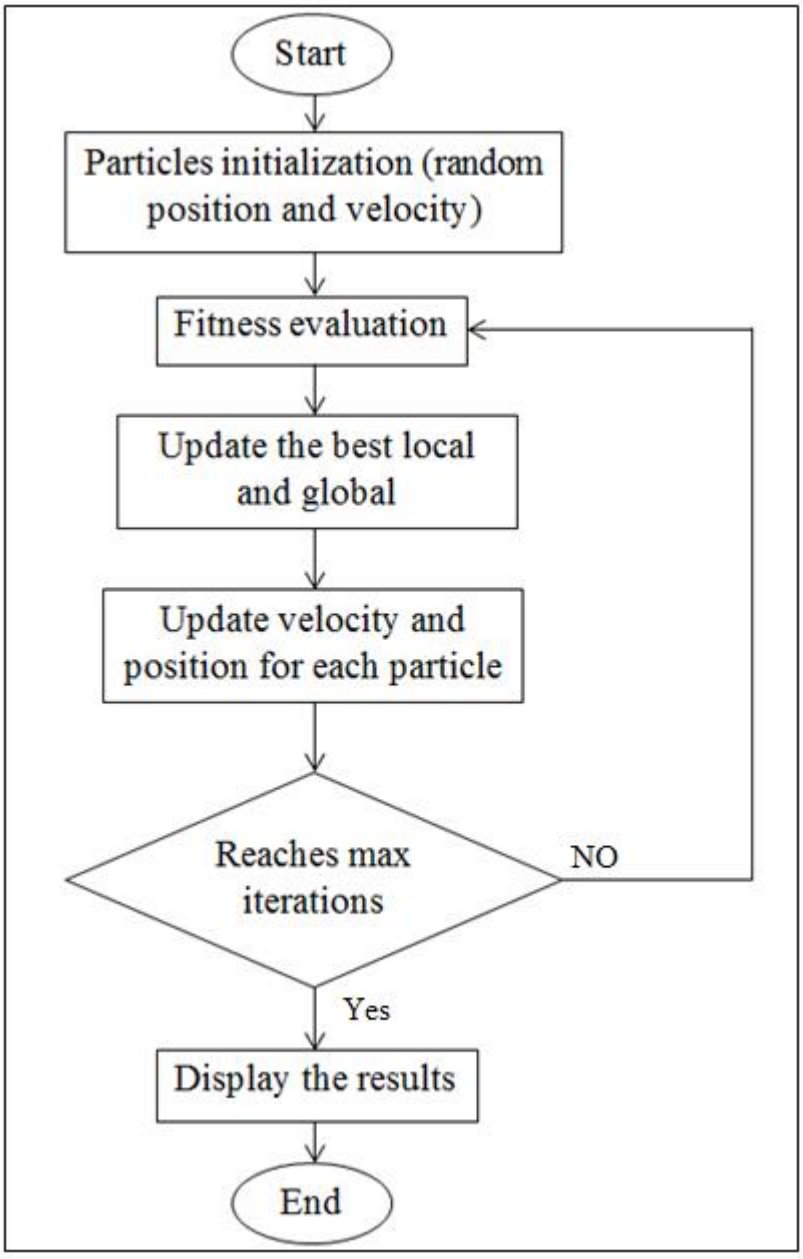


Figure 3.14 PSO flow chart.

The general model of PSO that has been applied in this study is described in Figure 3.15 below.

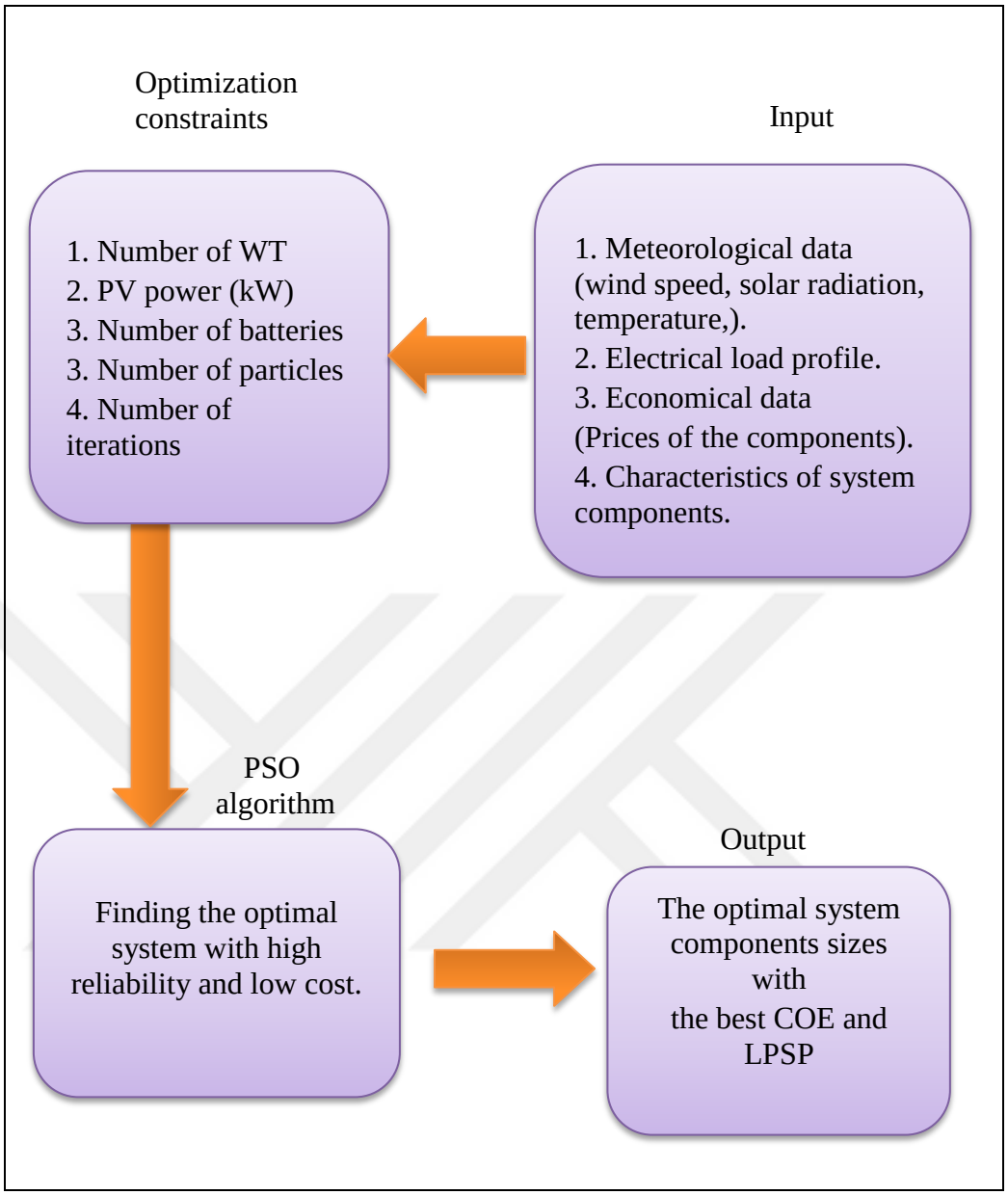


Figure 3.15 General model of PSO.

3.7.3 Techno-economic analysis using PSO

In This study is concerned in studying the techno-economic optimization of HRES using HOMER software and PSO algorithm. In PSO, the objective function is to minimize the COE and LPSP to have an optimal system with less costs taking into account the sizing of the system components, the load demand and the SOC. The PSO algorithm is implemented by using MATLAB environment. All variables are inserted such as the meteorological data (wind speed, solar radiation and ambient temperature), system components types and sizes (PV, WT, DG, battery and converter), prices (capital, replacement and O&M costs) and the lifetime of the

project. The number of iterations and particles are considered 40 and 20, respectively and the particles velocity and positions are taken randomly at the first time then they start to be updated in every iteration neglecting the worst values and keeping the best values.

In the following paragraphs, the complete flows of the algorithm for techno-economic analysis of HRES are indicated.

1) Start.
    a. Meteorological data.
    b. Houses load.
    c. Components characteristics
    d. Economic parameters
    e. Set the constants:
        - Maximum of Iteration=50.
        - Number of Particles=20.
    f. Set the constraints:
        - Maximum price of electricity, C=0.5
        - Maximum loss of load probability, W=0.3
    g. Assign the list of tasks as follows.
        - Nominal power of PV (kW).
        - Number of WTs.
        - Number of batteries.
        - Electrical load demand.
    h. The particles velocity and position are randomly selected and apply to find COE and LPSP.
    i. If the positions of randomly chosen particles exceed the limitation of COE or LPSP, return to (e).
    j. Evaluate each particle in the swarm and find the best fitness value among the whole swarm. Set the global best value.
2) Update iteration variable.
3) Update inertia weight.
4) Update velocities.
5) Update positions.

6) Apply to the objective function to find COE and LPSP.

7) Update individual best position.

8) Update global best position.

9) Stopping criterion. If the number of iteration exceeds the maximum number of iterations, then stop; otherwise go to step 2.

CHAPTER 4

4 RESULTS AND DISCUSSIONS

In this chapter, the results of the techno-economic analysis of different scenarios are presented. Five scenarios which are PV/Battery, WT/Battery, PV/DG/Battery, WT/DG/battery, and PV/WT/DG/Battery are analyzed to find out the optimum system that can meet the load demand with an acceptable price of electricity and reliability. The lifetime of the project is taken as 25 years. The lifetime of PV and WT is considered as the same lifetime of the project in all scenarios so there is no replacement needed. The different scenarios studies are conducted below.

4.1 Scenarios results of HRES

4.1.1 Scenario 1: PV/Battery System

In this scenario, among different configurations, the optimal system obtained in this case is having 245 kW PV with 104 units of batteries. The system produces 377939 kWh/year which is 100% of the total energy. The COE and the NPC are defined as 0.337 $ and 730165 $, respectively as mentioned in Table 4.1. The monthly average for one year of electric generation is shown in Figure 4.1.

Table 4.1 Optimal system sizes.

Scheme	P_{pv}(kW)	N_{WT}	P_{DG}(kW)	$N_{battery}$	COE ($)	NPC ($)
PV/Battery	245	-	-	104	0.337	730165

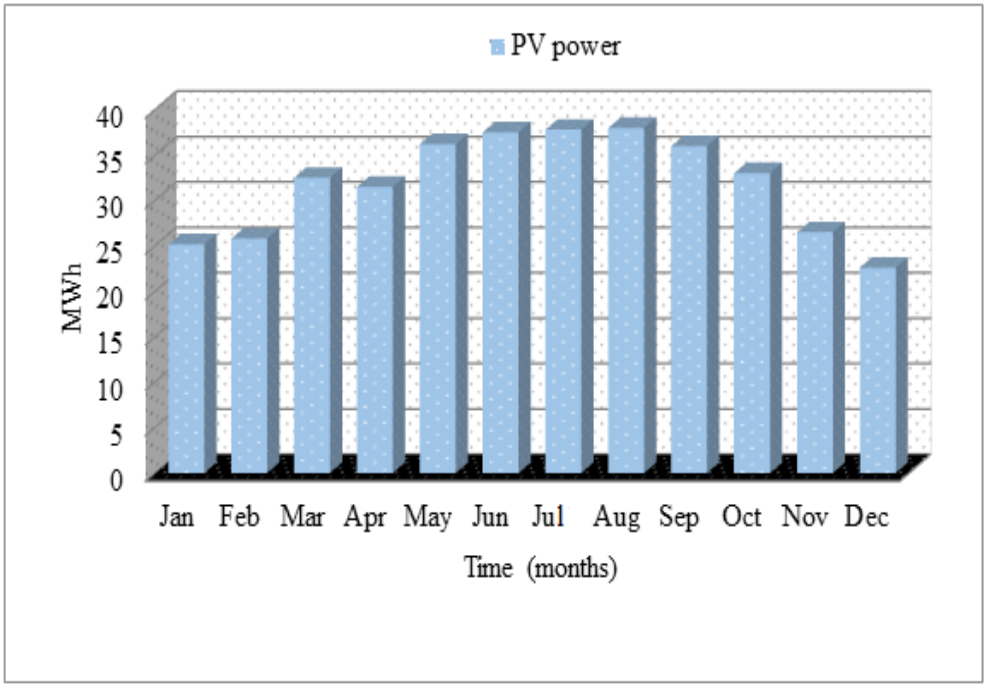


Figure 4.1 Monthly electric production.

Table 4.2 presents the net price for each component of the system. It can be observed that while the capital cost of PV is higher than batteries, the life time for PV is much higher than batteries because there is a replacement cost for battery so it means that the batteries have replaced during the lifetime of the project.

Table 4.2 Net prices of system components.

Component	Capital ($)	Replacement	O&M ($)
PV	34425.13	0.00	1224.94
battery	7034.15	4821.93	18720
converter	1766.35	556.83	171.41
system	43225.64	5378.76	20116.35

Figure 4.2 shows the energy generated output of the optimal system of this scenario. It has the PV output, load demand and SoC of the battery for the first two weeks in January. As we can see in the result, the energy generated by PV is high enough to

cover the load demand in the day and charge the battery at the same time. At night when there is no solar radiation, battery storage starts to supply electricity to meet the load demand and get charging in the second day. Due to the absence of DG, the renewable fraction is 100% and there are no gas emissions. However, this system is still not suitable cost-wise because it needs a high rate of PV energy to supply electricity for the load and charge the battery in the same time.

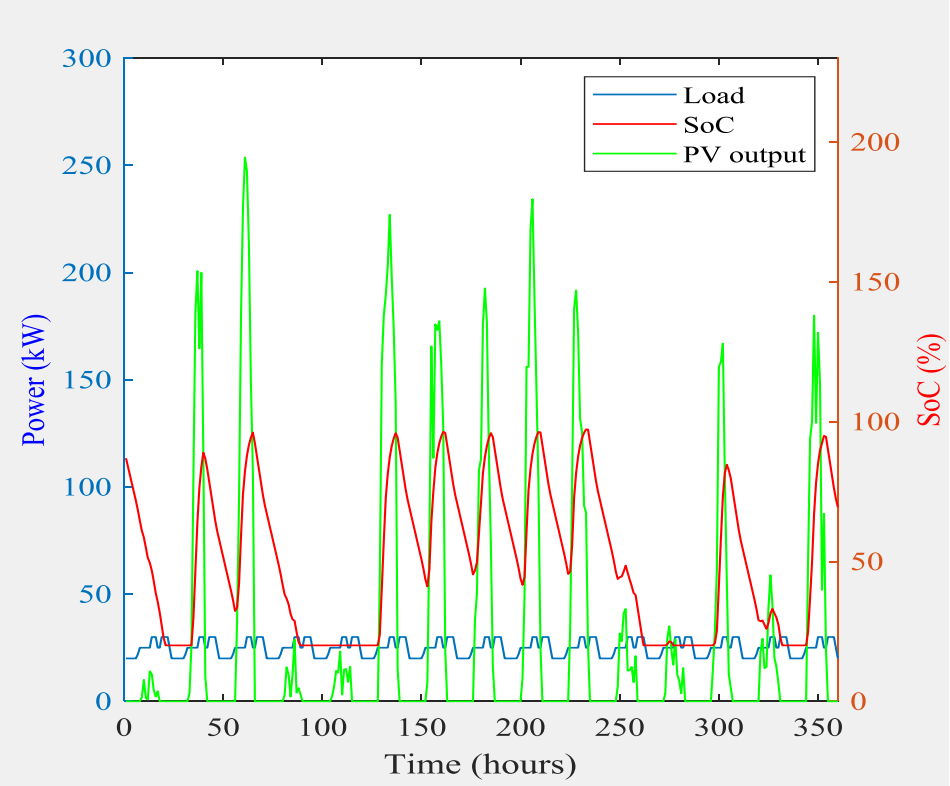


Figure 4.2 System output.

4.1.2 Scenario 2: WT/Battery

The optimal system is configured by 13 units of WT and 150 units of batteries as shown in Table 4.3. The WT produces 417426 kWh/year, which is the total energy production. COE and NPC found as 0.48 $ and 1.04M $, respectively. This system has high prices owing to the high capital cost of WT. Monthly average energy production is shown in Figure 4.3.

Table 4.3 Optimal system sizes.

Scheme	P_{pv}(kW)	N_{WT}	P_{DG}(kW)	$N_{battery}$	COE ($)	NPC ($)
WT/Battery	-	13	-	150	0.48	1.04 M

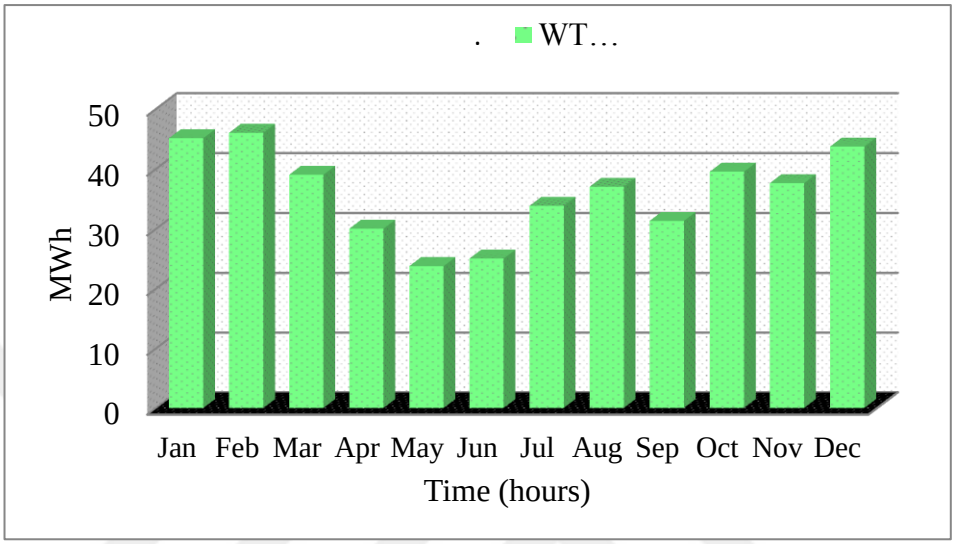


Figure 4.3 Monthly electric production.

The costs of the components are analyzed in Table 4.4. Although the price of the capital cost is high, the price of O&M is also high due to the many moving parts in the WT, so they need maintenance permanently. WT does not need replacement because the considered operating time is 25 years which is the life cycle of the system, so there is no price for replacement of WT.

Table 4.4 Net prices of system components.

Component	Capital ($)	Replacement	O&M ($)
WT	390000	0.00	138772.09
battery	108300	67604.73	288218.96
converter	37613.42	11857.32	3650.14
system	535913.42	79462.05	430641.18

Figure 4.4 shows the energy generation output of the optimal system in this scenario that consists of WT and battery. The WT depends on the speed of the wind so it may work and supply electricity for more hours compared to PV. Therefore, the batteries may operate for less amount of time than the first scenario. As indicated in the result, the electricity generated by WT could meet the load and keep the battery on good SoC. The batteries will provide the required power instead of WT to meet the load when the wind speed is low or very high that makes the WT in a constant mood.

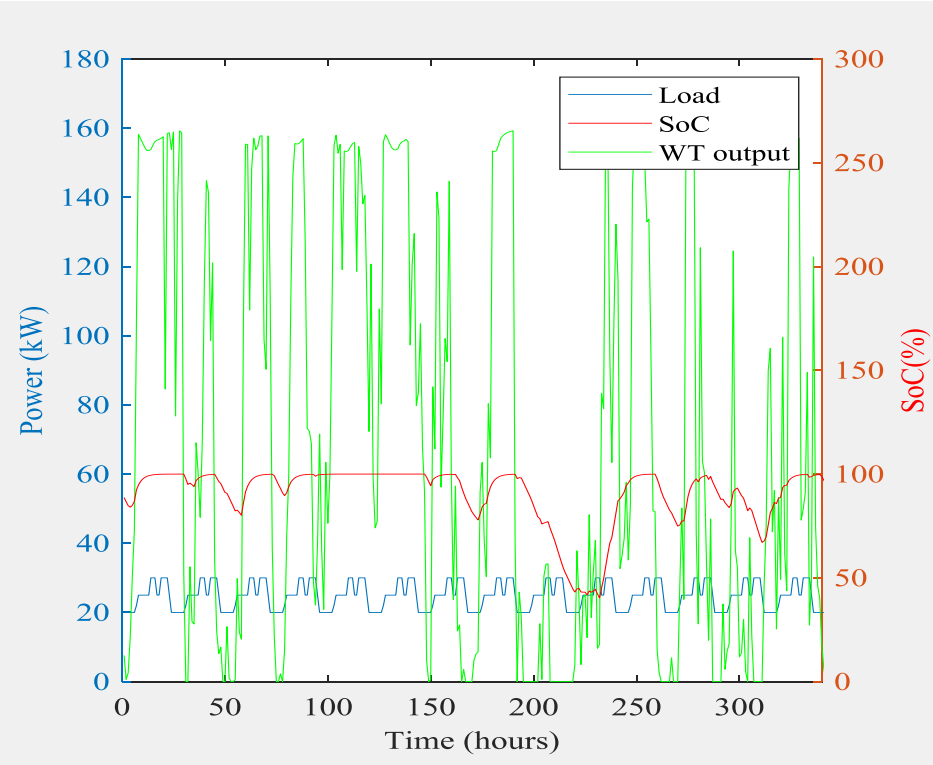


Figure 4.4 System output.

While this system is environmentally suitable, however, the capital and O&M costs are high.

4.1.3 Scenario 3: PV/DG/Battery

The optimal sizes of components in this system are 177 kW PV, 10 kW generator and 80 units of batteries as indicates in Table 4.5. The COE and NPC are found as 0.295 $ and 644897 $, respectively. The PV produces 273176 kWh/year and the DG produces 20477 kWh/year of the total energy production, which is 293653. That represents 93% and 6.9%, respectively. Figure 4.5 shows the monthly average electrical production. In the figure, it can be easily distinguished that DG operates at highest level from September to April while it operates at the lowest level in Jun and

August due to high solar radiation in September to April months. The highest solar radiation is in July so there is no need for DG.

Table 4.5 Optimal system sizes.

Schemes	P_{PV}(kW)	N_{WT}	P_{DG}(kW)	$N_{battery}$	COE ($)	NPC ($)
PV/DG/Battery	177	-	10	80	0.295	644897

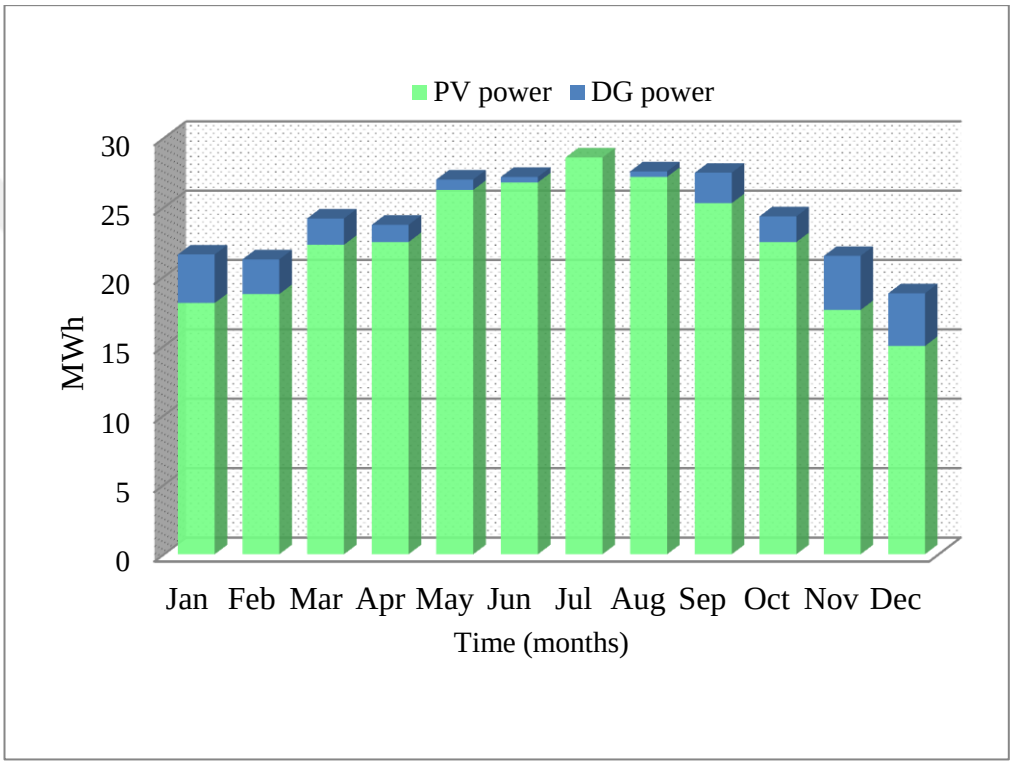


Figure 4.5 Monthly electric production.

Table 4.6 indicates the prices of system components during the lifetime of the project. It shows that the price of DG replacement is higher than its capital price, so it means that the DG has been changed more than once due to its short life time compared to the lifetime of the project. Although the price of it is low, the O&M price is high due to the moving parts of the generator and the fuel cost.

Table 4.6 Net prices of system components.

Component	Capital ($)	Replacement ($)	O&M ($)
PV	265616.58	0.00	9451.33
DG	5500	7100.64	7913.21
battery	57760	56098.23	153716.78
converter	22850	7203.29	2217.45
system	351726.62	70402.15	173298.76

Figure 4.6 shows the PV output with the load demand and SoC without the presence of DG. It is obvious to see in some hours, the generated power from PV is not enough to cover the load and the battery has reached to its minimum SoC, so there will be a shortage in supplying electricity for the load. When the generator is added to the system, it would work to meet the load in the case when both PV and battery are not supplying electricity as shown in Figure 4.7. It means that the DG would increase the reliability of the system by reducing the electricity shortage.

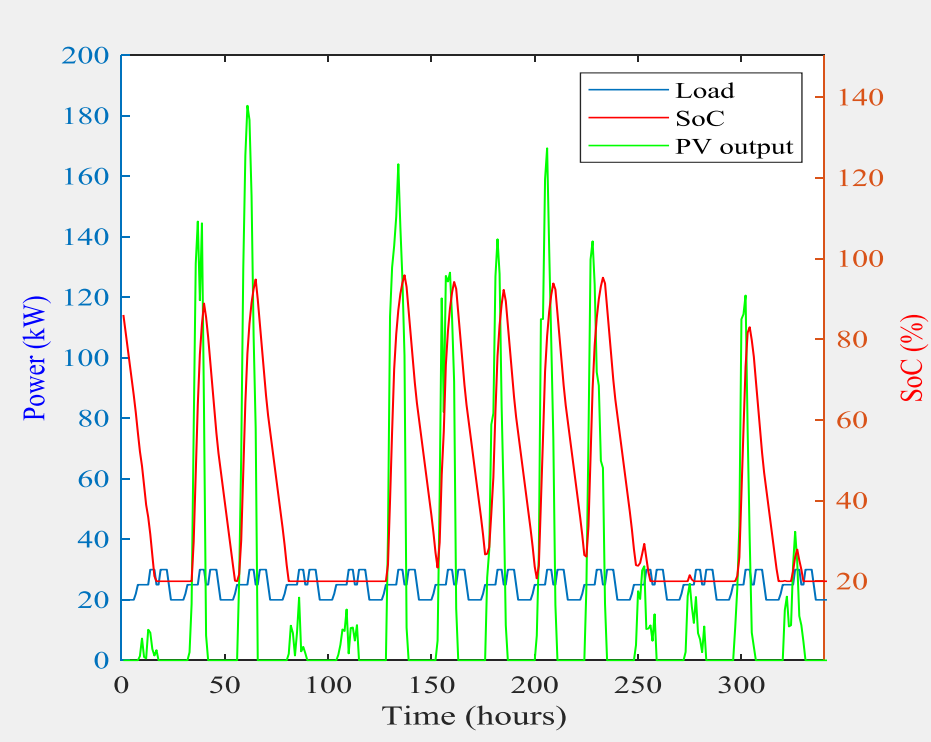


Figure 4.6 System output.

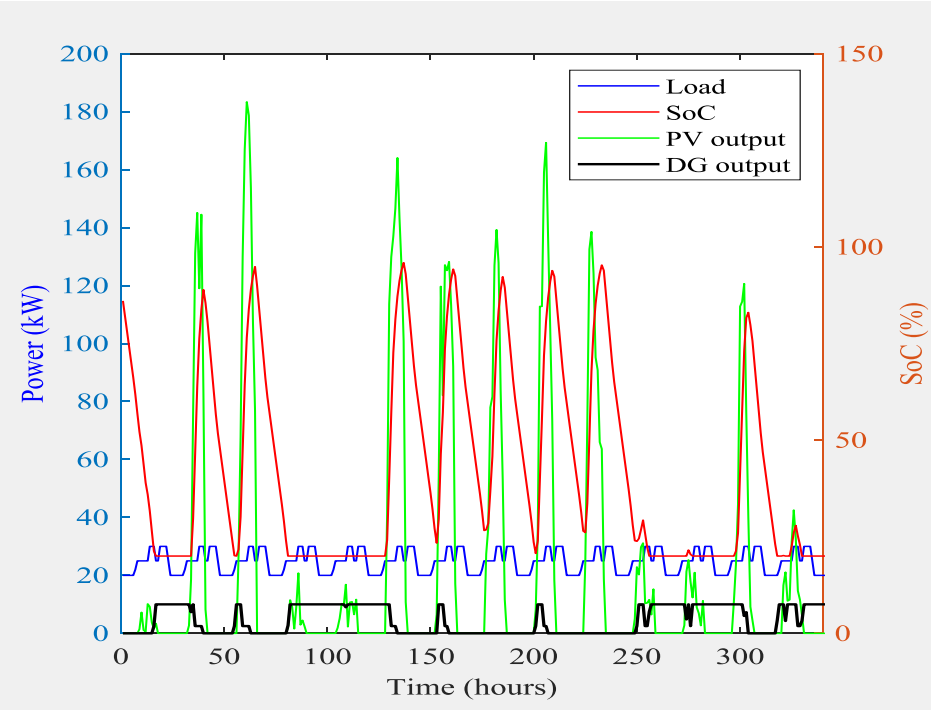


Figure 4.7 System output.

4.1.4 Scenario 4: WT/DG/Battery

The obtained optimal system consists of 10 units of WT, 10 kW DG and 95 units of batteries as shown in Table 4.7. The WT produces the largest amount of electricity, which is around 321097 kWh/year while the DG produces 22074 kWh/year that account 93% and 7%, respectively. The COE and NPC are found as 0.387 $ and 835714 $, respectively. Figure 4.8 represent the monthly average electrical generation.

Table 4.7 Optimal system sizes.

Schemes	P_{PV}(kW)	N_{WT}	P_{DG}(kW)	$N_{battery}$	COE ($)	NPC ($)
WT/DG/Battery	-	10	10	95	0.387	835714

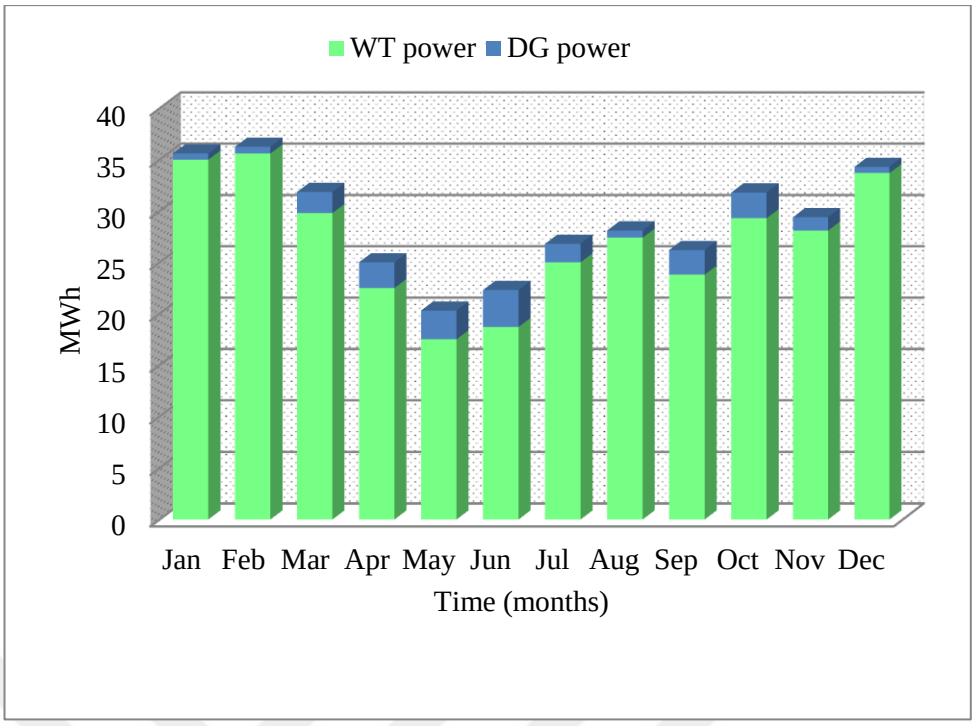


Figure 4.8 Monthly electric production.

Due to the presence of moving parts in both systems, which are WT and DG, in addition to the consumption of DG fuel, both systems need a high price of O&M costs as shown in Table 4.8. In this case, the replacement price of the DG is more than that in the case of PV/DG/battery, so it means that the generator has worked more hours.

Table 4.8 Net prices of system components.

Component	Capital ($)	Replacement ($)	O&M ($)
WT	300000	0.00	106747.76
DG	5500	7905.88	8954
Battery	68590	42816.33	182538.67
Converter	41237.86	12999.89	4001.86
System	415327.86	63722.11	302242.30

Figure 4.9 shows the energy generation output of the optimal system of this scenario. The figure indicated that the DG is working fewer hours than the case of PV. It

works just between 200 and 250 hours because the battery is kept more than its minimum SoC during the whole 14 days except these hours. It means that the WT energy can meet the electrical load demand efficiently and the DG is needed to increase the reliability of the system for a short time only.

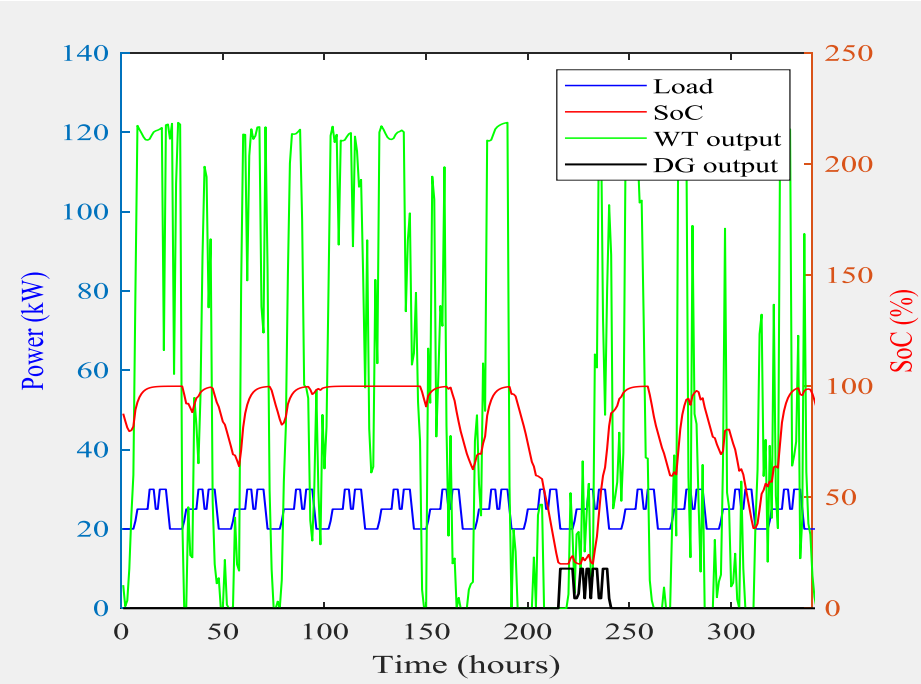


Figure 4.9 System output**.**

4.1.5 Scenario 5: PV/WT/DG/Battery

The optimal combination of this case is the system that consists of 107 kW for PV, 3 units of WT, 10 kW DG and 45 units of batteries as shown in Table 4.9. PV produces 165068 kWh/year; WT produces 96329 kWh/year and DG produce 27100 kWh/year that account for 57.2%, 33.4% and 9.39% of the total energy generated, respectively. The COE and NPC of the system are found as 0.25 $ and 568431 $, respectively.

Table 4.9 Optimal system sizes.

Schemes	P_{PV}(kW)	N_{WT}	P_{DG}(kW)	$N_{battery}$	COE($)	NPC ($)
PV/WT/DG/Battery	107	3	10	45	0.25	568431

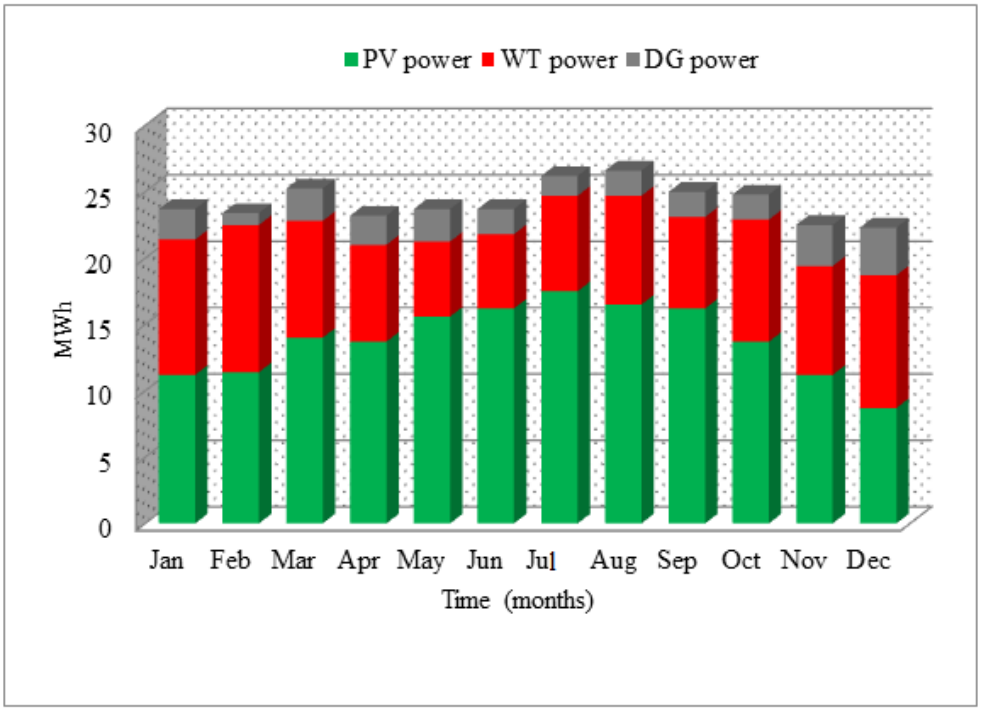


Figure 4.10 Monthly electric production.

Table 4.10 presents the prices of system components. As we can see, the usage of WT and PV reduced the number of batteries as well as the COE and NPC. Using wind and solar energy in the system can provide a better improvement over the costs.

Table 4.10 Net prices of system components.

Component	Capital ($)	Replacement ($)	O&M ($)
PV	160500	0.00	5711.01
WT	90000	0.00	32024.33
DG	5500	10007.22	10760.17
battery	32490	35113.85	86465.69
converter	19250	6068.40	1868.09
system	307740	51189.48	136829.28

4.2 Optimization result

The detailed comparative analysis for the result of the five scenarios is indicated in Table 4.11 and Figure 4.10. HOMER software and PSO algorithm are used to find out the technical and optimal system. In each scenario, the properties of the system components used are exactly the same with the same meteorological data. The main idea of this study is to design a reliable system with low cost, so the priority is to find a reliable system that can meet the load demand efficiently with low COE and NPC.

Table 4.11 Different cases of system configurations.

Schemes	$P_{pv}(kW)$	N_{WT}	$P_{DG}(kW)$	$N_{battery}$	NPC ($)	COE ($)	LPSP
Scenario 1							
PV/battery	245	-	-	104	730165	0.337	9.1%
Scenario 2							
WT/battery	-	13	-	150	1.04 M	0.44	9%
Scenario 3							
PV/DG/ battery	177	-	10	80	644897	0.295	9.6%
Scenario 4							
WT/DG/ battery	-	10	10	95	835714	0.38	9.9%
Scenario 5							
PV/WT/ DG battery	107	3	10	45	568431	0.25	9%

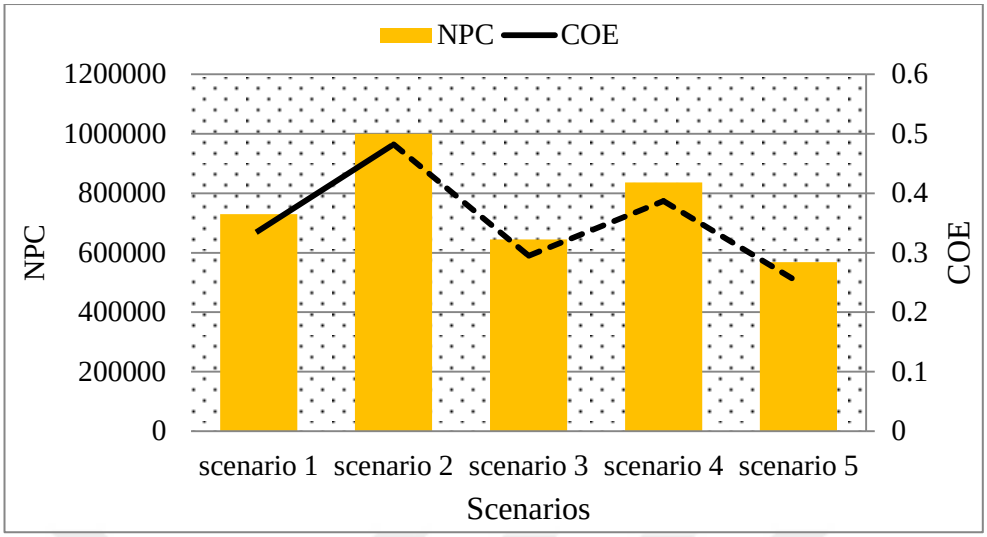


Figure 4.11 Different micro-grid configuration.

As demonstrated in Table 4.11 and Figure 4.11, the PV/WT/DG/battery HRES in scenario 5 has the lowest COE and NPC. Because of the high wind speed and solar radiation in the proposed site, PV/WT/DG/Battery HRES has a better economic effect than PV/battery, WT/battery, PV/DG/Battery and WT/DG/Battery systems.

The results obtained from PSO algorithm are presented in Table 4.12. Three configurations are presented to check the effect of sources on the system. In the first configuration, the system consists of 80 kW PV, 4 units of WT, 10 kW of DG and 40 unites of batteries with COE of 0.27 $/kWh. It is clear to see that the system is not able to meet the load demand because the LPSP is 0.32 so it means that there will be a shortage. In the second configuration, the system consists of 90 kW of PV, 4 unites of WT, 10 kW of DG and 43 units of batteries with COE of 0.24 $/kWh. It shows that the increasing of PV rate can decreases the LPSP to 0.17 but still this ratio is not acceptable. In the third configuration, the system consists of 106 kW of PV, 3 unit of batteries, 10 kW of DG and 43 unit of batteries with cost of energy of 0.22 $/kWh. The LPSP in this case is 0.1. We can figure out that this configuration has the lowest COE and LPSP among the others so it is considered the optimal system that can meet the load demand efficiently with low COE.

Table 4.12 PSO configurations.

Configurations	PV(kW)	N_{WT}	DG(kW)	$N_{battery}$	COE($/kWh)	LPSP
Configuration 1	80	4	10	40	0.29	0.32
Configuration 2	90	4	10	43	0.27	0.17
Configuration 3	106	3	10	43	0.22	0.1

The result of PSO algorithm is near to the result of HOMER so it means that the PSO algorithm is a good option to use in optimization of HRES and it is able to optimize the system and get the optimal one among different configurations. The comparative results analysis for HRES through the HOMER and PSO technique is presented in Table 4.13.

Table 4.13 Optimal system combination.

Schemes	P_{PV}(kW)	N_{WT}	P_{DG}(kW)	$N_{battery}$	COE ($)	LPSP %
HOMER	107	3	10	45	0.25	9%
PSO	106	3	10	43	0.22	10%

While the PV/Battery, WT/Battery, PV/DG/Battery and WT/DG/Battery are reliable systems that do not produce much harmful gas emission, these systems are not good enough due to their higher costs.

The HRES that constitutes of 107 kW PV, 3 units of WT, 10 kW DG and 45 units of batteries, obtained in the fifth scenario, is the optimal system for meeting the electrical load demand to achieve ZEB's requirements for typical 30 households in a rural place in Ankara.

4.3 Details of The Optimal System

4.3.1 Generated power

The optimal result of a micro-grid HRES that consists of WT/PV/DG/Battery is described below. Figure 4.12 shows the monthly average energy generated by

different components of the HRES for one year. The power generated by PV and WT depends on solar radiation and wind speed. As a result, the power generated by the PV and WT is high and most of the load demand is met by them, so it means that the meteorological data of the selected place is suitable to install renewable energy systems. The figure also shows that the generated PV power is more than the generated WT because the system has higher rate of PV that WT.

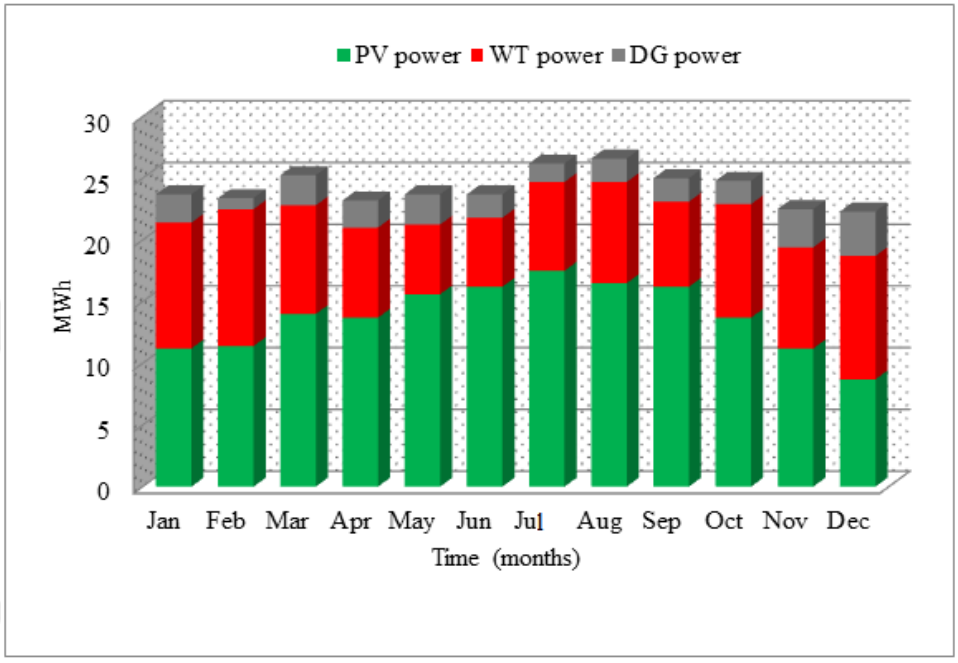


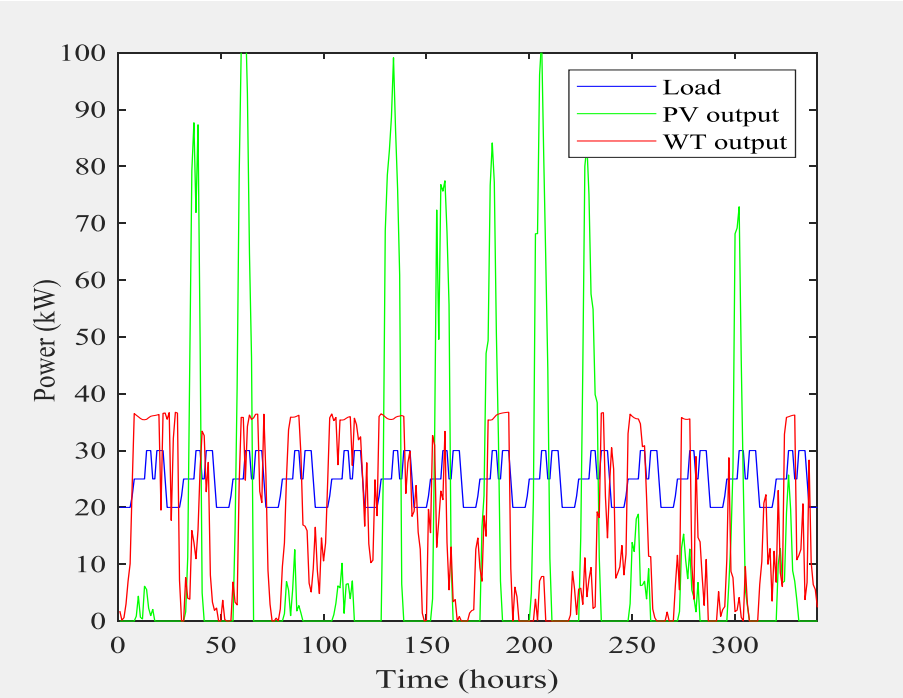
Figure 4.12 Monthly electric production.

The hourly power generated by renewable sources and load demand for two weeks in the months of January (representing winter) and July (representing summer) are shown in figures 4.12 (a) and (b). Battery storage is used to save electricity when it exceeds during the low load demand and aids the renewable energy sources to provide electricity for the load during the intermittency of renewable sources.

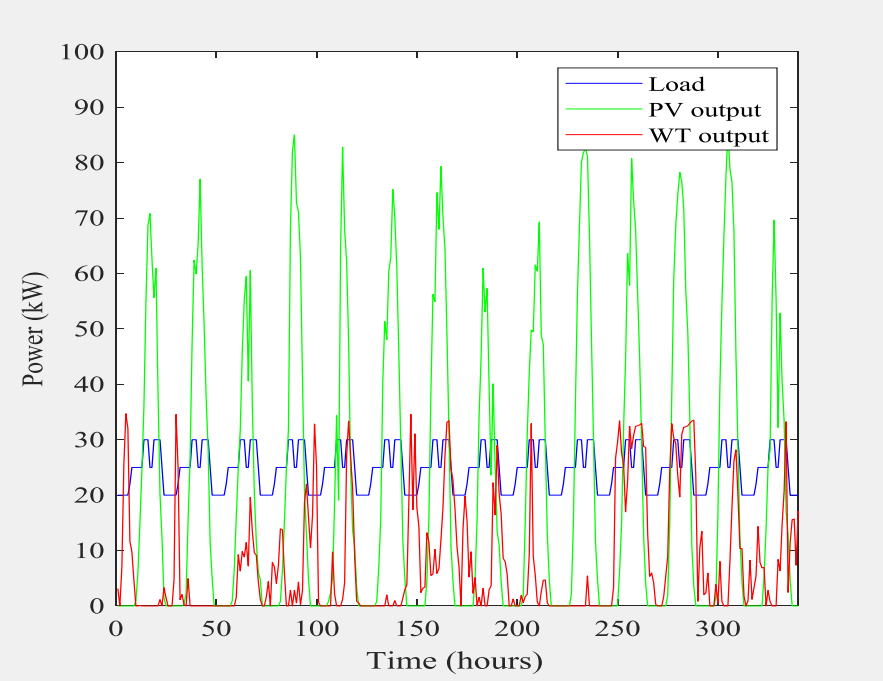
Figures 4.13 (a) and (b) shows the power generated by renewable sources and SoC of the batteries during the first ten days in January and July to see how renewable sources affect the charging of batteries.

The results show that the power generated by WT in January is more than July due to the high wind speed in January, while the PV generation in July is more than January due to the high solar radiation. Both generators are able to cover the load demand

and keep the battery at a high rate of SoC during the year, which can increase the lifetime of the batteries and reduce the cost of replacement.

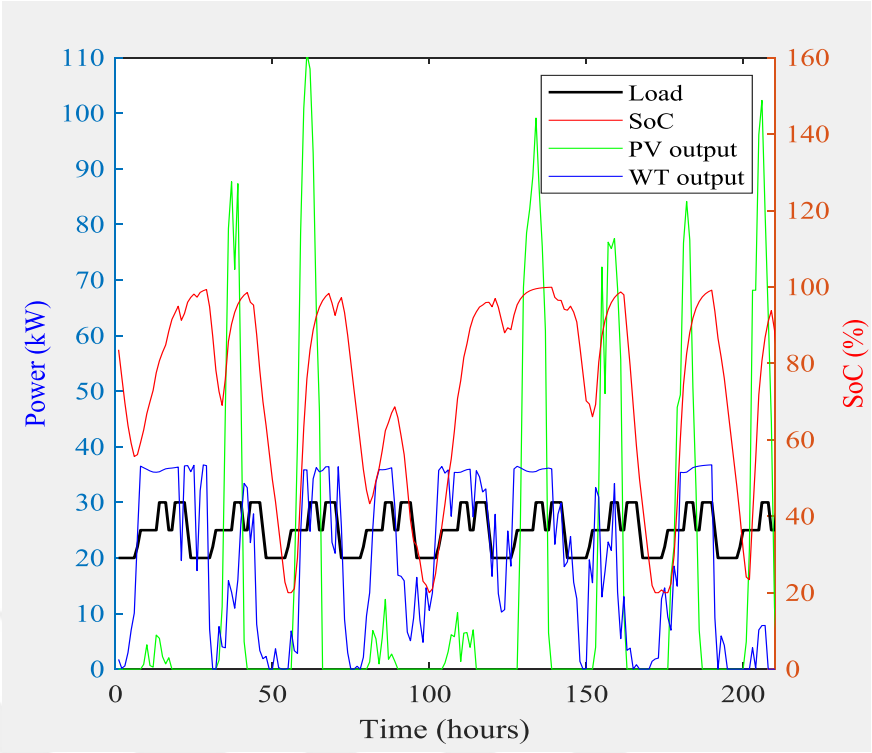


(a)

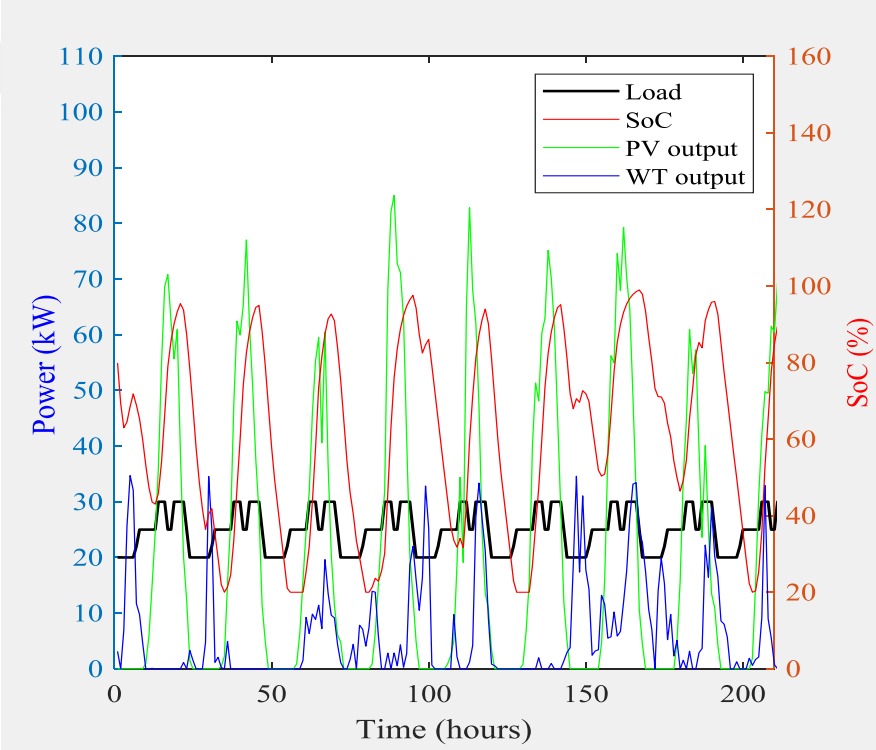


(b)

Figure 4.13 Hourly load demand and power generated by renewable sources of (a) First two weeks of January, (b) First two weeks of July.



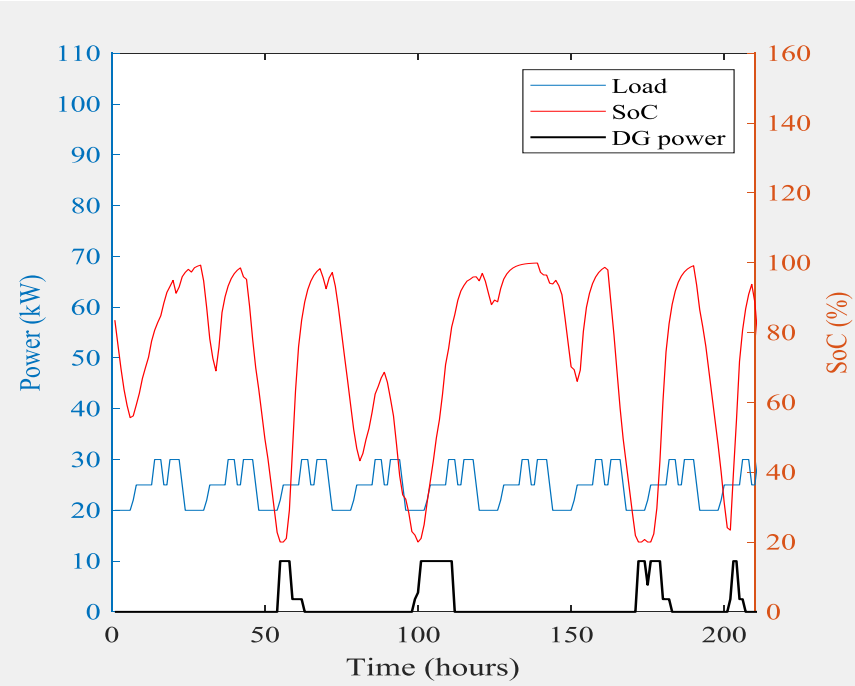
(a)



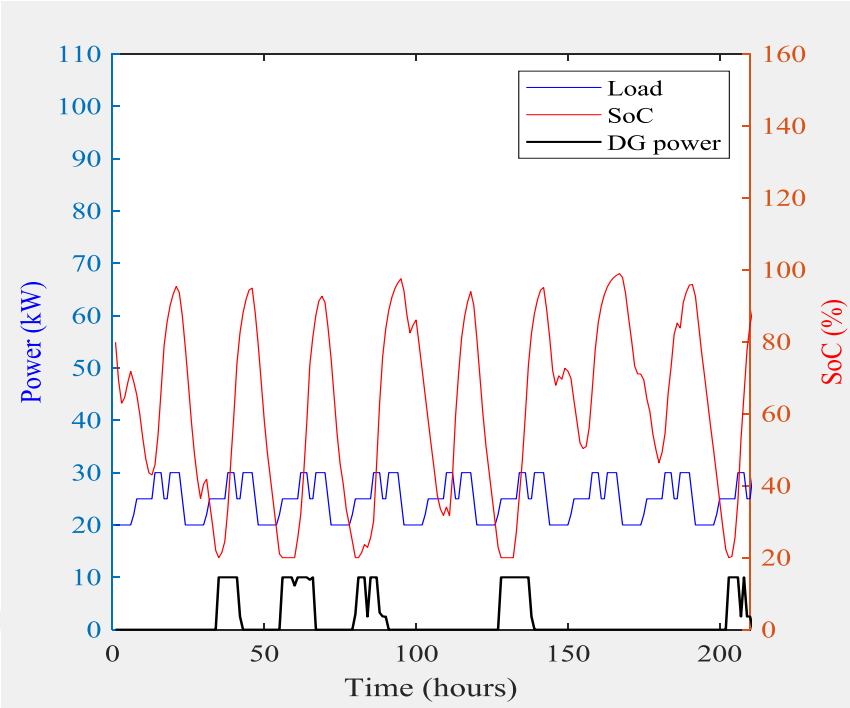
(b)

Figure 4.14 Hourly SoC and power generated by renewable sources of (a) First ten days of January, (b) First ten days of July.

DG is used instead of the battery to aid the renewable sources when the energy generated is not able to cover the load demand, and the battery reaches to its minimum SoC. Figures 4.14 (a) and (b) show the DG power, load demand and the SoC for the first ten days in January and July. The results show that DG operates when the battery reaches to its minimum SoC and the renewable sources need help to cover the load. Hence, the proposed system is able to cover the electrical load demand with an acceptable range of shortage by PV/WT/DG sources and batteries.



(a)



(b)

Figure 4.15 Hourly SoC, load and power generated by DG of (a) First ten days of January, (b) First ten days of July.

The cost analysis of the system components is mentioned in Table 4.10. PV has the highest capital cost than the WT and battery. The replacement cost of PV and WT is zero due to their long lifetime, while the replacement cost of DG is two times higher than the capital cost, so it means that it has replaced two times. The replacement cost of the battery is almost near to the capital cost, so it means that it has replaced one time. The COE is the average cost for each unit in kWh. It depends on the NPC of the system. The COE is found as 0.25 $/kWh while the NPC is 568431 $.

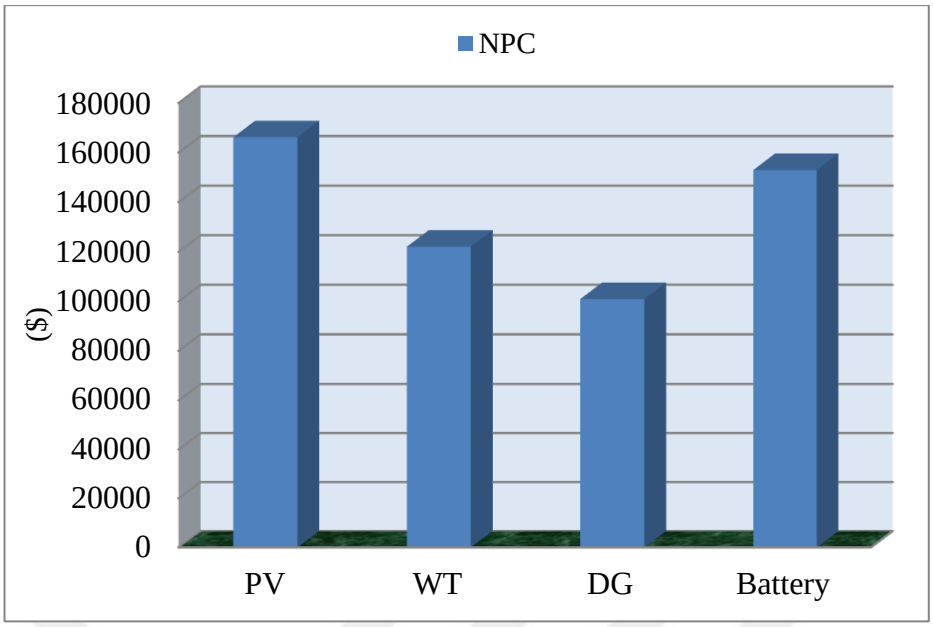


Figure 4.16 NPC of the system components.

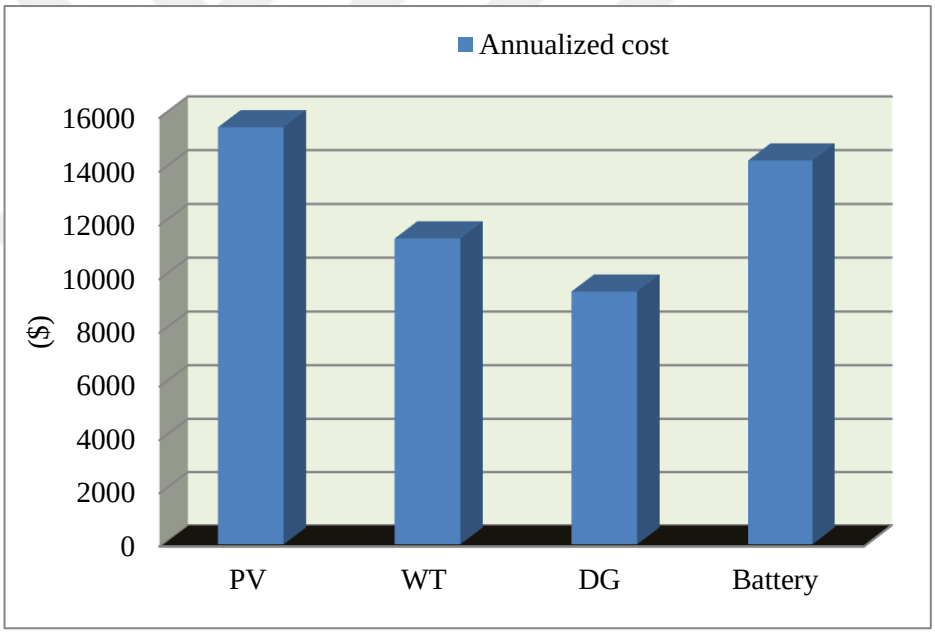


Figure 4.17 Annualized costs of the system components.

4.3.2 Emission

Although the renewable energy sources used in the system are clean and do not release any pollution but when the power generated is not enough to cover the load demand and the battery reached to its minimum SoC, the DG will replace renewable energy sources. In this case, different types of gasses are presented due to the burning of fossil fuel that the DG depends on. The annual emission is calculated by

the multiplying the emission factor by the total annual fuel consumption. Table 4.14 indicates the greenhouse emission in the proposed optimal system.

Table 4.14 Greenhouse emissions in the proposed optimal system.

Quantity	Value	Units
Carbon dioxide	24462	kg/year.
Carbon monoxide	185	kg/year.
Unburned hydrocarbons	6.74	kg/year.
Particulate matter	11.2	kg/year.
Sulfur dioxide	60.0	kg/year.
Nitrogen oxides	210	kg/year.

4.4 Sensitivity

The sensitivity is studied to find out the effect of changing some technical and economic factors of the system components on the system performance. In this study, fuel price, the effect of changing batteries on prices, the effect of changing batteries on emission, and the effect of changing the capital costs of PV and WT are used as sensitivity variables. The PV/WT/DG/LA battery is considered as a base system for this comparative study.

4.4.1 Effects of fuel price on the system costs

The fuel price that used in DG is variable due to the global market. In this study, nine prices are used to show the effect of fuel price on the COE and NPC. The prices used in sensitivity are 0.75 $, 0.85 $, 0.95 $, 1.05 $, 1.15 $, 1.25 $, 1.35 $, 1.45 $ and 1.55 $. O.75 $ is the base fuel price used in this study. The result showed that the COE and NPC of the system increase with the increase in fuel price. Doubling the fuel price increases the COE and NPC by around 14% and 13%, respectively.

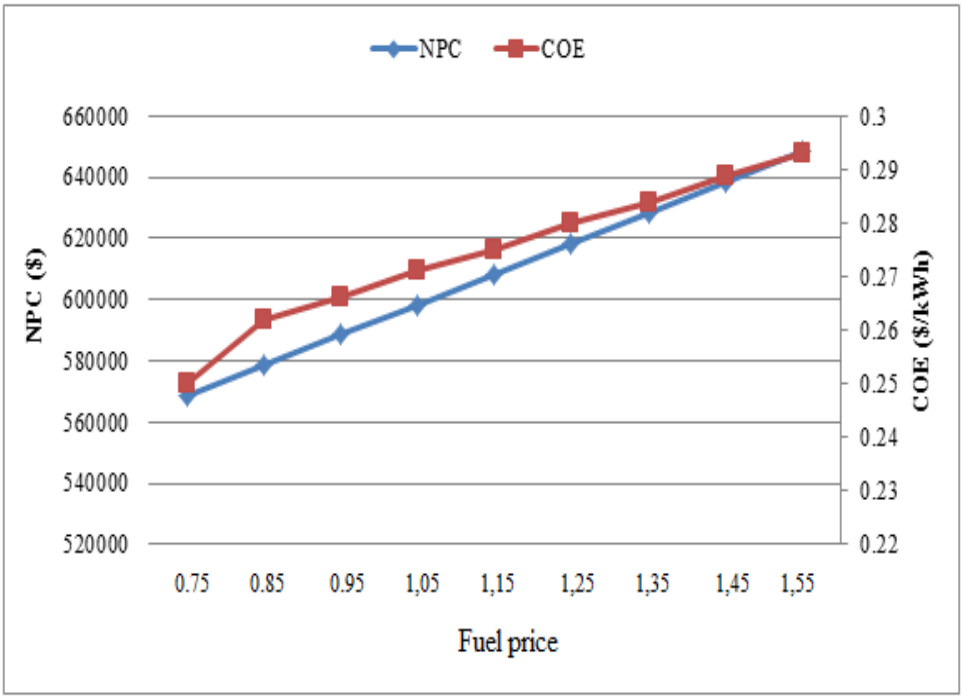


Figure 4.18 Variation of fuel price on the system cost.

4.4.2 Effects of changing batteries on system costs

According to the continuous technical development at the present time, there are different types of batteries being developed in the market. These types are of different sizes, capacities and prices according to the manufacturer. In this study, three different types of batteries are compared with the battery used in the optimal system to figure out their impact on the NPC and COE of the system. CELLCUBE FB 20-130 battery (VF battery chain), EnerStore 50 Agile Flow (zinc-bromine battery chain) and Tesla Powerwall 2.0 (LI battery chain) are used. The optimal system with LA battery is taken as a base in comparing with other types of batteries. Table 4.14 shows the technical and economical properties of the batteries used in the study [122].

Table 4.15 Technical and economical characteristics of batteries [122,159-163].

Name	Hoppecke 24 OPzS 3000	CELLCUBE FB 20-130 battery	EnerStore 50 Agile Flow	Tesla Powerwall 2.0
Type	LA battery	VF battery	ZF battery	LI battery
Nominal voltage (V)	2 V	48	100	220
Nominal capacity (kWh)	7.15	130	50	13.2
Maximum capacity (Ah)	3,570	2.71E+03	500	60
Maximum charge current (A)	610	383	150	31.8
Maximum discharge current (A)	610	599	300	31.8
Capital cost ($)	722	2300	780	6,500
Replacement cost ($)	665	2250	720	6,000
O&M cost ($/year.)	180	0	0	0
Lifetime (year)	10	20	30	10
Dimensions in meter (L×W×h)	0.21×0.5×0.8	4.5×2.1×2.4	2.2×1.2×2	0.15×0.75×1.1

The capital costs of the batteries are different from one to another. LI battery has the highest cost which is around 6000 $ while the LA battery has the lowest cost which is around 180 $. VF and ZF prices are 2250 and 720, respectively. The reason for the

existence of these price discrepancies is because of the technologies used in the manufacture of these batteries as well as the materials used

Although the LI battery has the highest cost, its lifetime is around 10 year which is considered as low lifetime comparing with the other batteries. ZF battery has the highest lifetime which is around 30 years. LA and VF have 10 years and 20 years, respectively.

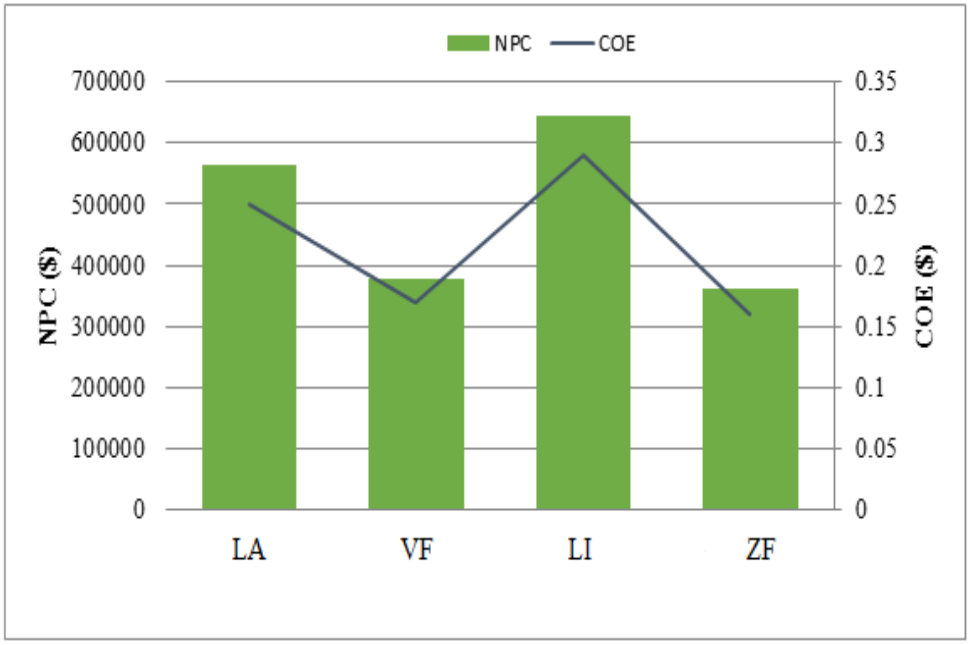


Figure 4.19 Affect of batteries on system costs**.**

It can be seen from Figure 4.19 that VF and ZF have lower COE and NPC than LA while LI has highest. LI battery increase the COE and NPC by around 14% and 13%, respectively while ZF and VF reduce the COE by around 34% and 32% and NPC by around 36% and 33%, respectively. Therefore, using another type of battery could reduce the total cost of the project.

Each battery unit has a specific size associated with it. Therefore, the space that each group of batteries take up is different based on the selected type of batteries. The overall size of battery can be found by multiplying the length, width and height of a unit of chosen battery and then multiplied with the required number of battery units. Accordingly, estimated overall size for LA, LI, ZF and VF are found as 4 m^3, 2.8 m^3, 138 m^3 and 154 m^3, respectively. It can be inferred that although the VF and ZF batteries are more suitable from the price side, they take up a large space comparing

with the LA and LI batteries. In stationary applications such as buildings, the size of batteries are usually not an essential criterion. However, the size of batteries is important if the system is installed in places with limited space.

4.4.3 Effects of changing batteries on emission

The type and the quality of the battery affect the total performance of the system because it provides electricity (when the renewable resources are not able to meet the load demand) whenever it has charge. If the battery has no charge, the DG will supply electricity for the load which release gasses emission. If the battery has a good quality or has stable charge and discharge, it will reduce the operating time of DG which subsequently reduces the gas emissions. Table 4.16 shows the effect of different batteries on greenhouse emission. The result shows that the system with ZF battery has the lowest gas emissions.

It can be concluded that selecting the suitable battery can improve the comprehensive performance of the HRES in terms of technology, environment and economy.

Table 4.16 Effect of different batteries on greenhouse emission.

Quantity	LA	VF	LI	ZF
Carbon dioxide (kg/year)	24462	9432	13330	5958
Carbon monoxide (kg/year)	185	71.3	101	45.1
Unburned hydrocarbons (kg/year)	6.74	2.60	3.67	1.64
Particulate matter (kg/year)	11.2	4.33	6.11	2.73
Sulphur dioxide (kg/year)	60.0	23.1	32.7	14.6
Nitrogen oxides (kg/year)	210	81.1	115	51.2

4.4.4 Effect of changing PV and WT prices on system cost

The costs of generating electricity from renewable energy have experienced a significant decrease over the past decade due to the development of technologies, economies of scale, increased supply chain competitiveness and growing developer

experience [164,165]. National Renewable Energy Laboratory (NREL) researchers indicated that the prices of renewable energy systems constantly decrease. The COE generated by WT decreased by around 62% from 1990 to 2000 per MWh, while the installation cost of PV reduced by around 15% from 2010 to 2011 [65,66].

Solar PV costs have decreased by 82% since 2010, concentrated solar energy has decreased by 47%, land wind energy by 39% and marine wind energy by 29%; This is according to cost data collected by the International Renewable Energy Agency (IRENA) from 17,000 power generation projects during 2019. There are no indications that the costs of solar and wind technologies will stope falling. Auctions and power purchase agreements indicate that the average prices of solar PV and wind energy can drop by 42% and 18%, respectively in projects scheduled to operate in 2021 compared to 2019 [166,167].

In this study, the capital costs of PV and WT multiplied by 0.6, 0.7, 0.8 and 0.9, respectively to see the effect of decreasing the prices on the system costs. Table 4.17 shows that COE and NPC reduced by around 16% and 18%, respectively when the capital costs multiplied by 0.6.

Table 4.17 COE and NPC of the system with 5 multipliers.

System	Capital multiplier	COE ($)	NPC ($)
PV/WT/DG/Battery	1	0.25	568431
	0.9	0.246	543381
	0.8	0.234	518331
	0.7	0.223	493281
	0.6	0.212	468231

CHAPTER 5

5 CONCLUSION AND FUTURE WORK

5.1 Conclusion

The problem of increasing demand for energy, reduction of fossil fuel resources, high prices of transmission lines and environmental has become one of the major issues in the world that must be addressed. Buildings consume a large proportion of the total energy consumed and therefore it is one of the major reasons for these problems. Most of the electricity generating stations which provide electricity for houses, factories, schools and universities depend on fossil fuel especially in rural and remote villages. This has negative outcomes such as air pollutions, raise in fuel price and the costs for system installation. Renewable sources of energy must be considered as a priority to solve or reduce these problems. Wind and solar are clean energy sources with vast potential to reduce the dependence on conventional energy sources and are being utilized for power generation worldwide. However, solar energy is available only on clear day while wind is very intermittent. The stochastic nature of these energy sources with dependence on environmental conditions raise the reliability issues of solar or wind power systems. An off-grid solar energy system or a wind energy system are not able to supply reliable power as such with suitable price because they need high rate of power and storage capacity. Off-grid hybrid renewable energy system (HRES) is considered as a solution. The HRES are those in which two or more energy sources are integrated to operate simultaneously to supply power with at least one renewable energy source. These systems can become appropriate alternative to conventional energy systems and can meet the requirements of institutions, industries and communities in urban and remote rural regions. In order to design a hybrid system, it is very important for the investor to consider the minimum configuration cost for fulfilling the load demand. In this study, the examination of installing PV, WT, DG and battery are carried out to supply electricity for 30 households in a remote area in Ankara.

Five configurations of systems were compared which are PV/Battery, WT/Battery, PV/DG/Battery, WT/DG/Battery and PV/WT/DG/Battery to have the optimal system that meets the load demand efficiently with low cost. HOMER software and PSO algorithm are applied to obtain the optimal configuration of the system and sizing of the system components. The meteorological data of Ankara (solar radiation, wind speed and ambient temperature) are tested for this purpose. In sensitivity analysis, effects of fuel price on system costs, changing batteries on system cost, changing batteries on gasses emission and changing PV and WT capital costs on system cost are carried out to verify the results. Three types of batteries are compared with the LA battery sensitivity. The results show that the renewable energy sources would be a favorable and feasible solution for ZEB. They also indicated that implementation of micro-grid HRES can be considered as the most promising solution to meet the load demand for rural and remote regions and can be applied for the studied place with a high energy quality. The HRES that constitutes of 107 kW PV, 3x10 kW WT, 10 kW DG and 45 units of batteries is the optimal choice for the electrical load of 30 households in Ankara. PV produces 165068 kWh/year, WT produces 96329 kWh/year and DG produce 27100 kWh/year that account for 57.2%, 33.4% and 9.39% of the total energy generated, respectively. The COE and NPC of the system are found as 0.257 $ and 568431 $, respectively. The results of sensitivity show that the COE and the NPC of the system increase with the increase in fuel price. Doubling the fuel price, increases the COE and NPC by around 14% and 13%, respectively. Using other types of batteries can reduce or increase the system costs and gas emissions. LI battery increases the COE and NPC by around 14% and 13%, respectively while it takes the least size of place. ZF reduces the COE and NPC by around 34% and 36%, respectively. VF reduces the COE and NPC by around 32% and 33%, respectively while it takes the highest size of place. Moreover, compared to other battery technologies, ZF battery illustrates the lowest gas emission among the others. The result also shows that reducing the capital costs for PV and WT to the half could reduce the COE and NPC by around 20% and 12%, respectively. The results are expected to be beneficial to the government, researchers and engineers working in the renewable energy and standalone systems.

5.2 Future work

Depending on previous and current studies, there is a great desire to develop ZEB and renewable energy systems. Although there are several types of renewable energy sources in Turkey, it still suffers from techno-economic studies on integration of other sources such as biomass, geothermal, micro-hydro, in the form of a stand-alone HRES. In addition to the types and characteristics of electric power storage units which are constantly evolving, there are some suggestions for future works that as:

1. Disseminate this study to the rest of Turkey and find out the suitability of installing renewable energy systems for ZEB in the rest of the regions.
2. Incorporating other renewable energy sources such as biomass, geothermal, micro-hydro with various types of energy storage technologies to present new selections of renewable systems under ZEB framework.
3. In sensitivity, a study of the effect of some other factors that could affect the efficiency of the system should be investigated more accurately and it would be better to compare the results of the current study with the actual results after the project was set up to ensure the accuracy of the study and for further decision making in rural electrification.

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