ANALYSIS OF FIRMNESS IN RENEWABLE ENERGY SOURCES WITH ENERGY STORAGE

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by

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ABSTRACT

Renewable energy has gained renewed attention due to recent developments in the energy sector, particularly as a potential solution to global warming and for reducing dependence on imported energy sources. This study focuses on the firm capacity that hybrid systems can provide to support the transition from thermal to renewable energy systems. The aim is to determine the required size of an energy storage system, such as a battery, to replace a 1 MW diesel generator or any other thermal system. A linear programming model was developed to minimize the size of the energy storage system required and lower the capital investment costs. Then the results of the mathematical model are used as inputs for another system called the Metric Calculator. The results obtained by the sensitivity analyses applied to the developed model such as different locations and different renewable energy technologies are analyzed and presented as case studies in this study. Case studies were presented to illustrate the results of the analyses. The findings indicate that it is possible to transition to renewable energy while maintaining firmness at its maximum by utilizing an energy storage system like a battery.

ÖZETÇE

Yenilenebilir enerji, özellikle küresel ısınmaya potansiyel bir çözüm olarak ve ithal enerji kaynaklarına bağımlılığı azaltmak için yeniden gündeme gelmiştir. Bu çalışma, termal sistemlerden yenilenebilir enerji sistemlerine geçiş sürecini desteklemek için hibrit sistemlerin sağlayabileceği sağlamlık kapasitesine odaklanmaktadır. Amaç, 1 MW dizel jeneratörü veya başka bir termal sistem yerine kullanılabilecek bir enerji depolama sistemi (pil gibi) için gereken boyutu belirlemektir. Gereken enerji depolama sistemi boyutunu minimuma indirmek ve sermaye yatırım maliyetlerini azaltmak için lineer programlama modeli geliştirilmiştir. Matematiksel modelin sonuçları daha sonra Metric Calculator adlı başka bir sistem için girdi olarak kullanılır. Geliştirilen modelde farklı lokasyonlar ve farklı yenilenebilir enerji teknolojileri gibi hassasiyet analizlerine uygulanan sonuçlar bu çalışmada vaka çalışmaları olarak analiz edilmiş ve sunulmuştur. Analiz sonuçlarının sunulduğu vaka çalışmalarıyla sonuçlar ortaya konulmuştur. Bulgular, pil gibi bir enerji depolama sistemi kullanılarak sağlamlık seviyesinin maksimumda tutulmasıyla yenilenebilir enerjiye geçişin mümkün olduğunu göstermektedir.

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CHAPTER I

INTRODUCTION

According to the United Nations Population Projection, the world population will reach 10.3 billion in 2040. This situation reveals the necessity of meeting the energy needs of more people.Energy consumption in the world is increasing day by day due to population growth, urban development and industrialization. Due to the increasing demand for electricity, the use of renewable energy sources is becoming widespread.The International Energy Agency predicts that after 2022, average annual electricity demand will increase by 2.7% per year, and as the use of renewable energy sources expands, they can meet more than 90% of the increasing net demand [1].Renewable energy is considered as a technology that can meet the energy demand of countries by reducing the needs of countries for imported energy and energies produced with fossil fuels. In addition, since there is no carbon emission in the production of renewable energy, measures are taken against global warming.Renewable energy appears to be the most efficient and cleanest alternative to replace fossil fuels such as coal and natural gas. In addition, renewable energy is a good alternative for the island countries that provide their energy with diesel generators away from the grid connection. However, renewable energy production has a variable production feature due to natural conditions and this is seen as a risk for the electricity grid.The increasing penetration of renewable energy sources such as wind and solar power in the electricity grid has led to an increased need for more reliable and stable power sources. We need to understand how much and how often the demand can be met with renewable energy. Dispatchability and firmness capacity are two key challenges that need to be addressed in order to fully realize the potential of renewable energy sources. In this study, the definitions of firmness capacity and dispatchability are given as follows:

Firmness is the ability of the energy obtained from a Variable Renewable Energy (VRE) source selected at a certain capacity to provide a fixed amount of electricity for each day and hour of that month, and a different amount for each month, as a result of 12-month analysis.

Dispatchability is the capacity to provide the desired power at the desired level without loss of energy at any time of the day.

The integration of renewable energy resources into the electricity grid is crucial for achieving a more sustainable energy future and reducing dependence on fossil fuels. However, the integration of renewable energy resources into the grid can be challenging due to their variable nature. Therefore, it is necessary to find ways to improve the dispatchability and firmness capacity of these resources in order to integrate them more effectively into the electricity grid.

Renewable energy systems lack these two concepts. For example, a wind energy plant cannot produce energy in the absence of wind. Therefore, it is not firm.Similarly, due to the direct use of sunlight in electricity generation and the absence of storage devices such as batteries in most installations, solar energy cannot be delivered and this causes energy throttling [14].The higher these concepts are held during electricity generation with renewable energy, the less the need for fossil fuels will be.For example, keeping these dispatchability and firmness capacity concepts at 100% in an off-grid island country that generates power with a diesel generator means that renewable energy will meet 100% of electricity demand without using any fossil fuels.It is necessary to use an energy storage system to keep the measurements at 100%. A battery of sufficient capacity can make it possible to reach the energy needed in all conditions and facilitate the integration of renewable energies such as wind and solar energy into the electricity grid.Also, due to the random behavior and unpredictability of solar radiation and wind speed, a battery energy storage system is required to supply the load in case of insufficient renewable generation [15].Battery storage can also help with frequency control and stability for short-term needs, and help with energy management or reserves for longer-term needs [16].

The aim of this study is to investigate the role of energy storage systems that are enabling island grids to transition to 100% renewable energy and find the size of the battery energy storage system (BESS) that can replace a 1 MW diesel generator or any other thermal system.There are a few studies on battery sizing for various applications however, this study is the first one developing a mathematical model to quantify the energy storage capacity requirement to fully replace a thermal generator with all its capabilities with a Variable Renewable Energy (VRE)+Energy Storage System(ESS) hybrid system.

1.1 Problem statement of thesis

The increasing penetration of renewable energy resources, such as wind and solar power, in the electricity grid has led to concerns about their dispatchability and firmness capacity. Dispatchability refers to the ability to generate power on demand, firmness capacity refers to ability of the energy obtained from a Variable Renewable Energy (VRE) source selected at a certain capacity to provide a fixed amount of electricity for each day and hour of that month, and a different amount for each month, as a result of 12-month analysis. The problem is that renewable energy resources are dependent on weather conditions and are therefore not always able to generate power on demand or maintain power output during grid disturbances. The aim of this study is to investigate the role of energy storage systems that are enabling island grids to transition to 100% renewable energy and find the size of the battery energy storage system (BESS) that can replace a 1 MW diesel generator or any other thermal system.

1.2 Motivation of thesis

The world is facing a pressing need to transition to renewable energy sources in order to combat climate change and reduce dependence on fossil fuels.Renewable energy resources, such as wind and solar power, have the potential to significantly contribute to this transition, but their integration into the electricity grid is not without challenges. Dispatchability and firmness capacity are two key challenges that must be addressed in order to fully realize the potential of renewable energy resources.Dispatchability refers to the ability to generate power on demand, while firmness capacity refers to ability of the energy obtained from a Variable Renewable Energy (VRE) source selected at a certain capacity to provide a fixed amount of electricity for each day and hour of that month, and a different amount for each month, as a result of 12-month analysis.Improving the dispatchability and firmness capacity of renewable energy resources is crucial for their effective integration into the electricity grid and for achieving a more sustainable energy future.

The motivation of this thesis is to investigate and explore innovative solutions to improve the dispatchability and firmness capacity of renewable energy resources, so as to ensure a more stable and reliable supply of electricity from renewable energy sources and to support the transition towards a more sustainable energy in the future.

1.3 Scope

The scope of this thesis is to investigate and explore methods for analysis of firmness capacity in renewable energy sources such as wind and solar power with energy storage. This thesis will focus on the following areas:

1-Investigating the role of energy storage systems that are enabling island grids to transition to 100% renewable energy and finding the size of the battery energy storage system (BESS) that can replace a 1 MW diesel generator or any other thermal system.

2- Conclusions and recommendations for future research on this topic, including areas for further investigation and potential opportunities for collaboration with industry stakeholders.

The research for this thesis will be based on literature review, technical calculations using data and case studies. Research will focus on the technical and economic aspects of the problem and solutions will be evaluated on the basis of feasibility and scalability.

CHAPTER II

LITERATURE REVIEW

There are not many articles about firmness metrics but there is a specific study on how to calculate firmness and dispatchability metrics and represent their solution to reach full firmness and dispatcability in target markets [14]. In this study, dispatchability and firmness are defined as follows; ''Dispatchability is defined as the capacity to adapt power output to required levels at any time of the day without wasting primary energy.” ''Firmness is defined as the capacity to provide a certain (threshold) power output when needed by the grid operator. In this study, the threshold was defined as 95% of the electricity demand.” In the study [14], the results of dispatchability and firmness in target markets where electricity demands are different were compared by specifying the mathematical equations along with the definitions of the expressions of dispatchability and firmness.In conclusion, this study showed that the hybrid solar energy system is not an additional source to fossil fuel power plants, but solar energy is a solution to obtain dispatchable and firm energy [14].

Other than this study, there are many studies and methodologies on photovoltaic (PV) - battery sizing and placement. A study presents an algorithm to determine the optimal size of a photovoltaic (PV) generation system, diesel generator and energy storage system (PV/diesel/ESS) that minimizes investment, fuel costs and CO2 emissions in a ship power system [15]. This algorithm has been developed by taking into account the seasonal and geographical changes of the sun’s rays on a determined route. When the energy produced from the PV and diesel generator in the system exceeds the total demand, the energy is stored by the battery. When the demanded energy is more than the produced energy, the battery is discharged. This makes the system firm [15].In conclusion, this study shows that the current cost required for hybrid PV/diesel/ESS electricity generation is lower than the cost required for diesel electricity generation [15].

In other study [17] , the minimum battery size and the best location in the distribution system are obtained by optimizing the amount of active and reactive power depending on the network topology [17].

In another study [18], a decision support tool has been developed for optimum sizing and investment decision of the grid-connected PV/battery system using electricity prices, weather data, PV/battery system cost and PV dynamics. The model uses the MILP program for savings in electricity bill and can determine whether it is economical to invest in PV for investment decision analysis. The model determines the best PV/battery system and optimal dimensions from the available options [18].

In another study [19], it is tried to reach the optimum configuration by finding the optimum size and placement of the PV arrays to examine the effects of adding a battery storage system to the distribution network using the Genetic Algorithm technique [19].

Finally, a BES sizing model is proposed that gives the optimal battery energy storage (BES) size for extending microgrids [20]. The simulation shows that the proposed model can determine the optimum BES size, technology, number and increases the accuracy of BES sizing solutions [20].

CHAPTER III

CONCEPT, TYPES AND SOURCES OF ENERGY

3.1 Concept of Energy

Energy is a property of physical systems that allows them to perform work. It can take various forms, including thermal, mechanical, electromagnetic, and chemical energy, and it can be transformed from one form to another. Energy is an essential component of the universe and it is involved in many physical and biological processes. The concept of energy is central to many fields of study, including physics, engineering, and economics. Energy is conserved, meaning that it cannot be created or destroyed, only transformed from one form to another. This principle is known as the law of conservation of energy, and it is a fundamental concept in the study of physics and engineering. The laws of thermodynamics describe how energy can be transformed and used, and they have important implications for the sustainable use of energy resources. The concept of energy is of great importance in many areas of science and technology, including renewable energy, climate change, and sustainability. By understanding and managing energy sources and uses, we can work towards creating a more sustainable and equitable future. The study of energy is important for understanding a wide range of phenomena, from the behavior of individual particles to the functioning of the entire universe.

3.1.1 Future of Energy

The world is moving towards a more sustainable and low-carbon energy future, driven by a growing recognition of the need to address climate change and reduce dependence on fossil fuels. This change is reflected in a number of trends and developments in the energy sector.These trends and developments can be explained as follows;

Increasing use of renewable energy: There has been a growing investment in renewable energy sources, such as wind, solar, and hydro power, as countries aim to reduce their dependence on fossil fuels and transition to more sustainable energy sources.

Decarbonization of the electricity sector: The electricity sector is undergoing a significant transition as countries aim to reduce greenhouse gas emissions. This is leading to the closure of coal-fired power plants and an increase in the use of clean energy sources.

Energy efficiency: There is a growing focus on improving energy efficiency and reducing energy waste across all sectors, including industry, buildings, and transportation.

Electrification of transport: There is a growing trend towards electrifying transportation, including the use of electric vehicles and the development of charging infrastructure.

Energy storage: The development of advanced energy storage systems is allowing for the integration of renewable energy sources into the electricity grid, improving the reliability and stability of the power system.

Digitalization of the energy sector: The use of digital technologies, including smart grid systems, is revolutionizing the way energy is managed, distributed, and consumed.

These trends are expected to continue in the coming years, leading to a more sustainable and low-carbon energy future. However, significant challenges remain, including the need to ensure energy access for all, address energy poverty, and develop cost-effective solutions for the integration of renewable energy into the electricity grid. In addition, the deployment of renewable energy technologies at scale requires a comprehensive approach that addresses the environmental and social impacts of these technologies, including the management of natural resources, land use, and community engagement. Furthermore, as renewable energy systems become more widespread, there is a growing need for effective energy storage solutions to overcome the intermittent nature of some renewable sources and ensure reliable power supply. The development and deployment of such storage systems present significant opportunities for innovation and investment, but also require careful consideration of technical, economic, and environmental factors. Therefore, collaboration among policymakers, investors, and communities is crucial to achieving a sustainable and inclusive energy future.

3.2 Types of Energy

There are various types of energy as Kinetic energy, Thermal energy, Potential energy, Nuclear energy, Electrical energy, Chemical energy, Radiant energy and Mechanical energy.

Thermal energy: The energy associated with the temperature and movement of particles in a substance.

Potential energy: The energy an object possesses due to its position or state, such as gravitational potential energy.

Nuclear energy: The energy released from the nucleus of an atom, either through nuclear fission or fusion.

Chemical energy: The energy stored in the bonds between atoms and molecules, it is released during chemical reactions.

Radiant energy: The energy associated with electromagnetic waves, such as light, x-rays, and radio waves.

Mechanical energy: The energy associated with the movement and position of an object, it is the sum of kinetic and potential energy.

Electrical energy: The energy associated with the movement of electrons, it is used to power electrical devices and equipment.

These forms of energy can be transformed from one form to another and can be combined in various ways to perform work. Understanding the different types of energy is important for understanding many physical and biological processes, as well as for developing new energy technologies.

3.2.1 Types of Electrical Energy

Electrical energy is the energy associated with the movement of electrons. There are several types of energy as Direct Current (DC) Energy, Alternating Current (AC) Energy, High Voltage Energy, Low Voltage Energy, AC/DC Energy and Renewable Energy.

Direct Current (DC) Energy: It is energy that is a constant flow of electric charge in one direction, as in a battery.

Alternating Current (AC) Energy: When a voltage (force) is applied to substances containing free electrons, the electrons begin to move. With the electrical movement of the electrons in the atom from the negative region to the positive region, the phenomenon we call ”current” occurs. AC is an electric current that changes direction periodically, it is the most common form of electrical energy used in homes and businesses.

High Voltage Energy: It is high voltage electrical energy that is generally used in large power transmission systems.

Low Voltage Energy: It is a low voltage electrical energy typically used in small electrical appliances and devices.

AC/DC Energy: It is electrical energy that can be converted from AC to DC and vice versa, as in a rectifier.

Renewable Energy: It is the energy obtained from natural resources such as wind, solar, hydro, geothermal and biomass that are renewed faster than they are consumed.

These different forms of electrical energy have different properties and applications, and understanding them is important for designing and using electrical systems and devices.

3.3 Sources of Electrical Energy

Various energy sources in nature are used to generate electricity.These sources are two types, these are renewable sources and non-renewable sources.

3.3.1 Non-Renewable Energy Sources

Non-renewable energy is the energy obtained from natural sources, finite, cannot be reused. Non-renewable energy sources are not sustainable. Another feature of non-renewable resources is that they are only found at certain points in the world. These resources need soil with certain geological features to form. In addition, since they are sources of sulphur, carbon and nitrogen, they harm the environment. However, it has a more balanced structure in terms of quantity and energy potential compared to renewable energy sources. It is seen as an important energy source for many industries, but the damage these non-renewable energy sources cause to the environment is undeniable. There are also many disadvantages such as the fact that the resources are not sustainable and subject to a limited supply process.

The most common non-renewable energy sources are fossil fuels and Nuclear energy.

Fossil Fuels: Coal, oil, and natural gas are formed from the remains of plants and animals that lived millions of years ago. These fuels are used for heating, transportation, and electricity generation.

Coal is a non-renewable fossil fuel that is primarily composed of carbon, along with smaller amounts of other elements such as sulfur, nitrogen, and hydrogen. It is formed from the remains of plants that lived millions of years ago, which over time have been buried and subjected to high temperatures and pressures, causing them to transform into coal.

Coal is primarily used for electricity generation, but it is also used as a fuel for heating and in some industrial processes. It is a major contributor to global greenhouse gas emissions and air pollution, and its extraction and use are associated with a range of environmental impacts, including deforestation, land degradation, water pollution, and the displacement of local communities.

Oil, also known as petroleum, is a non-renewable fossil fuel that is primarily composed of hydrocarbons, a type of organic compound made up of hydrogen and carbon atoms. It is formed from the remains of plants and animals that lived millions of years ago, which over time have been buried and subjected to high temperatures and pressures, causing them to transform into oil.

Oil is primarily used for transportation, as fuel for vehicles such as cars, trucks, and airplanes. It is also used for electricity generation and as a feedstock for a range of chemical products, including plastics and fertilizers.

Like other non-renewable energy sources, oil is associated with a range of environmental impacts, including greenhouse gas emissions, air pollution, and the risk of oil spills and other accidents during production and transportation. In addition, the extraction and use of oil is often politically and socially controversial, with many countries relying on oil imports and the production and export of oil playing a significant role in global economics and politics.

Natural gas is a non-renewable fossil fuel that is primarily composed of methane, a colorless and odorless gas. It is formed from the remains of plants and animals that lived millions of years ago, which over time have been buried and subjected to high temperatures and pressures, causing them to transform into natural gas.

Natural gas is primarily used for heating and electricity generation. It is also used as a feedstock for the production of chemicals and as a fuel for transportation in the form of compressed natural gas (CNG) or liquefied natural gas (LNG).

Compared to other fossil fuels, such as coal and oil, natural gas is considered to be a cleaner energy source, as it produces lower greenhouse gas emissions and air pollution when burned for energy. However, the extraction and use of natural gas are still associated with environmental impacts, including the release of methane during production and transportation, and the risk of gas leaks and other accidents.

As a result, there is a growing interest in reducing the use of natural gas, oil, coal and transitioning to cleaner, more sustainable energy sources, such as renewable energy. This is being driven by concerns about the impacts of climate change, as well as the need to reduce air pollution and promote energy security.

Nuclear Energy: Nuclear energy is generated through nuclear reactions that take place in the nucleus of an atom, typically through the process of nuclear fission.

These energy sources are finite, and their extraction and use are associated with environmental impacts, such as air and water pollution, greenhouse gas emissions, and the risk of nuclear accidents.

Therefore, there is a growing interest in transitioning to renewable energy sources, which are cleaner and more sustainable. However, non-renewable energy sources will likely continue to play a significant role in the world's energy mix for the foreseeable future.

3.3.2 Renewable Energy Sources

Renewable energy refers to energy that is generated from natural sources that can be replenished or renewed within a relatively short period of time. These sources include sunlight, wind, water, geothermal heat, and biomass. Renewable energy is considered to be a clean and sustainable source of energy because it does not consume finite sources, and its use typically results in fewer greenhouse gas emissions and other pollutants compared to non-renewable sources.

Renewable energy can be obtained in many ways, such as the use of solar panels to capture sunlight and convert it into electricity, wind turbines to generate electricity from wind, hydroelectric dams to generate electricity from moving water, wave turbines to generate electricity from the waves and geothermal power plants to generate electricity from underground heat.

Renewable energy has gained significant attention and investment in recent years due to its potential to reduce dependence on fossil fuels, reduce the impacts of climate change, and create new economic opportunities. Many countries and businesses have set ambitious goals to increase the use of renewable energy and transition away from non-renewable sources.

The figure 1 below shows the electricity generation sources between 2000-2020 according to the international energy agency(IEA) in Organisation for Economic Co-Operation and Development (OECD) countries. The figure shows a clear trend towards renewable energy. While renewable energy sources are increasing, coal is falling rapidly.Gas is now the most common fuel source for electricity generation in the OECD. It is a fossil fuel that is cleaner than coal but contributes to global warming.

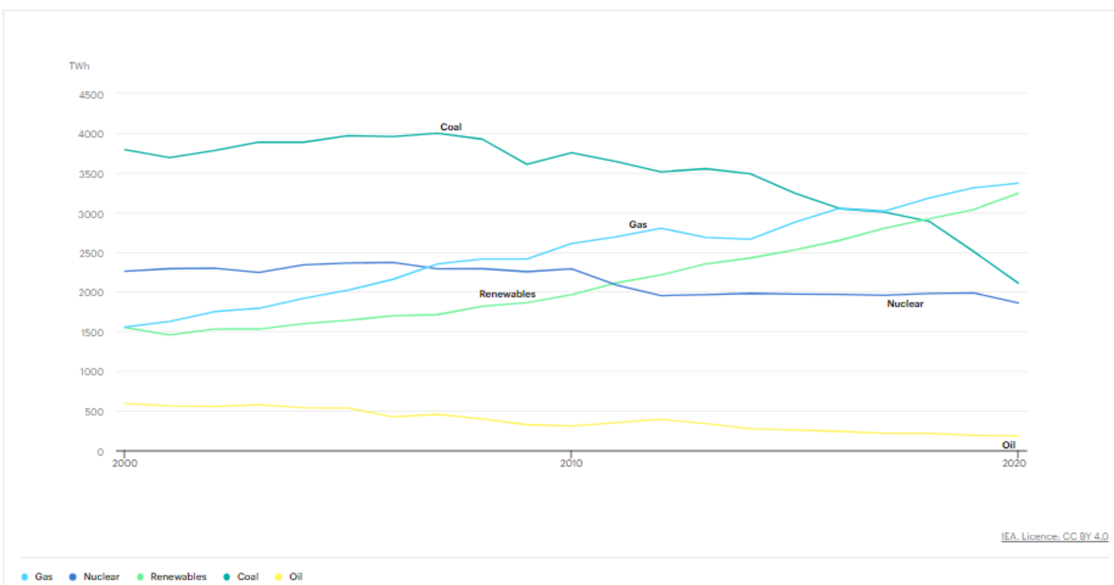

Figure 1: Sources of electricity generation according to OECD, 2000-2020

Renewable energy has importance in many areas such as environmental benefits, energy security, economic benefits, energy access, long-term sustainability and technological innovation. We can explain these areas in more detail as follows;

Environmental benefits: Renewable energy sources produce little to no greenhouse gas emissions and other pollutants that contribute to air and water pollution. This can help reduce the impacts of climate change and improve public health by reducing harmful emissions.Renewable energy sources provide several environmental benefits over non-renewable sources. Here are some of the environmental benefits of renewable energy:

-Renewable energy reduces greenhouse gas emissions. Renewable energy sources produce little to no greenhouse gas emissions, which can help reduce the impacts of climate change. The burning of fossil fuels for energy is a major contributor to global greenhouse gas emissions, and the transition to renewable energy can help reduce these emissions.

-Renewable energy reduces air and water pollution. Renewable energy sources produce little to no air or water pollution compared to fossil fuel sources. This can help improve public health and reduce the negative impacts of pollution on the environment.

-Reduces water usage: Many renewable energy technologies, such as wind and solar, require little to no water for energy production, unlike fossil fuel sources which often require large amounts of water for cooling and other processes.

-Renewable energy reduces land use impacts. Renewable energy sources typically require less land use than non-renewable sources, especially when compared to mining and extraction activities associated with fossil fuel production.

-Renewable energy protects biodiversity. Renewable energy sources can help reduce the negative impacts on biodiversity associated with the extraction, transportation, and use of non-renewable sources.

Generally, renewable energy sources provide a cleaner and more sustainable source of energy than non-renewable sources, and can help reduce the negative impacts on the environment associated with energy production and consumption.

Energy security: Renewable energy sources can reduce dependence on foreign energy imports and provide a more stable and diversified energy supply.Renewable energy can improve energy security in various ways by diversifying energy sources, reducing foreign dependency on energy, providing more reliable energy source, reducing energy waste, and providing energy in emergencies.

-Diversifying energy sources: Renewable energy sources provide a more diverse and decentralized energy supply, which can help reduce dependence on a single source of energy. This can help reduce the risks associated with disruptions in supply, such as political instability or conflicts over resources.

-Reducing foreign dependency on energy: Many countries depend on foreign energy imports, which can make them vulnerable to price volatility and supply disruptions. Renewable energy sources can provide a more stable and self-sufficient source of energy, reducing dependence on foreign energy imports and improving energy security.

-Providing a more reliable source of energy: Renewable energy sources are often more reliable than non-renewable sources, especially in remote areas or areas with unreliable grid infrastructure. For example, solar panels and wind turbines can provide a reliable source of electricity in areas that are off the grid or have limited access to electricity.

-Reducing energy waste: Renewable energy sources often provide energy in a more efficient way than non-renewable sources. For example, solar panels and wind turbines produce energy without wasting resources or generating excess heat, which can help reduce energy waste and improve energy security.

-Providing energy in emergencies: Renewable energy sources can provide a reliable source of energy during emergencies, such as natural disasters or power outages. For example, solar panels and wind turbines can provide electricity to critical infrastructure such as hospitals, emergency services, and communication networks.

Generally, renewable energy can improve energy security by providing a more diverse, reliable, and self-sufficient source of energy that is less vulnerable to supply disruptions and price volatility.

Economic benefits: Renewable energy can create jobs and new economic opportunities in manufacturing, installation, and maintenance of renewable energy systems. It can also provide a cost-effective energy source in some cases.Economic benefits: Renewable energy can create jobs and new economic opportunities in manufacturing, installation, and maintenance of renewable energy systems. It can also provide a cost-effective energy source in some cases.Overall, the economic benefits of renewable energy include job creation, cost savings, opportunities for economic growth, energy independence, and improved public health.

-Job creation: Renewable energy projects can create jobs in manufacturing, installation, and maintenance, among other areas. For example, the solar industry alone employs over 240,000 workers in the United States, according to the National Renewable Energy Laboratory.

-Cost savings: Renewable energy sources can provide cost savings over the long term, especially as the cost of technology decreases and economies of scale are realized. For example, the cost of solar panels has decreased significantly in recent years, making solar energy more cost-competitive with traditional sources of electricity.

-Economic growth: Renewable energy can provide opportunities for economic growth in areas such as manufacturing, research and development, and export markets. For example, many countries have invested in the development of renewable energy technologies as a way to create new export markets and attract foreign investment.

-Energy independence: Renewable energy sources can provide greater energy independence by reducing dependence on imported fossil fuels, which can be subject to price volatility and supply disruptions.

-Improved public health: Renewable energy sources can provide public health benefits by reducing air pollution and associated health problems. For example, the use of renewable energy can help reduce the emissions of pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter, which can have negative impacts on human health.

As renewable energy technologies continue to improve and become more cost-competitive with traditional sources of energy, these economic benefits are likely to become even more prominent.

Energy access: In many parts of the world, especially in rural areas, access to electricity is limited or non-existent. Renewable energy sources can provide a reliable and decentralized source of electricity to these areas. This can help improve quality of life, support economic development, and provide access to critical services such as healthcare and education.Renewable energy sources such as solar and wind can help reduce energy costs by providing a low-cost and sustainable source of power. This is particularly important in areas where traditional sources of energy, such as diesel generators, are expensive and inefficient.Renewable energy can help improve energy security by providing a decentralized and distributed source of power. This can help reduce reliance on imported fossil fuels and traditional grid infrastructure, which can be vulnerable to disruptions and outages.Renewable energy can increase resilience to natural disasters and other shocks by providing a decentralized and distributed source of power. This can help ensure that critical services such as hospitals and emergency response systems are able to function during power outages.

Long-term sustainability: Renewable energy sources are sustainable and do not consume finite sources, unlike fossil fuels which are non-renewable and are expected to become increasingly scarce and expensive over time. Renewable energy sources such as solar, wind, hydro, and geothermal produce little or no greenhouse gas emissions, which is crucial in the fight against climate change. By replacing fossil fuels with renewable energy, we can significantly reduce our carbon footprint and help reduce the negative impacts of climate change. Unlike fossil fuels, renewable energy sources such as solar and wind are abundant and freely available. This means that we don't have to consume finite sources to produce energy, helping to protect natural sources for future generations.

Technological innovation: The development and generalize of renewable energy sources can drive technological innovation and create opportunities for new products and services.Renewable energy is a rapidly improving field, and for this reason, it requires significant research and development efforts. The high demand for renewable energy has created a strong incentive for researchers and innovators to develop new and innovative technologies, spurring technological advancement and breakthroughs.The transition to renewable energy is creating entirely new industries and markets. As the demand for renewable energy increases, so does the need for related products and services. This has opened up new opportunities for businesses, leading to the development of new technologies and products.As technology advances and economies of scale are achieved, the cost of renewable energy technologies is decreasing. This creates a efficent cycle in which the growth of the renewable energy market drives down the cost of the technology, making it more accessible to a wider range of consumers. Renewable energy technologies provide new solutions to long-standing energy challenges. For example, energy storage technologies allow for the reliable integration of variable renewable energy sources such as wind and solar power into the grid, providing a more stable and secure source of energy. Renewable energy technologies are constantly improving, leading to greater efficiency and productivity. This is especially important in sectors such as transportation, where electric vehicles powered by renewable energy can significantly reduce emissions and improve overall efficiency.

Generally, renewable energy is an important driver of technological innovation, incentivizing research and development, creating new industries, driving down costs, providing new solutions to energy challenges, and increasing efficiency and productivity. By continuing to invest in renewable energy, we can foster continued growth and innovation in the technology sector, while also creating a more sustainable and resilient energy system.

In conclusion, renewable energy has the potential to provide a clean, sustainable, and reliable source of energy that can benefit the environment, society, and the economy.

3.3.2.1 Geothermal Energy

Geothermal energy is a renewable energy source that harnesses heat from the Earth's core and converts it into electricity. This energy is produced from natural reservoirs of hot water and steam found deep beneath the Earth's surface.There are 3 main types of geothermal power plants: dry steam power plants, flash steam power plants, dual steam cycle power plants.

Dry steam power plants: It is the oldest method used to generate electricity from geothermal sources. Very high temperature geothermal sources are used to generate electricity. It is the simplest type of geothermal power plant systemically and the lowest cost. These plants use steam directly from underground reservoirs to drive turbines and generate electricity.

There are two types, condenserless and condenser cycle.In the condenserless steam cycle, the steam extracted from the geothermal well is discharged into the atmosphere after passing through a turbine.The advantage of this cycle is that since there is no condenser, the construction and operating costs of the power plant are less than the power plants with condensers. An undesirable result of this cycle is that the direct discharge of geothermal steam into the atmosphere causes environmental pollution.

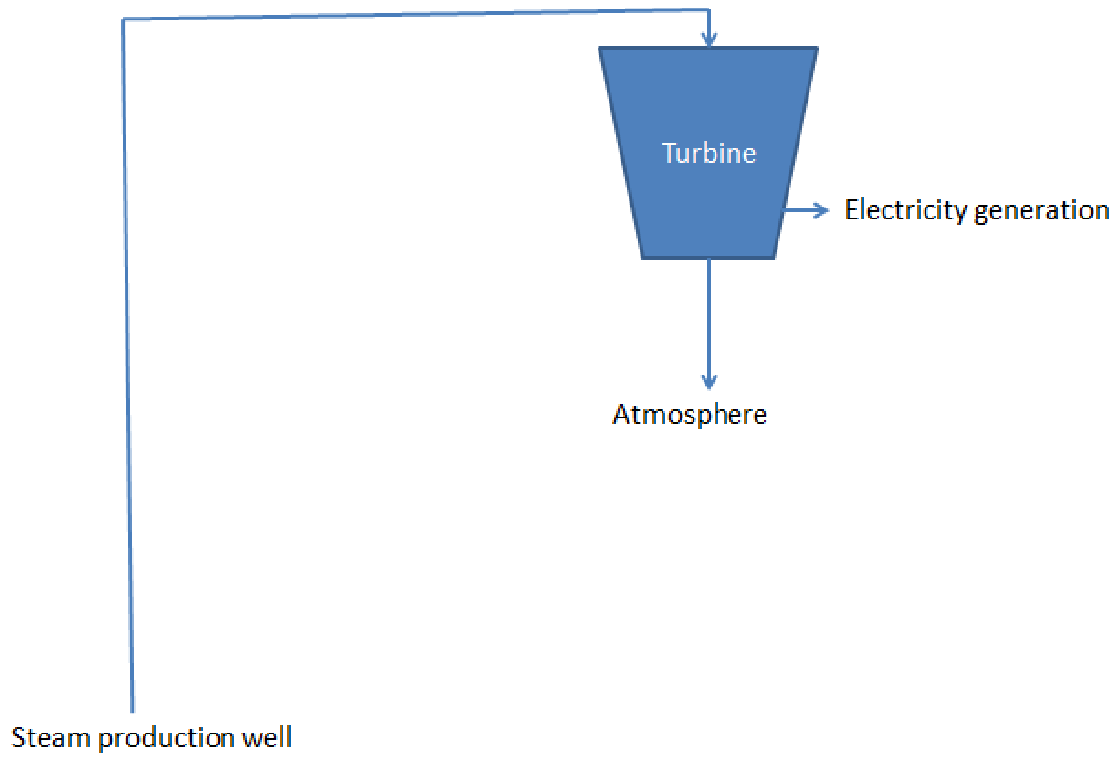

Figure 2: Condenserless steam cycle geothermal power plant

Condenser steam cycles have a condenser at the exit of the turbine.After the geothermal steam passes through the turbine, it enters a condenser. The steam condensed in the condenser is injected underground again. Thanks to the condenser, the steam leaves the turbine at lower pressure and lower temperature. In this way, a greater proportion of the thermal energy of the steam is converted into power. For this reason, steam cycles with condensers produce more electricity than those without condensers. Additionally, condenser steam cycles also contribute to the efficiency of geothermal power plants by reducing the amount of water used. The condensed steam can be recycled back into the system, reducing the need for fresh water and minimizing the plant's environmental impact. Furthermore, the use of a condenser also helps to increase the operational lifespan of the turbine, reducing the frequency of maintenance and downtime.

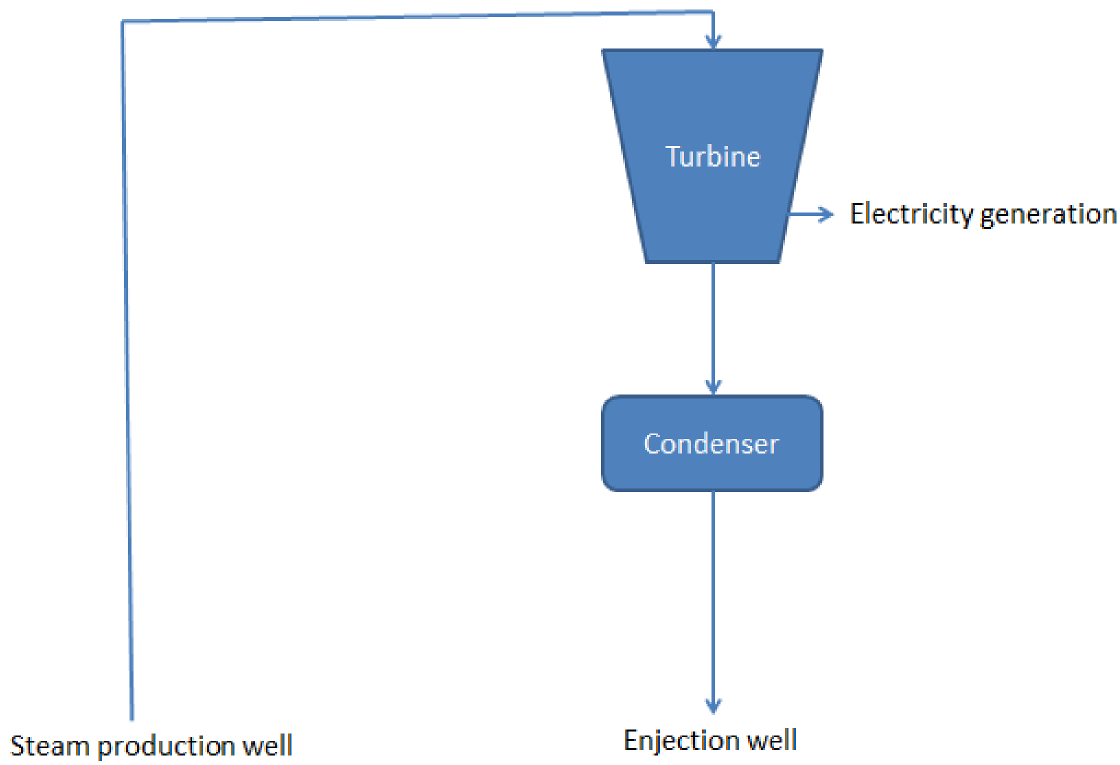

Figure 3: Condenser steam cycle geothermal power plant

Flash steam power plants:Hot water from the geothermal reservoir is pumped up through a production well and into a separator tank. The water is under very high pressure and temperature due to the natural heat of the earth's crust. Once the hot water reaches the separator tank, the sudden drop in pressure causes some of the water to "flash" into steam. This steam is then separated from the remaining water. The steam is then directed into a turbine, where it expands and rotates a generator to produce electricity.The remaining water is reinjected into the geothermal reservoir, where it is reheated and ready to be pumped up again. Flash steam power plants are one of the most common types of geothermal power plants in use today. They are particularly effective in areas where the geothermal reservoirs are relatively shallow, and the water is very hot and under high pressure. While flash steam power plants can be more complex to operate than other types of geothermal power plants, they are also capable of producing large amounts of electricity, making them an important part of the global renewable energy mix.

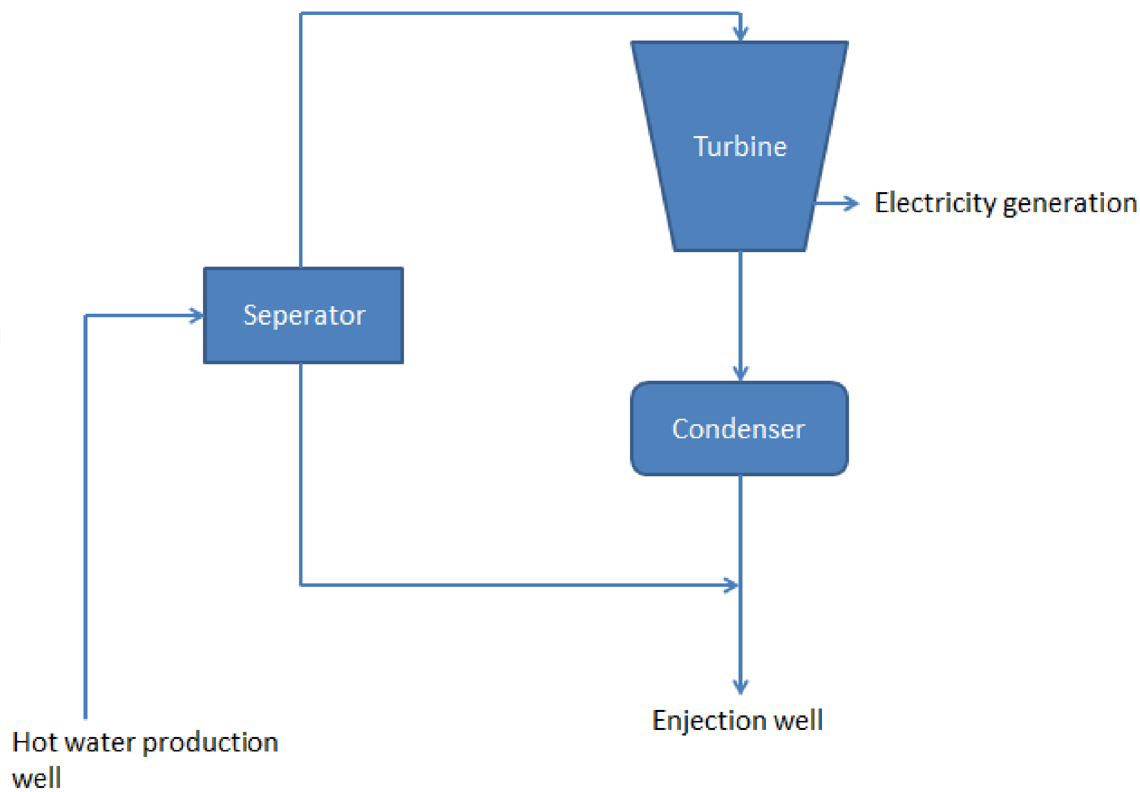

Figure 4: Flash steam geothermal power plant

The advantage of a flash steam power plant is that it can generate electricity with a relatively low temperature geothermal resource. However, the high pressures involved can make the equipment expensive to build and maintain, and there are concerns about the sustainability of geothermal reservoirs if they are not managed properly.

Dual steam cycle power plants: Hot water from the geothermal reservoir is pumped up through a production well and into a heat exchanger. This hot water is not hot enough to flash into steam, so it is used to heat up a secondary fluid, usually an organic fluid with a low boiling point. The secondary fluid is pumped through a heat exchanger, where it absorbs the heat from the hot water and turns into steam.

This steam is then used to rotate a turbine, which generates electricity.After the secondary fluid has passed through the turbine, it is cooled back down to a liquid state using a condenser, and then pumped back to the heat exchanger to start the process over again.The hot water from the geothermal reservoir is reinjected into the ground, where it is reheated and ready to be pumped up again.

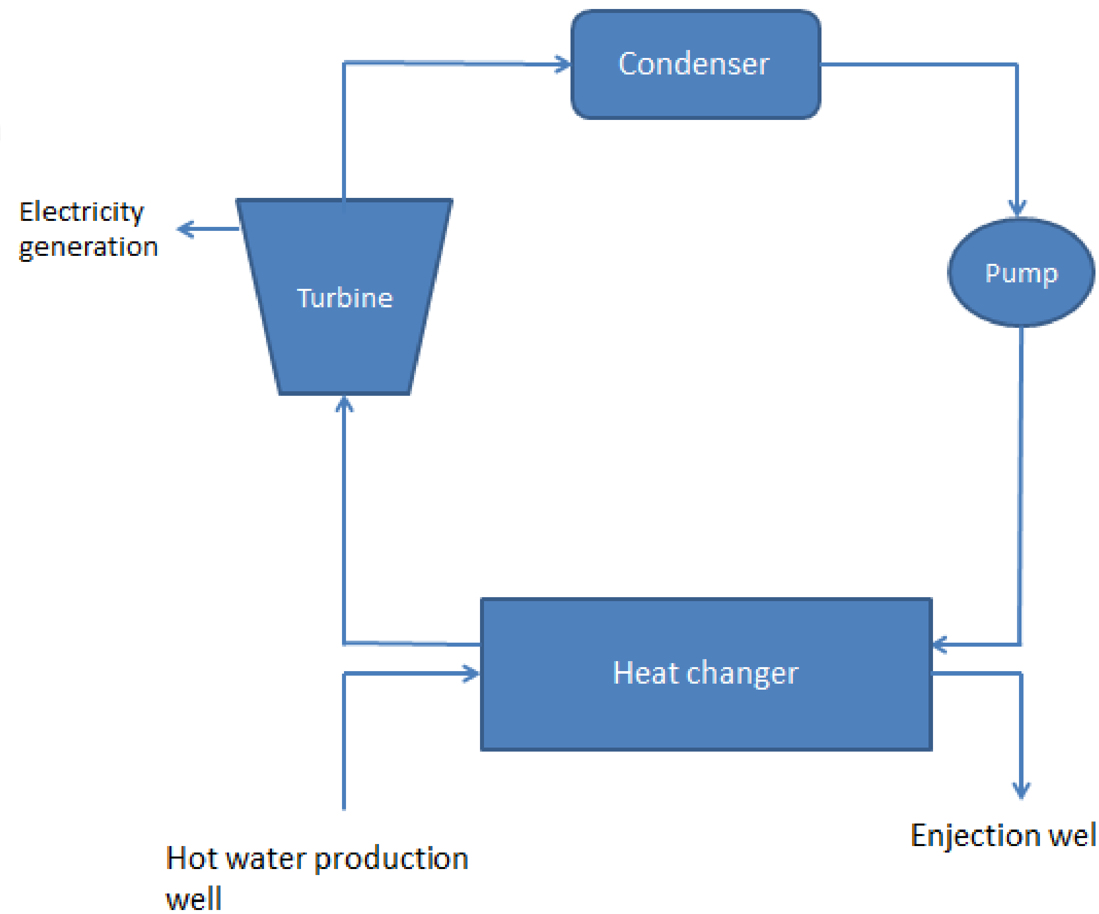

Figure 5: Dual steam cycle geothermal power plant

The advantage of a dual steam cycle power plant is that it can generate electricity using lower temperature geothermal sources, which are more common than high temperature sources. It is also less prone to scaling and mineral deposits than flash steam power plants, which can clog up pipes and equipment. However, the organic fluids used in the process can be expensive, and the efficiency of the power plant can be affected by the temperature difference between the geothermal water and the secondary fluid.

Geothermal energy has several advantages according to other energy sources, such as being renewable, low emissions, reliable and cost-effective.We can explain these advantages as follows;

Renewable: Geothermal energy is a renewable resource, as the heat it produces is continuously replenished by the Earth's core.

Low emissions: Geothermal energy produces very low emissions, as it does not burn fossil fuels and therefore does not release carbon dioxide or other pollutants into the atmosphere.

Reliable: Geothermal power plants can operate 24/7, providing a consistent source of electricity.

Cost-effective: While the initial capital cost of building a geothermal power plant can be high, the operational costs are relatively low, making geothermal energy a cost-effective option over the long-term.

However, there are also some challenges associated with geothermal energy. Geothermal energy is only available in areas where there are natural reservoirs of hot water and steam, which can limit its widespread use.Building a geothermal power plant can be expensive, as it requires specialized equipment and drilling deep into the Earth's surface.While geothermal energy produces very low emissions, there are still concerns about its potential impact on the surrounding environment, such as the risk of earthquakes and land subsidence.

3.3.2.2 Hydroelectric Energy

Hydroelectric energy is a type of renewable energy that is generated taking advantage of the power of moving water. Hydroelectric power plants use dams, reservoirs, and water turbines to convert the kinetic energy of flowing water into electricity.The process of generating electricity from hydroelectric power involves the following steps:

- Water is stored in a reservoir behind a dam. The height of the dam creates potential energy in the water.
- Water is released from the reservoir, and it flows through a penstock, which is a large pipe that carries the water to the turbine.
- The water turns the blades of the turbine, which spins a generator to produce electricity.
- The water then exits the turbine and is released downstream.

Figure 6 shows these steps.

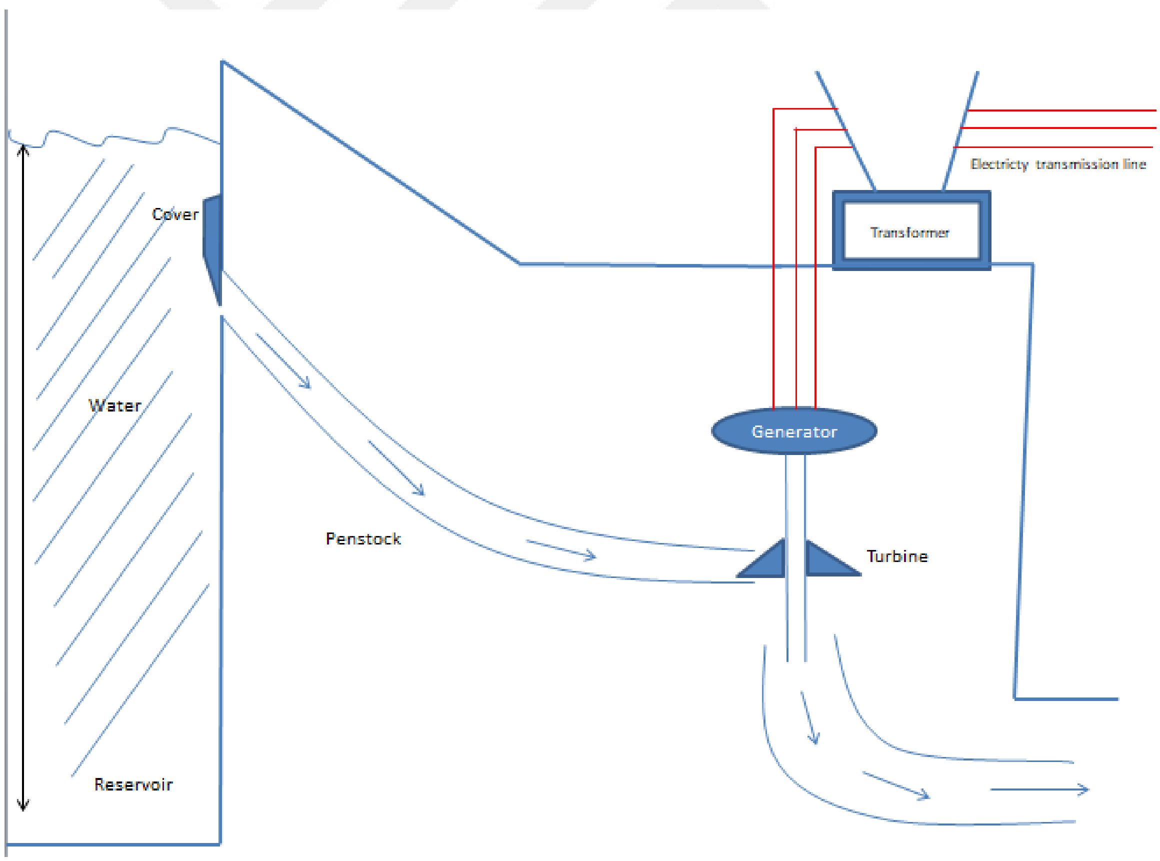

Figure 6: Hydroelectric power generation

There are 4 types of hydroelectric power plants. These are damless hydroelectric power plants, hydroelectric power plants with dams, tidal hydroelectric power plants and depression hydroelectric power plants.

Damless hydroelectric power plant : Damless hydroelectric power plants, also known as run-of-river hydroelectric power plants, generate electricity using the natural flow of rivers or streams, without the need for a dam or a large reservoir. These power plants takes advantage the kinetic energy of flowing water to turn a turbine, which drives a generator to produce electricity.The force of the water flowing through the turbine blades causes the turbine to spin and thereby the generator produce electricity. The water then flows out of the turbine and back into the river or stream.

One of the main advantages of damless hydroelectric power plants is that they have a lower environmental impact than traditional hydroelectric power plants with dams. They do not require large reservoirs, which can flood habitats and displace wildlife. Additionally, they do not have the same negative effects on downstream ecosystems, such as altering the flow and temperature of the river.Another advantage is that damless hydroelectric power plants can be built on a smaller scale, making them ideal for rural areas or remote communities. They can also be more cost-effective than traditional hydroelectric power plants, as they require less infrastructure.However, there are also some challenges associated with damless hydroelectric power plants. They are dependent on the availability and reliability of water flow in the river or stream, which can fluctuate over time due to changes in weather patterns or water usage. This can affect the consistency and reliability of electricity generation. Additionally, the construction and operation of these power plants can have an impact on local ecosystems and fish populations if not properly managed.

Hydroelectric power plants with dams: Dams are built on the river and water is collected here. This water has a certain potential energy. Therefore, even in dry years, electricity can be produced in such hydroelectric power plants. It is the most widely used type of hydroelectric power plant in the world.You can see the working principle in figure 6.

Tidal hydroelectric power plants: Tidal hydroelectric power plants generate electricity from the kinetic energy of ocean tides. These power plants rely on the rise and fall of ocean tides, which are caused by the gravitational pull of the moon and the sun.The basic principle of a tidal hydroelectric power plant is similar to a conventional hydroelectric power plant, in which the flow of water is used to turn turbines that generate electricity. However, in a tidal hydroelectric power plant, the flow of water is caused by the rise and fall of the tides, rather than the flow of a river.As the tide rises, water flows through gates in the barrage and turns turbines to generate electricity. When the tide falls, the gates are closed and the water is trapped behind the barrage. The water is then released through the turbines when the tide rises again, generating more electricity.

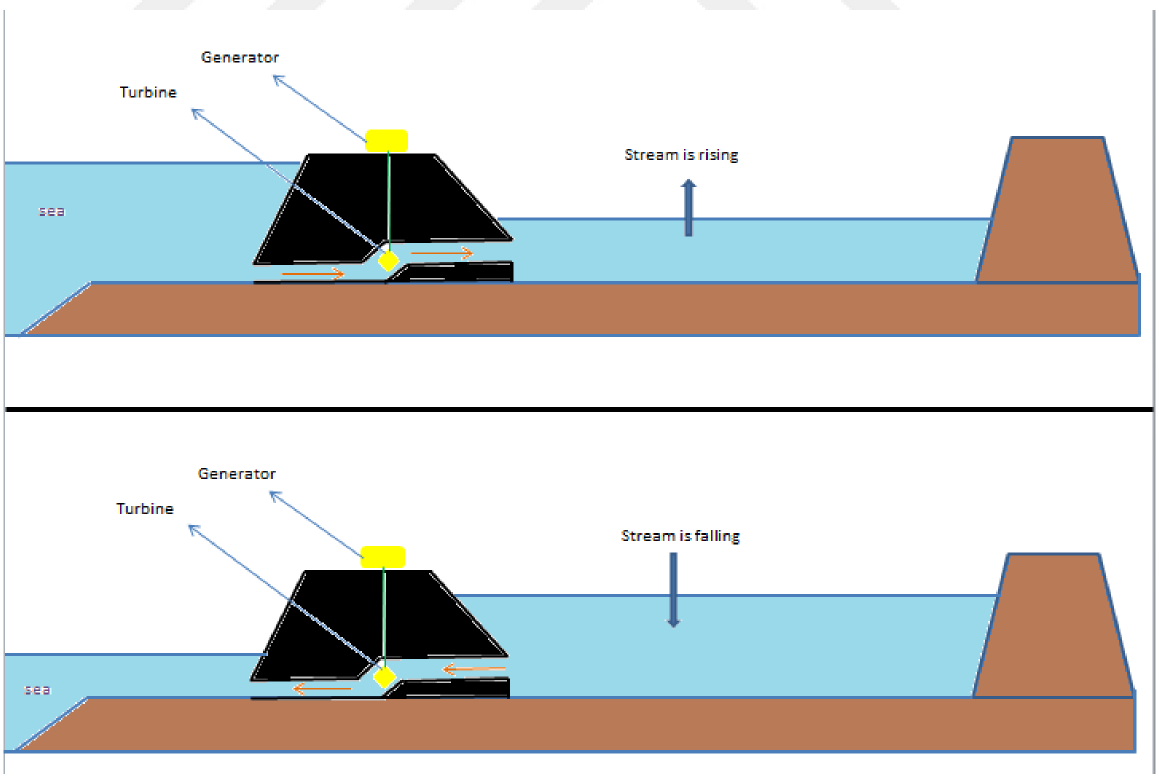

Figure 7: Tidal hydroelectric power generation

Tidal hydroelectric power plants have several advantages over conventional hydroelectric power plants. They do not require a large amount of water storage, and they can generate electricity continuously, regardless of the time of day or weather conditions. However, tidal hydroelectric power plants also face several challenges, including high construction costs, environmental concerns, and limited suitable locations due to tidal models.

Depression hydroelectric power plants: They are power plants that generate electricity by utilizing the excessive evaporation of water in deserts that are lower than the sea or in very hot regions with a coastline.A suitable bay in the warm region is separated from the sea by walls. The water in the lake, which is formed by separating from the sea, evaporates rapidly with the effect of the temperature and the water level drops below the sea level.Sea water, at a flow rate equal to the amount of water that evaporates daily, is poured into this lake with the help of a tunnel. The water coming from the tunnel is given to the turbine with a certain drop and electricity is produced. Another method is to transport sea water to pits located below sea level in deserts and generate electricity by the same method.

In conclusion, hydroelectric energy is a reliable and efficient source of renewable energy. It is also a flexible source of energy that can be used to respond to changes in demand quickly. Additionally, hydroelectric power plants have a long lifespan and require low maintenance costs. However, the construction of dams and reservoirs can have significant environmental impacts, such as altering the flow of rivers and impacting aquatic ecosystems.

3.3.2.3 Wave Energy

The type of energy obtained from the movement of waves formed in the seas and oceans is called wave energy. The energy production in sea and ocean waves takes place with wave energy turbines. These turbines generate energy by utilizing the surface movements and wave pressures of the waves.Wave power plants, also known as wave energy converters, are facilities that takes advantage the energy of ocean and sea waves to generate electricity.There are several different types of wave energy converters, including oscillating water column (OWC) devices, point absorbers, and attenuators. Each type of device operates differently and is suited to different wave conditions and locations.

Oscillating water column (OWC) devices are a type of wave energy converter (WEC) that harnesses the energy from ocean waves to generate electricity. They consist of a partially submerged chamber with an opening at the bottom that faces the sea. As waves pass over the opening, the air trapped in the chamber is forced to move back and forth, driving a turbine and generating electricity.

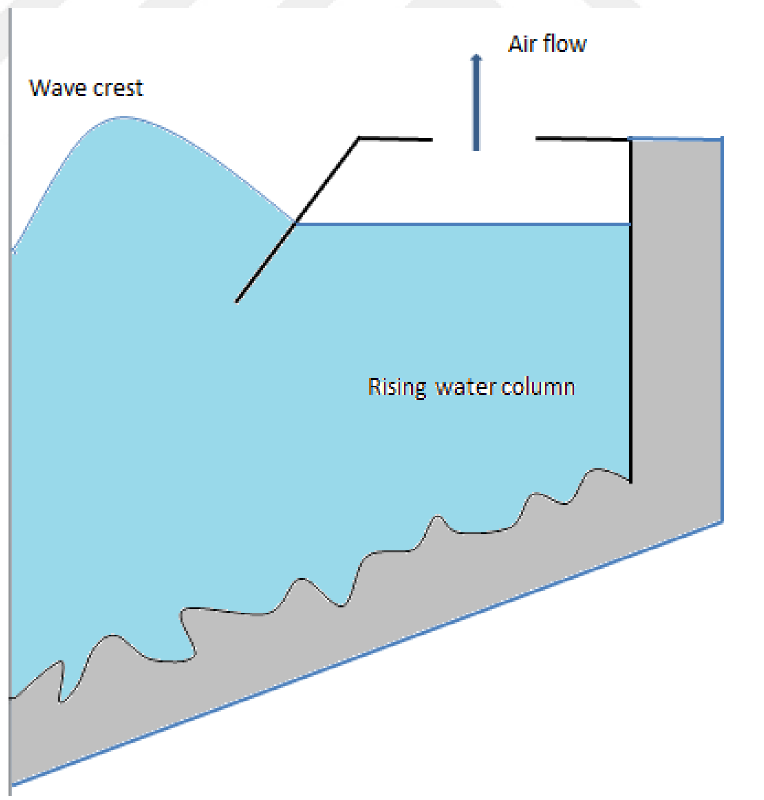

Figure 8: Priciple of OWC action with wave crest

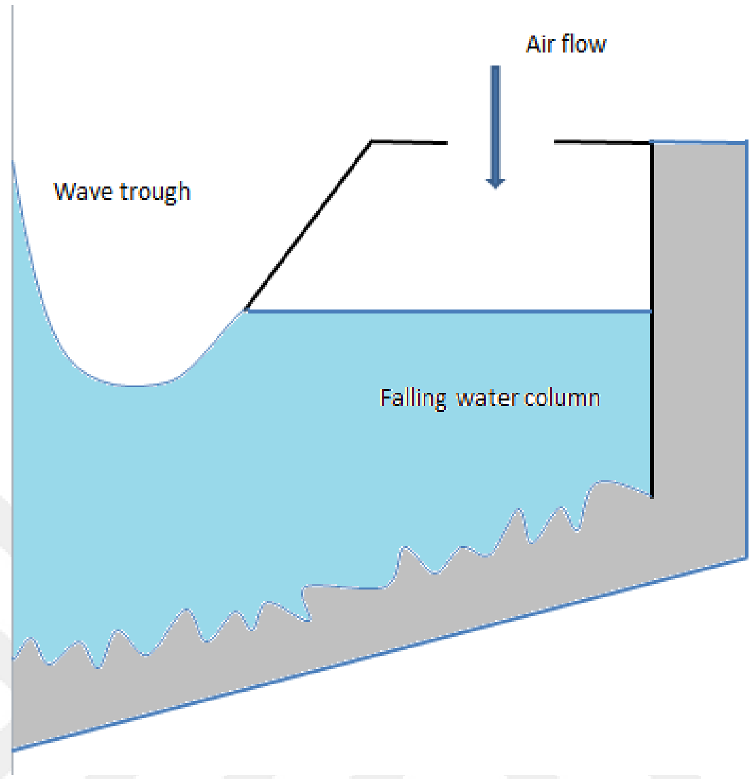

Figure 9: Priciple of OWC action with wave trough

OWCs are considered a promising technology for wave energy conversion because they have a relatively simple design and can be constructed using easiliy available materials. They also have the potential to be installed at a variety of locations along coastlines and in open sea environments.

However, OWCs also have some limitations. They are sensitive to wave height and require a minimum wave height to start generating electricity. They are also vulnerable to damage from storms and rough seas, which can result in high maintenance and repair costs. Additionally, they may have an impact on marine ecosystems and coastal erosion.

Point absorbers are a type of wave energy converter device that generate electricity from the movement of ocean waves. They consist of a buoyant device, usually cylindrical or spherical in shape, which is tethered to the ocean floor.As waves pass by, the buoyant device moves up and down, causing the mechanical motion of a power take-off (PTO) system that converts the kinetic energy of the waves into electrical energy.

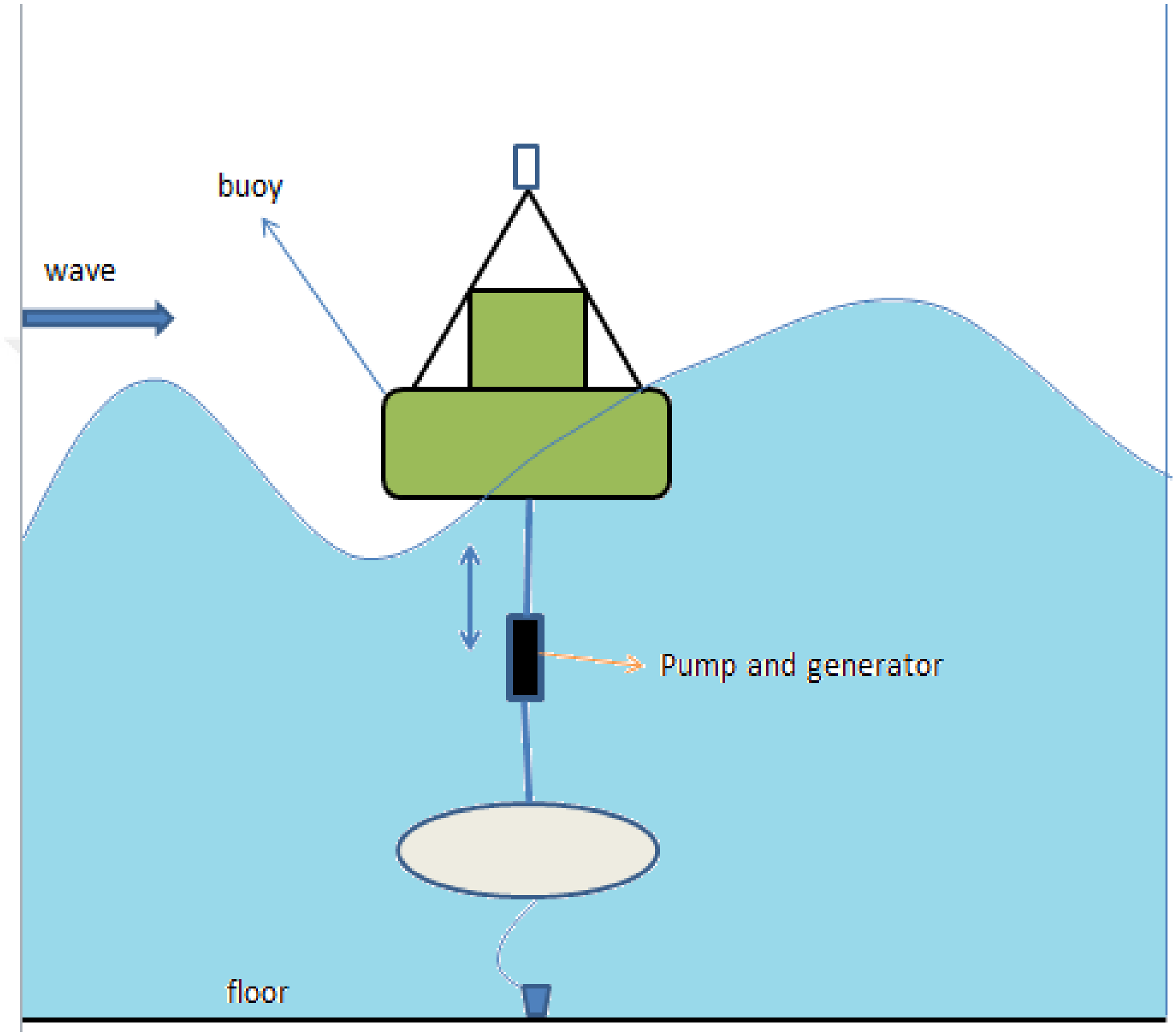

Figure 10: Point absorber

Point absorbers are designed to be highly efficient at capturing energy from waves, and can be used in a variety of wave conditions. They are also relatively compact, making them suitable for use in open sea locations where space is limited. The power output of a point absorber depends on a number of factors, including the size and shape of the buoyant device, the type of PTO system used, and the characteristics of the wave environment.

Attenuators are devices that are used to reduce or attenuate the energy of a wave. In the context of wave energy conversion (WEC) systems, attenuators are used to produce energy from ocean waves.Attenuators are designed to convert the kinetic energy of ocean waves into electrical energy. They typically consist of a buoyant structure that is anchored to the seabed, and one or more power take-off (PTO) systems that convert the mechanical motion of the buoy into electrical power.

Attenuators are still in the development phase and have not yet been widely deployed on a commercial scale. However, they hold promise as a potentially cost-effective and environmentally friendly source of renewable energy.

Wave power plants have several advantages over other types of renewable energy sources, such as being highly predictable and reliable, as ocean waves are consistent and do not depend on weather conditions. They are also less visible than wind turbines and can be located further open sea reducing their impact on marine life and coastal landscapes.

However, wave power plants also face some challenges, such as being relatively expensive to build and maintain, and requiring strong and consistent wave energy to operate efficiently. They may also face environmental and regulatory challenges, such as concerns over the impact on marine ecosystems and navigation safety. Despite these challenges, wave power has the potential to play an important role in the future energy mix, especially in coastal regions with high wave energy resources. While wave power plants are still in the early stages of development and deployment, they have the potential to generate significant amounts of electricity from a renewable and non-polluting source.

3.3.2.4 Wind Energy

Wind energy is the energy that first converts the kinetic energy of the wind into mechanical energy and then into electricty energy. Wind turbines are used to capture the wind's energy and convert it into electricty energy.

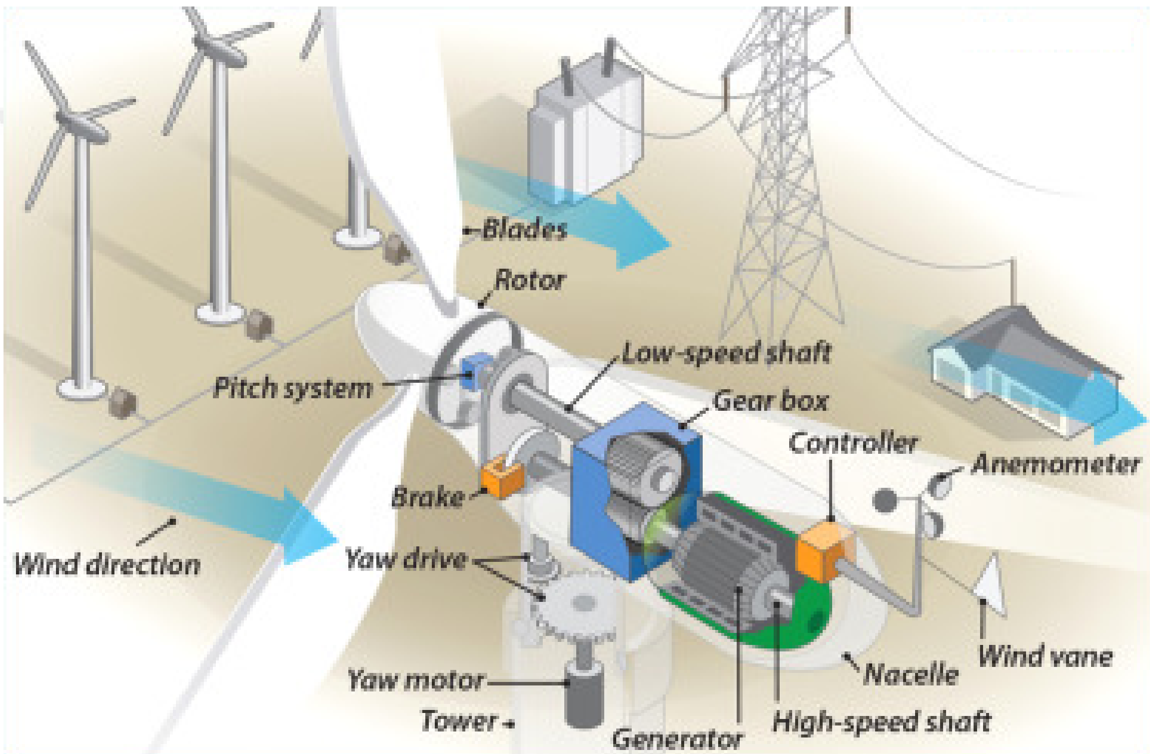

Figure 11: Wind power plant [1]

Wind turbines typically consist of three main components: the rotor, which contains the blades; the nacelle, which houses the generator and other key components; and the tower, which supports the rotor and nacelle. When the wind blows, it causes the rotor blades to turn, which in turn spins the generator and produces electricity.

Wind turbine types are as in the table in Figure 12. The explanations of the specified turbine types are given below the table.

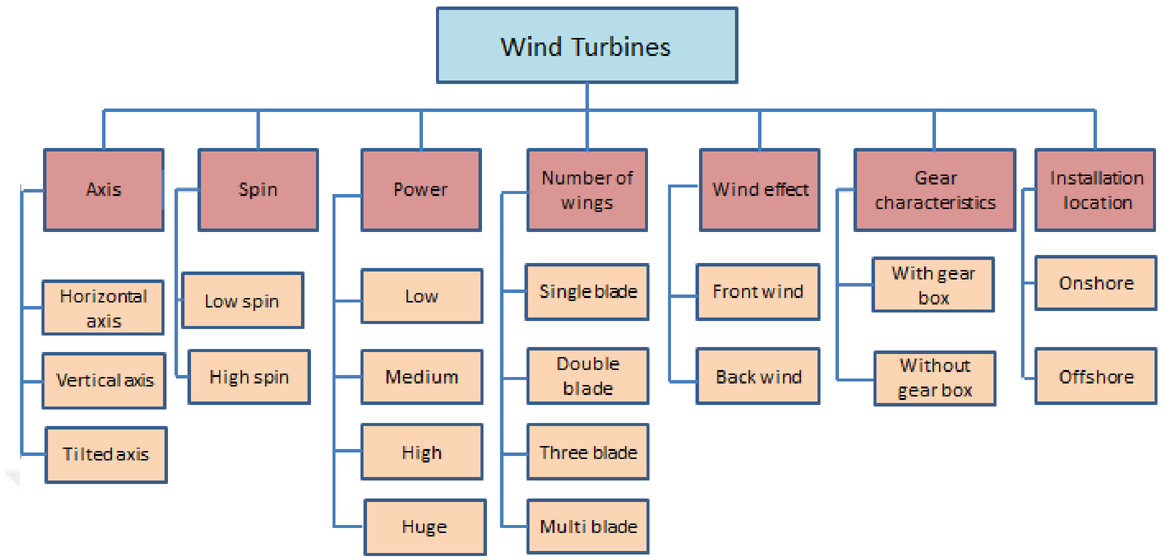

Figure 12: Types of wind turbines

Types of Wind Turbines According to Rotation Axis:Wind turbines are divided into three groups according to their axis of rotation; horizontal axis wind turbines, vertical axis wind turbines, tilted axis wind turbines.

- Horizontal Axis Wind Turbines : The blades are perpendicular to the wind direction, the axis of rotation is parallel to the wind direction. Most commercial wind turbines are horizontal axis. The efficiency of these turbines is about 45%.In addition to their high efficiency, horizontal axis wind turbines (HAWTs) also have the advantage of being easily scalable, making them suitable for use in both large and small wind farms. They can also be placed on towers, allowing them to capture stronger winds at higher altitudes. However, HAWTs do have some disadvantages, such as the need for a yaw control system to keep the rotor facing into the wind and the potential for noise pollution. Despite these challenges, HAWTs remain a popular choice for wind energy generation.

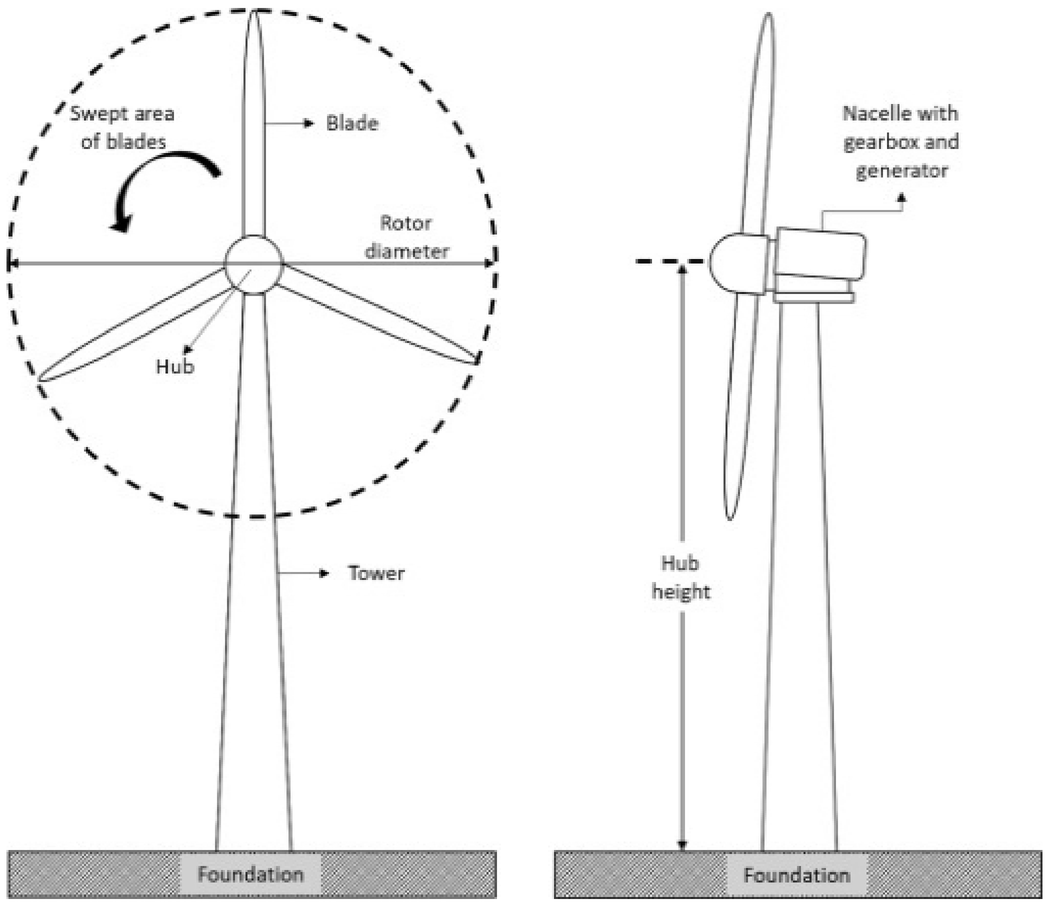

Figure 13: Horizontal axis wind turbines [2]

• Vertical Axis Wind Turbines: The turbine shaft is vertical and perpendicular to the direction of the wind. It is produced for experiments rather than commercial use. Since they can be placed on the ground, the need and cost of towers are eliminated. Since the system can be turned to the desired wind direction, there is no need for a rudder system. The efficiency of these turbines is lower than the horizontal axis wind turbines. Since the generator and gearbox are placed on the ground, it is not necessary to use a tower, so there is no tower expense.

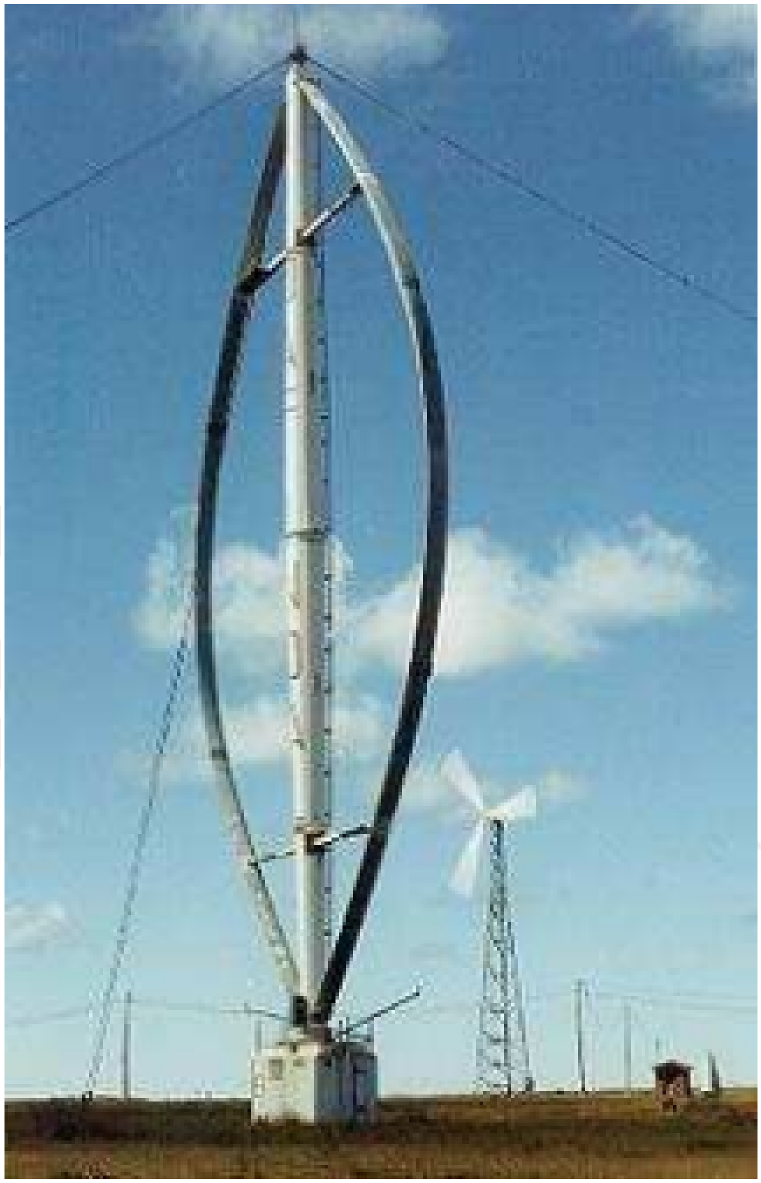

Figure 14: Vertical axis wind turbines [3]

• Tilted Axis Wind Turbines: These are wind turbines whose rotation axes make an angle with the vertical in the direction of the wind. There is a certain angle between the blades of this type of turbines and the axes of rotation.

Wind turbines are classified as high and low spin in terms of spin.

Types of Wind Turbines According to Their Powers: Wind turbines are divided into four according to their power.

• Low Power Wind Turbines: These are turbines with a maximum power of less than 30 kW.

• Medium Power Wind Turbines: These are the turbines with the maximum power they can produce between 30-100 kW.

• High Power Wind Turbines: These are the turbines with the maximum power they can produce between 100-1000 kW.

• Huge Power Wind Turbines: These are turbines with a maximum power of 1 MW and above.

Types of Wind Turbines by Number of wings: According to the number of wings, wind turbines are of four types: single blade, two blades, three blades and multiple blades.

• Single Blade Wind Turbines: Aerodynamically unstable. To control the mechanism, it is necessary to make additional structures on the hub. It is noisier than other multiblade wind turbines. The purpose of use is to reduce the high rotational speed acting on the blades.

• Double Blade Wind Turbines: They are used in different propeller diameters ranging from 10 m to 100 m. Unlike the three-bladed wind turbine, it has a moment of inertia relative to the horizontal axis of the tower. At low wind speeds, the blades cannot be activated.

• Three-bladed Wind Turbines: The most used model in modern wind turbines is the three-bladed one. The main reason for this is that the propoller has a constant moment of inertia at all speeds. In addition, the three-bladed propeller does not impose an additional load on the wind turbines due to this advantage.

• Multi Blade Wind Turbines: Multi Blade wind turbines are the first undeveloped examples of wind turbines. These turbines, which were used only for water pumping for years, were produced as multi-bladed in order to meet the torque requirement in this process. Multiblade wind turbines operate at low speed. The width of the turbine blades increases as you go from the propeller hub to the tips. By connecting the propeller shaft to the gearbox, the generator shaft speed is increased and generators that find application in automobiles are used.

Types of Wind Turbines According to the Direction of Wind: According to the direction of the wind, wind turbines are divided into two as turbines that receive the wind from the front and those that receive the wind from the rear.

• Wind Turbines That Take The Wind From The Front:In horizontal axis turbines, if the rotor face is oriented towards the wind, they are called front wind turbines. The most important advantage of these turbines is that they are not exposed to the shading effect of the tower. It is the most widely used turbine type. These turbines have a body rotation mechanism to turn the rotor against the wind.

• Wind Turbines That Take The Wind From The Back: The rotors of the back wind turbines are behind the tower. Their important advantage is that there is no need for a body rotation mechanism. The flexible feature of the wings provides an important advantage in terms of weight and power dynamics of the machine. Thus, the tower load is reduced. However, the power surge that occurs as the blade passes through the tower can damage the turbine more than the front wind machines.

Types of Wind Turbines According to the Gear Characteristics :In typical wind energy system, a wind turbine must contain the coupling equipment (gear box), generator and control system. In terms of wind turbine units drive systems; It can be divided into two classes as turbine generator systems with and without gearbox.

• Wind Turbines with Gearbox: Generators are low-pole, high-speed. Therefore, gear ratios such as 1/50, 1/70 are used to match the speed of the propeller with the generator speed.

• Wind Turbines Without Gear Box: Since the generators are multipolar and low speed, there is no need for a gear system. It is applied in two different ways as direct driven electrically excited synchronous generator and direct driven permanent magnet synchronous generator.

Wind turbines are classified as onshore and offshore in terms of where they are installed.

There are several types of wind power plants.

Onshore wind turbines: these are the most common type of wind power plant and are located on land. The turbines are typically installed in areas with strong and consistent winds, such as hills, ridges, and open plains.

Offshore wind turbines: these are similar to onshore turbines, but are located in water, such as oceans, lakes, and rivers. Offshore turbines can be larger than onshore turbines and can generate more electricity due to the stronger and more consistent winds over water.

Floating wind turbines: these are a type of Offshore wind turbine that are not fixed to the seabed but instead float on the surface of the water. This allows them to be located further Offshore and in deeper water than traditional Offshore turbines.

Hybrid wind-solar systems: these combine wind turbines with solar panels to generate electricity from both wind and sunlight. This approach can provide more consistent power output than relying on wind or solar alone.

Distributed wind turbines: these are smaller wind turbines that are located near the point of use, such as on farms, in rural areas, or at remote sites. They can be used to supplement or replace grid power, especially in areas with unreliable or nonexistent grid connections.

Community wind turbines: these are owned and operated by local communities or cooperatives, and are typically smaller-scale wind turbines that generate electricity for the local area. This can help to reduce dependence on fossil fuels and support local economies.

Wind energy has the following advantages.

- Wind energy does not produce greenhouse gas emissions or other pollutants, making it a clean source of energy.

• Wind energy is becoming increasingly cost-competitive with traditional sources of electricity.

• The wind energy industry has created thousands of jobs in manufacturing, construction, and other fields.

• Wind projects can be developed relatively quickly compared to other types of power plants.

However, wind energy also has some disadvantages.

• The amount of wind energy produced depends on the wind speed and can be variable, making it less predictable than other types of energy sources.

• Wind turbines can produce noise, which can be a concern for nearby residents.

Wind energy is considered a renewable energy source because the wind is a naturally occurring and abundant resource that does not produce greenhouse gas emissions or other pollutants. Wind power is also becoming increasingly cost-competitive with traditional sources of electricity, such as coal and natural gas.In generally, wind power is a promising renewable energy source that has the potential to play an important role in the transition to a low carbon economy.

3.3.2.5 Biomass Energy

Organic materials are substances that contain carbon atoms dependent to hydrogen atoms, as well as other elements such as oxygen, nitrogen, sulfur, and phosphorus. Organic materials can be found in living organisms, such as plants and animals, as well as in dead and decaying organic matter, such as wood, crop residues, and animal waste. These materials can be used as raw materials for the production of biofuels and other bioproducts.

Biomass energy refers to energy produced from organic materials. It is a renewable energy source because these materials can be replenished over time, either through natural processes or through agricultural practices.There are different ways to convert these materials into energy.The method used to obtain energy from biomass depends on the type of feedstock and the desired end product.

• Combustion: The most common method of producing energy from biomass is by burning it in a combustion chamber or boiler to produce steam, which can be used to drive a turbine and produce electricity.

• Gasification: Biomass can also be converted into a gas by heating it in the absence of oxygen. The resulting gas can be used to produce electricity in a gas turbine.

• Anaerobic digestion: This is a biological process that breaks down organic matter in the absence of oxygen, producing biogas, which can be used to generate electricity.

• This involves breaking down organic materials in the absence of oxygen, which produces biogas that can be burned to produce electricity.

Biomass resources are organic materials that can be used as fuel to produce energy. They include a wide range of plant and animal materials.A few examples of biomass resources are as follows;

• Plants with oilseeds such as sunflower and soybean

• Plants high in starch, such as potatoes, wheat, sugar beets or corn

• Fiber crops such as flax, hemp

• Protein-rich plants such as peas and beans

• Agricultural waste such as straw, roots or bark

• Forest waste

• Animal manures. Especially the feces of animals such as cattle, horses, sheep or chickens

• Industrial or domestic wastewater or wastes of large industrial establishments

There are several points to consider while producing biomass energy:

• Sustainability: The production of biomass energy should be sustainable, meaning that the biomass should be grown, harvested, and used in a way that does not harm the environment or deplete natural resources.

• Raw material selection: The selection of raw material is important, as it affects the efficiency and effectiveness of biomass energy production. Ideally, raw material should be easily available, affordable, and require minimal processing.

• Processing technology: The choice of processing technology depends on the type of biomass raw material and the intended end use. For example, thermal technologies like combustion and gasification are more suitable for woody biomass, while anaerobic digestion is suitable for wet organic waste.

• Storage and transportation: Biomass raw material needs to be stored properly to prevent moisture and decay, and transported efficiently to the processing facility.

• Emissions reduction: The production of biomass energy can generate emissions, such as particulate matter, nitrogen oxides, and sulfur dioxide. Therefore, it is important to use technologies and processes that minimize these emissions and reduce their environmental impact.

• Social and economic considerations: The production of biomass energy can have social and economic impacts, such as job creation and income generation for rural communities. These considerations should be taken into account when developing biomass energy projects.

Biomass energy has several advantages as a renewable energy source. It is widely available, locally produced and can help reduce greenhouse gas emissions and dependence on fossil fuels. Additionally, using biomass energy can help reduce waste by removing organic materials from storage areas and other disposal methods.

3.3.2.6 *Solar Energy*

Solar energy is the energy that is produced by the sun's radiation, which is captured and converted into usable energy through various technologies. There are two main ways to utilize solar energy. These are photovoltaic (PV) systems and solar thermal systems.

Solar thermal systems, also known as concentrating solar power (CSP) systems, use mirrors or lenses to concentrate sunlight onto a receiver that absorbs the energy and converts it into heat. The heat is then used to produce electricity or to provide heating and cooling.There are several types of concentrating solar power system, as Parabolic trough systems, Power tower systems, Dish Stirling systems, and Fresnel systems.

Parabolic trough systems: These systems use parabolic mirrors to focus sunlight onto a receiver tube located at the focal point of the mirror. The receiver tube contains a heat transfer fluid that is heated by the concentrated sunlight and used to generate steam, which drives a turbine to generate electricity.Parabolic trough system is given Figure 15.

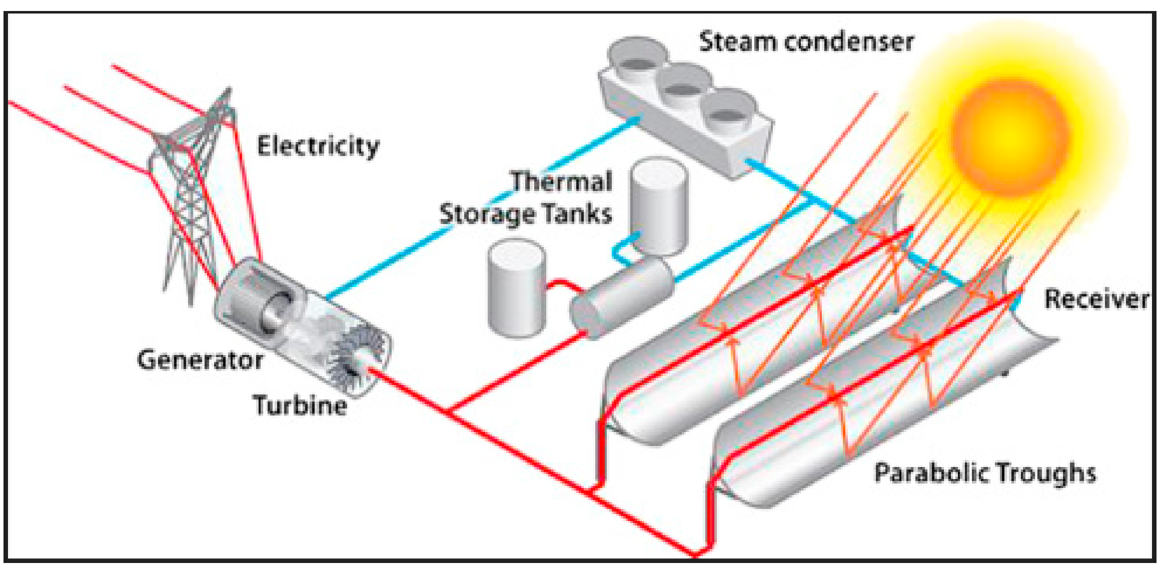

Figure 15: Parabolic trough system [4]

Power tower systems: These systems use a large field of mirrors called heliostats to track the sun and reflect sunlight onto a receiver tower located at the center of the field. The receiver tower contains a heat transfer fluid that is heated by the concentrated sunlight and used to generate steam, which drives a turbine to produce electricity.Power tower system is given in Figure 16.

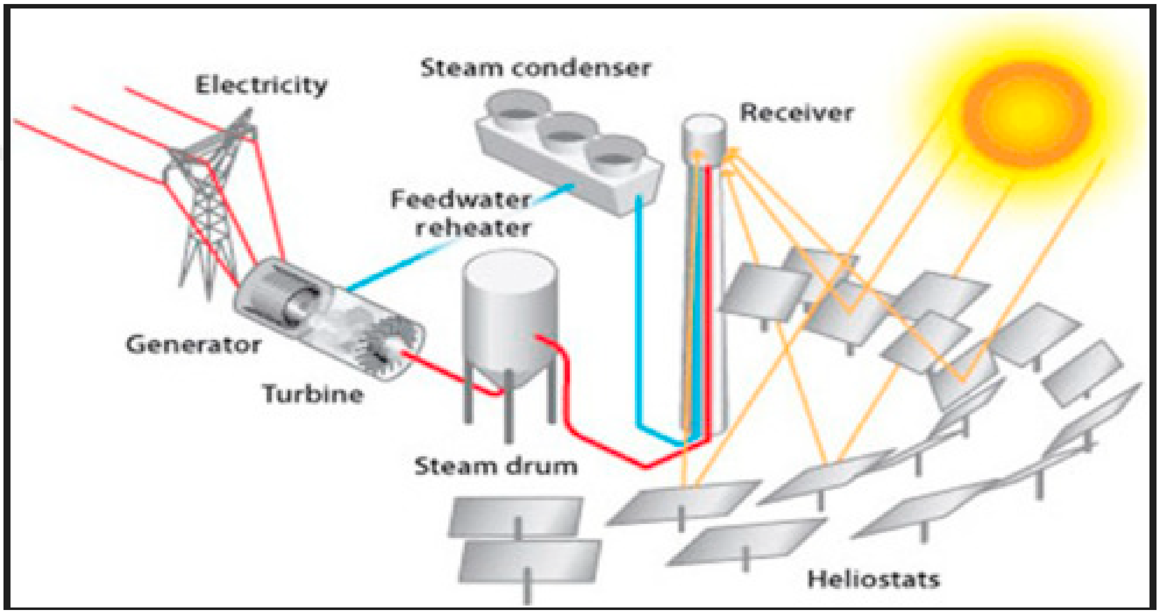

Figure 16: Power tower system [5]

Dish Stirling systems: These systems use a dish-shaped mirror to focus sunlight onto a receiver at the focal point of the mirror. The dish-shaped mirrors used in these systems are typically made of highly reflective materials, such as glass or metal, and can be several meters in diameter. The mirrors are designed to track the movement of the sun throughout the day, ensuring that the maximum amount of sunlight is focused on the receiver. The receiver contains a Stirling engine, which converts the heat into mechanical energy that drives a generator to produce electricity. Dish Stirling systems have high conversion efficiencies, typically in the range of 25-30%, making them an attractive option for distributed power generation in areas with high solar radiation. Dish Stirling system is given in Figure 17.

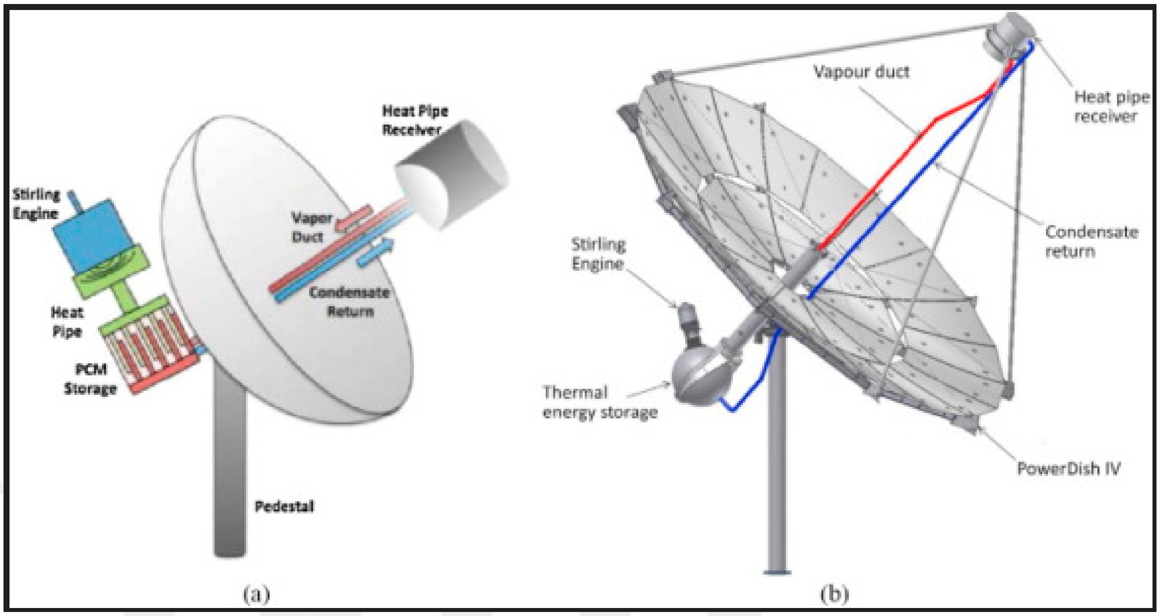

Figure 17: Dish Stirling system [6]

Fresnel systems: These systems use a series of flat mirrors arranged in a Fresnel lens configuration to concentrate sunlight onto a receiver. The receiver contains a heat transfer fluid that is heated by the concentrated sunlight and used to generate steam, which drives a turbine to generate electricity. Fresnel system is given in Figure 17.

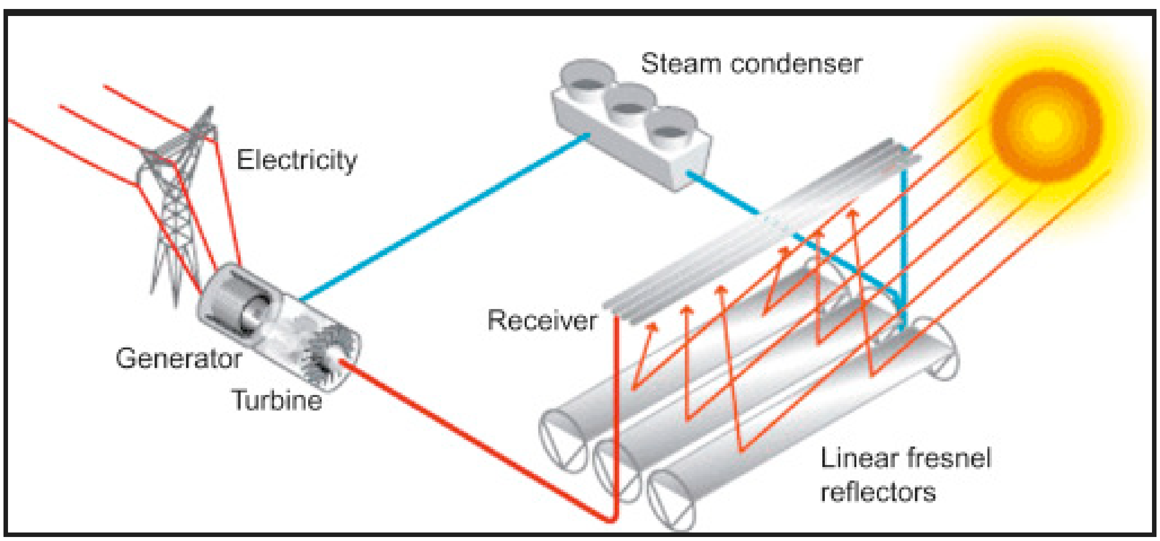

Figure 18: Fresnel system [7]

Solar thermal systems have several advantages over other types of solar energy systems, including their ability to produce electricity even when the sun is not shining (due to the ability to store the heat generated during the day) and their potential for use in industrial processes that require high-temperature heat. However, they also require large land areas, and their efficiency is limited by the availability of sunlight and the thermal losses in the heat transfer fluid.

Solar photovoltaic (PV) systems, are a type of solar energy technology that convert sunlight directly into electricity using solar panels. Solar photovoltaic systems can be installed on rooftops, on the ground, or integrated into building materials like walls.

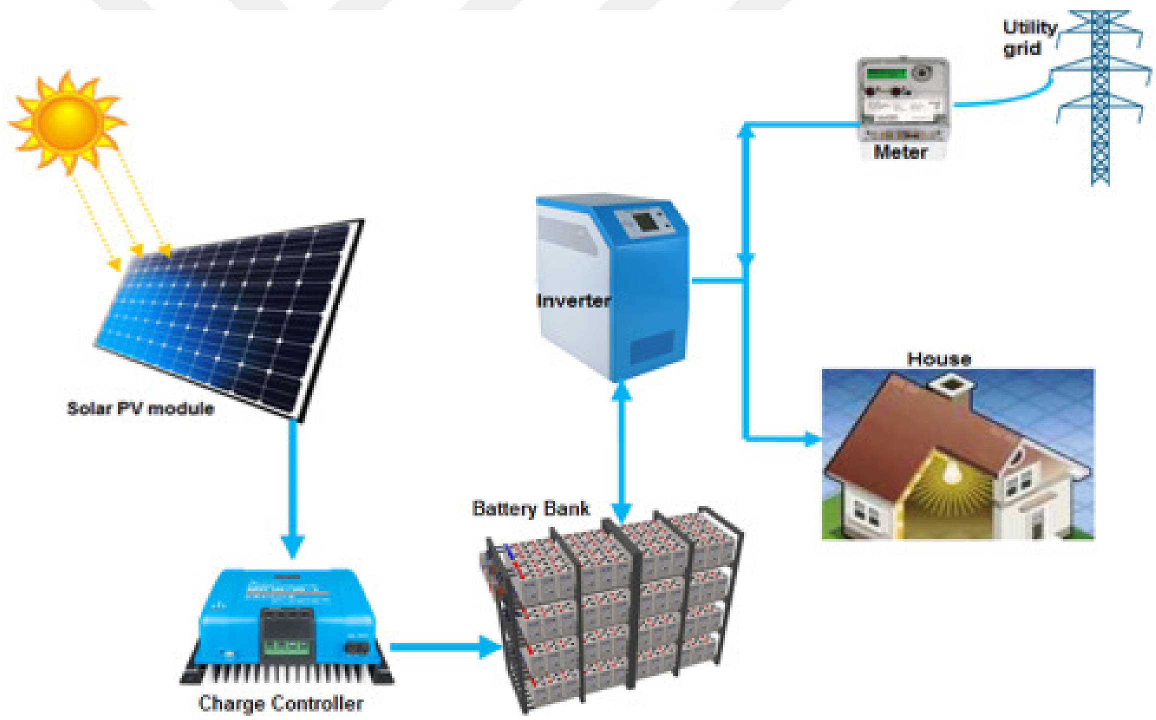

Figure 19: Photovoltaic system [8]

The basic components of a solar photovoltaic system are given in Figure 19.These solar photovoltaic system components are explained as follows.

1-Solar panels (modules): The solar panel is the basic element of the solar energy system used for electricity generation. These are made up of photovoltaic cells, which convert sunlight into DC (direct current) electricity. Crystalline silicon, Amorphous silicon, Gallium arsenic, Cadmium telluride, etc. materials are used in construction of solar cell.Silicium is used as the most common solar cell material.

A solar cell, also known as a photovoltaic cell, converts sunlight directly into electrical energy using the photovoltaic effect. The photovoltaic effect is a physical phenomenon in which certain materials produce an electric current when exposed to light.A solar cell is made up of layers of different materials, typically silicon-based, that create an electric field. When light hits the cell, it excites the electrons in the semiconductor material, allowing them to flow as an electric current through the cell and produce electricity. This electricity can then be used to power devices or stored in batteries for later use.To explain the electricity production from solar cells in more detail;

• Sunlight falls on the solar cell and is absorbed by the photovoltaic cells. There are P-type semiconductor materials with more electrons and N-type semiconductors with few electrons in the cell.

• Sunlight removes electrons from P-type semiconductor material.

• The energized electrons flow towards the N-type semiconductor material.

• This creates direct current (DC), which is a constant unidirectional flow of electrons. Electrons are used in charging batteries or in different areas by flowing through the established circuits and return to the P-type semiconductor material.

Solar cells have become an increasingly popular form of renewable energy due to their efficiency, durability, and environmental benefits. They are widely used in both small-scale applications, such as powering homes and electronic devices, and in large-scale utility installations. Solar panels can be mounted on rooftops, ground-mounted on land, or even integrated into building materials such as windows or roofing tiles. As the technology continues to improve and costs decrease, solar energy is becoming more accessible and affordable for individuals and businesses alike.

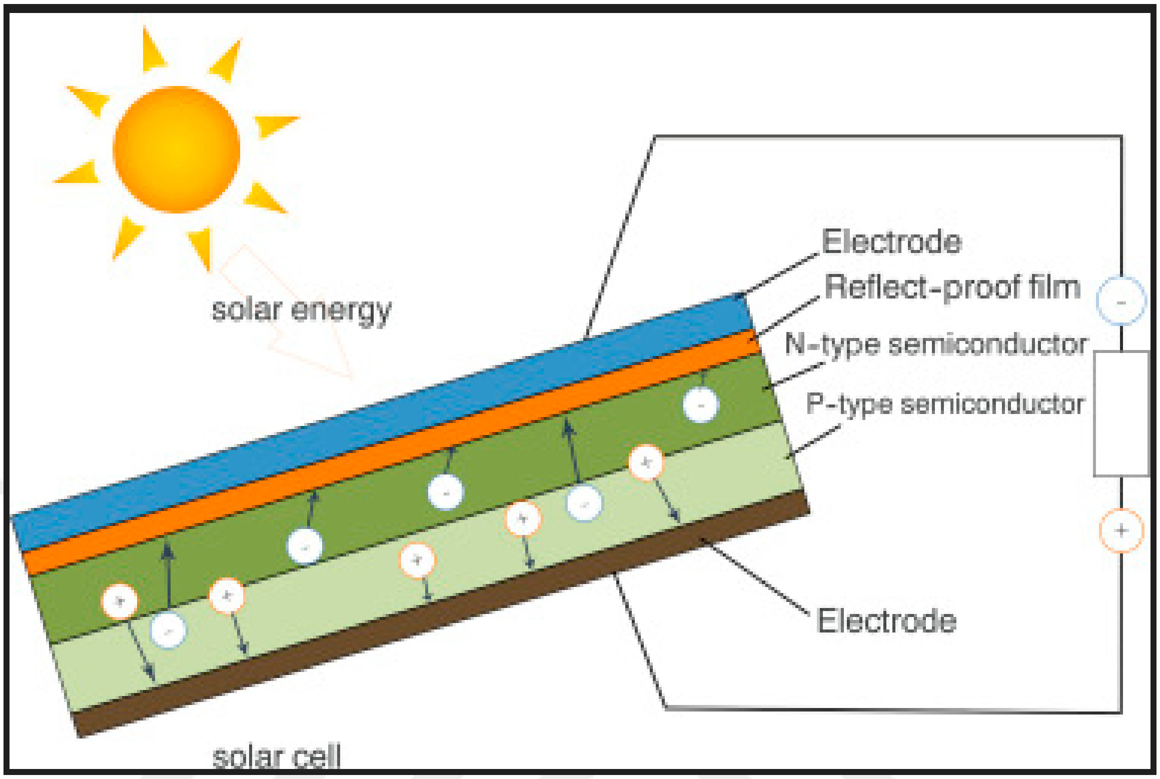

Figure 20: Solar cell working principle [9]

The efficiency of a solar cell depends on various factors such as the type of material used, the quality of the cell, and the intensity and wavelength of the sunlight. Modern solar cells can have efficiencies ranging from 15-25%, meaning they can convert 15-25% of the sunlight that hits them into electricity.

There are three main types of solar cells:

• Monocrystalline solar cells: These cells are made from a single, pure crystal of silicon. They have a uniform black color and are the most efficient type of solar cell, converting up to 22% of the sun's energy into electricity. Monocrystalline solar cells are also the most expensive type of solar cell.

• Polycrystalline solar cells: These cells are made from multiple crystals of silicon. They have a blue color and are less efficient than monocrystalline solar cells, typically converting 15-18% of the sun's energy into electricity. However, polycrystalline solar cells are less expensive to produce than monocrystalline cells.

• Thin-film solar cells: These cells are made by depositing a thin layer of photovoltaic material onto a substrate, such as glass or plastic. Thin-film solar cells are less efficient than monocrystalline and polycrystalline solar cells, typically converting 10-12% of the sun's energy into electricity. However, they are less expensive to produce and can be made flexible, allowing for a wider range of applications.

The solar cell equivalent circuit diagram is given in figure 20.

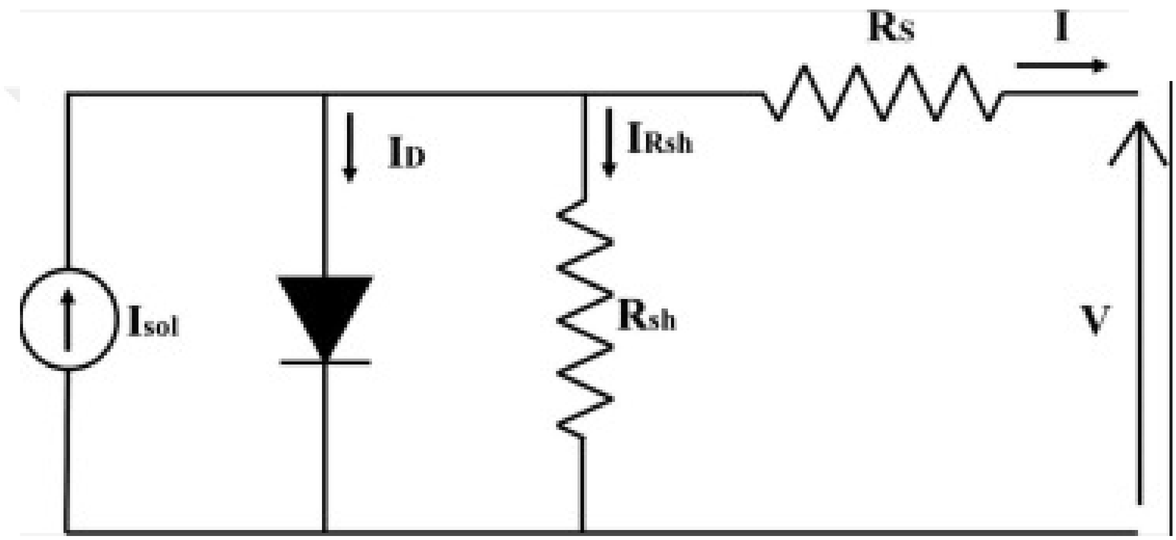

Figure 21: Solar cell equivalent circuit diagram [10]

ISC : Solar Cell Current

ID : Diode Current

IRsh : Shunt Current

Rsh : Shunt Leakage Resistance

Rs : Internal Resistance of Circuit Elements

I : Load Current

V : Load Voltage

Solar modules are obtained by connecting the solar cells in series or parallel according to the desired current and voltage values.Solar system is installed by combining solar modules.

2-Inverter: In a photovoltaic (PV) system, the electricity produced by the solar panels is direct current (DC) electricity, which is not compatible with most household appliances and the electric grid. To convert the DC electricity to alternative current (AC) electricity, which is compatible with these devices, an inverter is required.

An inverter is a device that converts DC electricity from the PV panels into AC electricity that can be used in your home or fed into the electric grid. The inverter is connected to the solar panels and the AC load or the electric grid.

There are three main types of inverters used in PV systems:

• String Inverters: This is the most common type of inverter used in residential and commercial PV systems. It is designed to manage a string of solar panels that are connected together in a series. The DC electricity generated by the panels is fed into the inverter, which then converts it into AC electricity that can be used by your home or fed back into the grid.

• Microinverters: Microinverters are small inverters that are installed on each solar panel. This allows each panel to operate independently, which can increase system efficiency and performance, especially in situations where shading is an issue.

• Power Optimizers: Power optimizers are similar to microinverters in that they are installed on each solar panel. However, instead of converting DC to AC electricity, they optimize the power output of each panel before it is fed into a central string inverter.

In generally, the inverter is an essential component in a PV system as it allows for the conversion of DC electricity produced by the solar panels to AC electricity that can be used in your home or fed back into the electric grid.

3-Battery : In solar energy systems, one of the most important parts after the panels is the batteries. Thanks to the batteries, the electrical energy produced by the solar panels is also stored in the batteries connected to the system for later use.

Thanks to an efficient power generation when the weather is nice, the electrical energy stored in the batteries can be used for needs.

One of the most important factors in making battery use mandatory is that the sun's rays are not always available. In this case, batteries are an important element in these systems in terms of storage and later use. These batteries, which are connected to the system, have low costs and do not require much maintenance.

More detailed informations about batteries are explained in chapter IV.

4-Charge Controller : A charge controller is an electronic device used in solar photovoltaic (PV) systems to regulate the voltage and current from the solar panels to the battery bank or inverter. It is also known as a charge regulator or battery regulator.

The main function of the charge controller is to prevent overcharging and undercharging of the batteries in the solar PV system. Overcharging can damage the batteries and undercharging can reduce their lifespan and capacity.

The charge controller monitors the battery voltage and regulates the charging current to ensure that the batteries are charged at the appropriate level. It also protects the batteries from overvoltage, overcurrent, short circuit, and reverse current from the battery bank to the solar panels during the night or when the solar panel voltage is lower than the battery voltage.

There are two types of charge controllers:

PWM (Pulse-Width Modulation) charge controller: This type of charge controller is used in small-scale solar systems. It regulates the charging current by rapidly turning the solar panel's output on and off, which controls the amount of energy sent to the battery.

MPPT (Maximum Power Point Tracking) charge controller: This type of charge controller is used in larger solar PV systems. It maximizes the amount of energy extracted from the solar panel by adjusting the load so that the solar panel is always operating at its maximum power point. It is more efficient than PWM charge controllers and can increase the energy output of a solar system by up to 30%.

5-Meter: Meter measures the electricity produced by the solar panels and the amount of electricity consumed by your home or business.

Solar panels can be used in various applications. Some applications are as follows;

-Solar panels can be installed on rooftops or as standalone systems to generate electricity for homes and businesses.

-Solar panels can be used to power remote locations, such as cabins or campsites, where grid power is not available.

-Solar panels can be used to power irrigation systems, water pumps, and other equipment on farms and ranches.

-Solar panels can be used to power electric vehicles, including cars, buses, and trains.

-Solar panels are commonly used on satellites and other spacecraft to generate power.

-Solar panels can be used to power mobile charging stations, lighting, and communication systems in disaster zones.

-Solar panels can be used to power military equipment, including communication systems, surveillance systems, and field hospitals.

-Solar panels can be used to power sensors and other equipment for environmental monitoring, including weather stations, air quality monitors, and water quality sensors.

Solar energy has numerous advantages that make it an attractive alternative to fossil fuels. One of the main benefits of solar energy is that it is renewable, meaning it can be used as long as the sun exists. Additionally, solar energy is environmentally friendly, producing no pollutants or greenhouse gases. Solar panels also require little maintenance and can last for decades. As the cost of solar energy decreases, it will become more accessible and cost-effective for households and businesses. Solar energy can provide a sense of energy independence, allowing individuals and businesses to generate their own electricity. It is also versatile, with applications ranging from powering homes and businesses to charging electric vehicles and even powering satellites. The solar industry is also a growing sector that has the potential to create jobs and boost local economies. Finally, solar energy systems can be scaled up or down depending on the energy needs of the user, making it a flexible source of energy.

Solar energy like any other technology, has its disadvantages. One of the most significant disadvantages of solar energy is its dependence on direct sunlight to generate electricity, which can limit its applicability in areas with cloudy or rainy weather. Another disadvantage is the high initial investment required to install solar panels, which can make it challenging for some individuals or businesses to adopt the technology. Additionally, solar farms can require a significant amount of land, which may be a concern in areas with limited available land. The manufacturing process for solar panels can also produce greenhouse gas emissions and toxic waste, which can have environmental impacts. Furthermore, solar energy is an intermittent energy source and may require energy storage systems, such as batteries, to provide uninterrupted power supply, which can be costly. However, with proper planning, technology advancements, and policy support, many of these disadvantages can be mitigated.

CHAPTER IV

ENERGY STORAGE SYSTEMS

Batteries are an essential component of renewable energy power plants as they help to store excess energy generated by renewable sources such as solar and wind power. This stored energy can be used during times when the renewable source is not available, such as during periods of low sunlight or wind.

When selecting a battery for a renewable energy power plant, factors such as cost, lifespan, maintenance requirements, and energy density should be considered. Additionally, advancements in battery technology and improvements in manufacturing processes are continuously being made, which can lead to improved performance and reduced costs in the future.

There are several battery types used in renewable energy plants such as Lead acid batteries, Lithium ion batteries, Flow batteries, Sodium-sulfur batteries.

4.1 Lead-Acid Batteries

Lead-acid batteries are one of the most commonly used types of batteries in renewable energy power plants, particularly for off-grid or remote applications. These batteries consist of lead plates submerged in an electrolyte solution of sulfuric acid. When an electrical charge is applied to the battery, a chemical reaction occurs, producing electrical energy that can be stored and later used to power devices or appliances. Lead-acid batteries are also known for their reliability and durability, making them a popular choice for renewable energy storage. However, they require regular maintenance to ensure their performance and lifespan. Additionally, lead-acid batteries can pose environmental risks if not disposed of properly due to their lead content and sulfuric acid electrolyte. Despite these challenges, lead-acid batteries remain a cost-effective option for renewable energy storage in many applications. The structure of the lead-acid battery is shown in Figure 22.

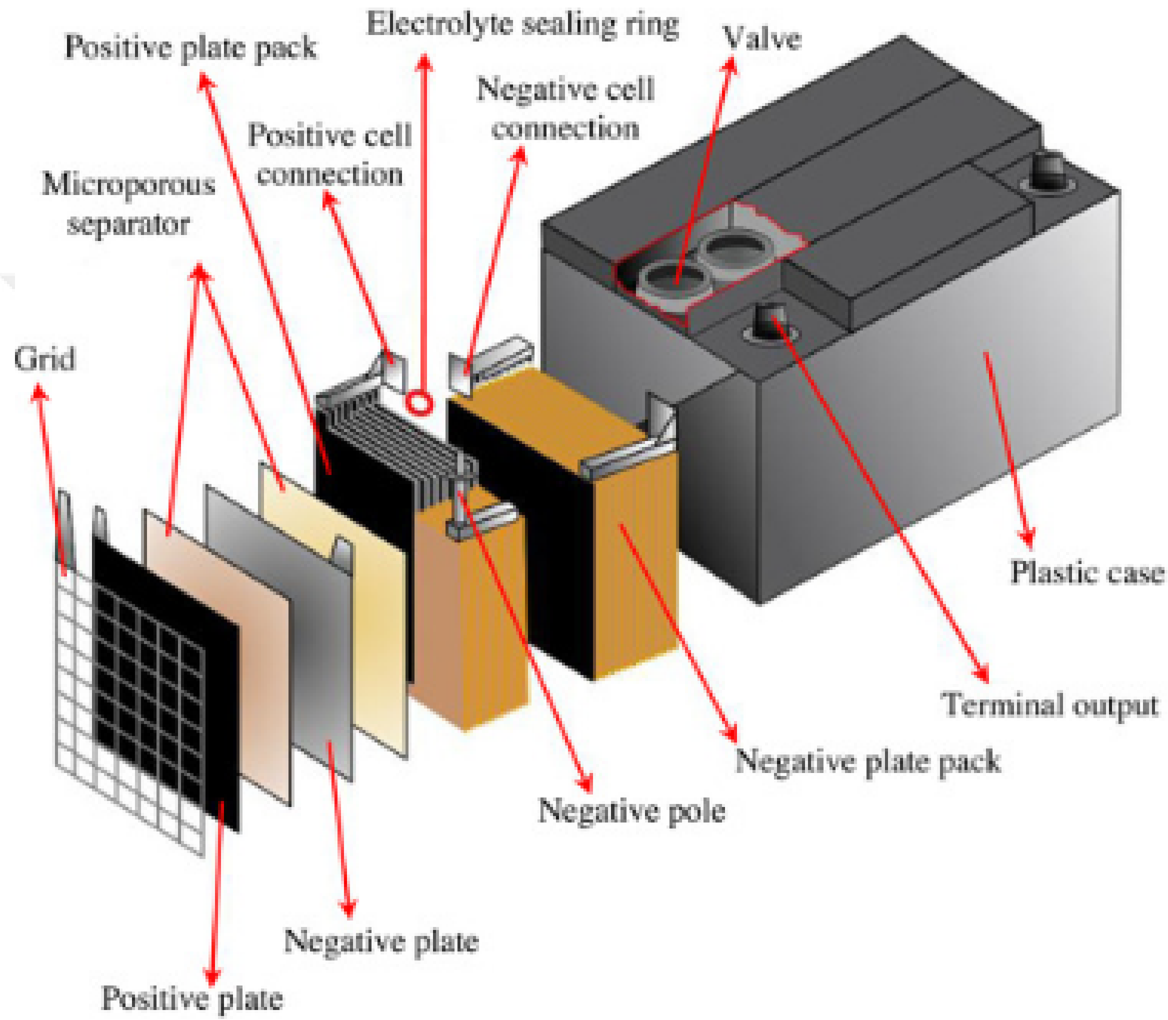

Figure 22: Structure of lead-acid battery [11]

The depth of discharge (DoD) of lead-acid batteries can change depending on the type and application of the battery.The depth of discharge (DoD) is the "useful capacity" of the battery that can be used without being damaged, without losing its capacity and life. It can be lowered below this value, but in this case, the charge-discharge cycle (cycle) of the battery will be shortened. Generally, the DoD for lead-acid batteries should be kept below 50% to maximize the battery's lifespan and performance. Going beyond this depth of discharge can result in reduced battery capacity and a shorter overall lifespan. Some high-performance lead-acid batteries, such as those used in industrial or backup power applications, may be designed for deeper discharge cycles up to 80% or more. However, it is important to note that deeper discharge cycles can significantly reduce the battery's overall lifespan and increase the risk of premature failure.

The cycle life of lead-acid batteries can change depending on the specific type and usage conditions. Generally, a lead-acid battery can withstand hundreds of discharge and recharge cycles, with a typical range of 300 to 700 cycles. However, the cycle life can be affected by factors such as depth of discharge, charging and discharging rates, temperature, and maintenance practices. Over time, the cycle life of a lead-acid battery can decrease, leading to a reduction in its overall capacity and performance. Proper maintenance, including regular charging and equalization, can help to extend the cycle life of lead-acid batteries.

Generally, lead-acid batteries have an efficiency range of 70% to 85%. This means that only 70% to 85% of the energy stored in the battery can be retrieved, while the remaining percentage is lost as heat or chemical reactions. The efficiency of lead-acid batteries also decreases as they age and undergo repeated charge and discharge cycles. Therefore, it is important to properly maintain lead-acid batteries to ensure their optimal performance and efficiency.

Lead-acid batteries are reliable, durable, and cost-effective. They have been used for many years in a variety of applications, from automotive to backup power systems. They can provide a high surge of power when needed, making them suitable for starting motors or powering large loads. However, they do have some limitations. Lead-acid batteries are heavy, bulky, and require regular maintenance, including topping up the electrolyte solution and ensuring that the terminals are clean and free from corrosion. Over time, the lead plates can also degrade, reducing the battery's overall capacity.

Despite these limitations, lead-acid batteries remain a popular choice for renewable energy power plants. They are readily available, easy to install, and can provide reliable and consistent power for many years with proper care and maintenance. Additionally, they are recyclable, which helps reduce environmental impacts.

4.2 Lithium Ion Batteries

Lithium-ion (Li-ion) batteries are a type of rechargeable battery that are commonly used in various applications, including renewable energy systems, electric vehicles, consumer electronics, and more. These batteries use lithium ions to move between the cathode and anode during charging and discharging cycles, which allows them to store and release electrical energy.The structure of the lithium ion battery is shown in Figure 23.

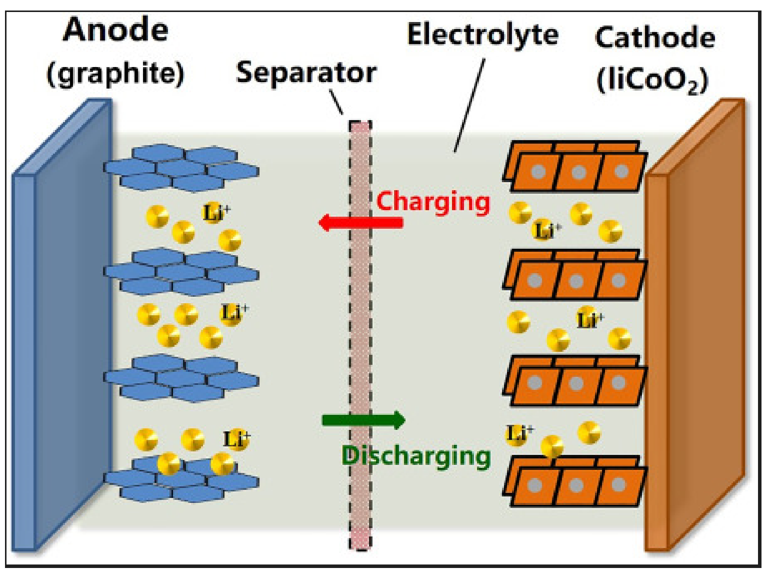

Figure 23: Structure of lithium ion battery [12]

One of the key advantages of Li-ion batteries is their high energy density, which means they can store a lot of energy in a relatively small space. This makes them ideal for use in portable electronic devices and electric vehicles where weight and space are important considerations.

The depth of discharge (DoD) of a lithium-ion battery varies depending on the specific battery chemistry, but in general, lithium-ion batteries can safely discharge to around 80% DoD without significantly affecting the battery's cycle life.The depth of discharge (DoD) is the "useful capacity" of the battery that can be used without being damaged, without losing its capacity and life. Some high-performance lithium-ion batteries may have a deeper DoD, but this can come at the cost of reduced cycle life or increased risk of damage to the battery. It is generally recommended to avoid discharging lithium-ion batteries below 20% DoD to maximize their cycle life and performance.

The cycle life of a lithium-ion battery refers to the number of charge-discharge cycles the battery can undergo before its capacity falls below a certain threshold. Generally, lithium-ion batteries have a cycle life of several hundred to several thousand cycles, depending on factors such as the battery chemistry, operating conditions, and usage patterns. High-quality lithium-ion batteries can have a cycle life of over 1,000 cycles, while lower-quality batteries may only have a cycle life of a few hundred cycles. It is important to note that the cycle life of a lithium-ion battery can be affected by factors such as temperature, depth of discharge, and charging/discharging rates, so proper maintenance of the battery is important for maximizing its cycle life.

Another advantage of Li-ion batteries is their high efficiency, which means they can convert a high percentage of their stored energy into usable electrical power. The efficiency of lithium-ion batteries varies depending on factors such as the discharge rate, temperature, and age of the battery. Generally, the efficiency of a lithium-ion battery is between 80-90%, meaning that 80-90% of the energy stored in the battery can be converted into usable electrical energy. This efficiency can decrease over time as the battery ages or is exposed to high temperatures, which can lead to increased internal resistance and decreased energy storage capacity. However, with proper maintenance and use, lithium-ion batteries can maintain high efficiency levels over many charge-discharge cycles.They also have a lower self-discharge rate compared to other battery types, which means they can hold their charge for longer periods of time when not in use.

However, Li-ion batteries also have some disadvantages. They can be more expensive compared to other battery types, which can make them less accessible for certain applications. They are also more sensitive to high temperatures and can be more prone to thermal runaway or fire if not properly designed or used. Additionally, the materials used in Li-ion batteries can have environmental and social impacts, particularly if they are not properly recycled or disposed of at the end of their useful life.

4.3 Flow Batteries

Flow batteries are a type of rechargeable battery that uses two chemical components dissolved in liquids, which are separated by a membrane. During charging and discharging, the liquids flow through separate chambers and exchange ions across the membrane, generating an electrical current. Flow batteries are well-suited for large-scale energy storage applications, such as grid-level energy storage, due to their ability to store and discharge large amounts of energy over long periods of time. In addition, flow batteries have a longer lifespan compared to other battery technologies and are more environmentally friendly, as the chemicals used in the battery can be recycled. However, flow batteries currently have a lower energy density and higher cost compared to other battery technologies, making them less suitable for smaller-scale applications. Despite these challenges, the technology is rapidly advancing, and flow batteries are expected to become increasingly important in the transition to a more sustainable and renewable energy future. The structure of the flow battery is shown in Figure 24.

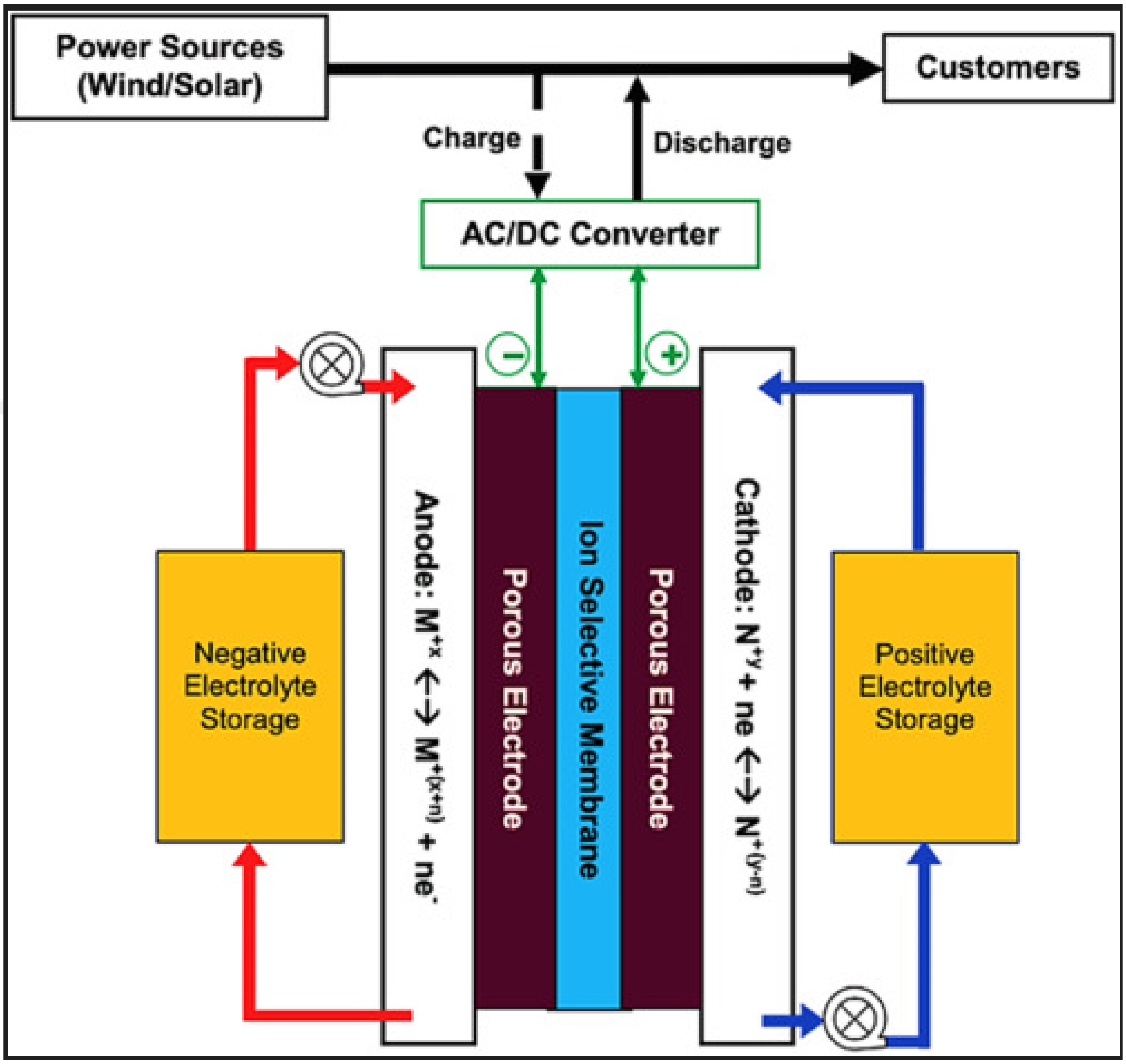

Figure 24: Structure of flow battery [13]

The capacity of energy storage in a flow battery can change depending on the specific type and design of the battery. However, flow batteries are known for their scalability and high capacity, making them ideal for large-scale energy storage applications. Some flow batteries can store hundreds of megawatt-hours of energy, which can be used to supply power to entire communities or support renewable energy integration into the grid. Additionally, flow batteries can be charged and discharged continuously without degrading the battery, which can lead to longer lifetimes and more efficient energy storage.

Generally, flow batteries have a longer cycle life than traditional batteries like lead-acid and lithium-ion batteries. Some flow batteries can have a cycle life of up to 10,000 cycles or more, while others may have a cycle life of around 2,000 cycles. The cycle life of a flow battery can also be affected by factors such as the rate of charge and discharge, temperature, and maintenance. However, flow batteries are designed to have a long service life, making them suitable for applications where long-term energy storage is required.

The depth of discharge (DOD) of flow batteries can vary depending on the specific type and model.The depth of discharge (DoD) is the "useful capacity" of the battery that can be used without being damaged, without losing its capacity and life. However, in generally, flow batteries can typically achieve a deeper DOD compared to other types of batteries, ranging from 80% to 100%. This means that a flow battery can discharge up to 80-100% of its stored energy before needing to be recharged. The deep DOD capability of flow batteries makes them ideal for applications that require extended periods of energy storage, such as grid-scale energy storage for renewable energy integration or backup power for critical infrastructure.

The efficiency of flow batteries varies depending on the specific type and design, but they generally have an efficiency of around 70-85%. This means that during charging and discharging, around 15-30% of the energy is lost as heat or other forms of energy. However, some flow battery designs claim to have efficiencies as high as 90

There are flow batteries with various chemicals;

1-Vanadium Redox Flow Batteries (VRFB): These are the most common type of flow battery and use vanadium ions in different oxidation states as the active material. They can operate for many years with little degradation and are considered a promising technology for large-scale energy storage.

2-Zinc-Bromine Flow Batteries: These batteries use a zinc bromide electrolyte and offer high energy density and low cost. However, they may experience problems such as zinc dendrite formation and electrolyte leakage..

3-Iron-Chromium Flow Batteries: These batteries use an iron-chromium electrolyte and can offer high energy density and low cost, but they may experience problems such as electrode corrosion and low efficiency.

Flow batteries have been used in a various of applications, including grid-scale energy storage, renewable energy integration, and backup power for critical facilities. However, their high upfront costs and complex system design have limited their widespread adoption compared to other battery technologies such as lithium-ion.

4.4 Sodium-Sulfur Batteries

Sodium-sulfur (NaS) batteries are a type of high-temperature battery that operates at around 300-350 degrees Celsius. They consist of a solid beta-alumina ceramic electrolyte that separates liquid sodium and sulfur electrodes.The structure of the sodium-sulfur ion battery is shown in Figure 25.

When the battery is charged, sodium ions migrate through the ceramic electrolyte to the sulfur electrode, where they are reduced to form solid sodium polysulfides. When the battery is discharged, the sodium ions migrate back through the electrolyte to the sodium electrode, while the sulfur reacts with the sodium polysulfides to form solid sulfur and release energy in the form of electricity. NaS batteries are considered highly efficient due to their low internal resistance and high energy density. They are commonly used for large-scale energy storage, such as in power grids or renewable energy installations, and can store energy for long periods of time without significant degradation. However, the high operating temperature of NaS batteries requires careful thermal management to prevent damage and ensure safe operation. Additionally, the use of liquid sodium and sulfur electrodes can pose safety risks and require specialized handling procedures.

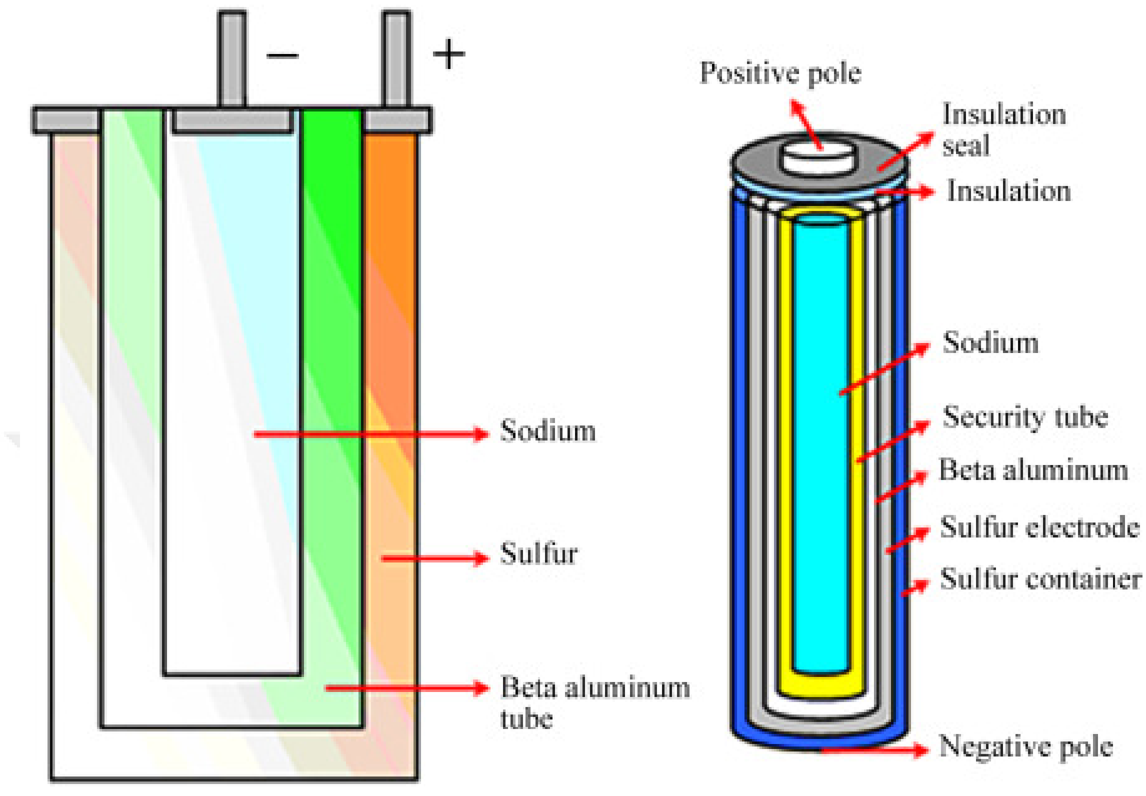

Figure 25: Structure of sodium-sulfur battery [11]

Sodium-sulfur batteries have a high energy storage capacity, ranging from tens to hundreds of kilowatt-hours (kWh) or even megawatt-hours (MWh) for larger grid-scale systems. The specific capacity depends on the size and design of the battery, but they are often used in large-scale energy storage applications due to their high energy density.

The energy density of sodium-sulfur batteries is relatively high compared to other types of batteries, ranging from 200-400 Wh/kg. This is due to the high energy density of the liquid electrolyte and the high specific energy of the sodium and sulfur electrode materials. However, it is important to note that the energy density can change depending on the specific design and operating conditions of the battery.

Sodium sulfur batteries have a high depth of discharge (DoD) in the range of 80-100%, meaning that they can discharge up to 80-100% of their rated capacity before needing to be recharged. However, it is important to note that discharging the battery to its full capacity may decrease its overall cycle life and efficiency. Therefore, it is recommended to operate sodium-sulfur batteries within a DoD range that maximizes their performance and longevity.

Sodium-sulfur batteries have a high efficiency, typically ranging from 85% to 90%. But, their efficiency can change depending on factors such as temperature, discharge rate, and depth of discharge. At high temperatures, the efficiency can be as high as 95%. Sodium-sulfur batteries are known for their high energy density, which means they can store a large amount of energy in a relatively small space. This makes them a good option for applications such as large-scale energy storage systems for power grids. However, they also have some disadvantages, such as a high operating temperature requirement and safety concerns due to their high energy density and reactive materials.

Sodium-sulfur (NaS) batteries have a relatively long cycle life, with manufacturers claiming up to 15 years or more of service life. They can typically withstand thousands of charge/discharge cycles, with some models claiming up to 5,000 cycles. The exact cycle life of a NaS battery can depend on a variety of factors, including operating conditions, depth of discharge, and maintenance practices.

However, NaS batteries also have some disadvantages. They operate at very high temperatures, which requires the use of insulation and cooling systems, increasing their cost and complexity. They also require careful maintenance and safety measures due to the highly reactive nature of sodium and sulfur.

CHAPTER V

METHODOLOGY

When conducting capacity expansion plan studies for renewable energy, it is cvery important to consider firmness since it directly impacts the stability and reliability of the power grid. Firm power, which is always available regardless of the weather or other factors, is typically supplied by non-renewable sources like coal and natural gas. Conversely, non-firm power is only available when certain conditions are met, such as when there is sufficient wind or sunlight.

Solar and wind power plants are variable renewable energy sources and are classified as non-firm power sources. They are dependent on the weather and other environmental conditions, which can result in significant fluctuations in power output. For example, during cloudy weather, a solar power plant may generate insufficient electricity, and a wind farm may generate insufficient electricity during calm weather. This unpredictability poses a challenge to maintaining a consistent and reliable power grid, particularly in island regions where the power grid is disconnected from the mainland.To provide stable and reliable power grids, countries, especially those reliant on renewable energy sources, often require firm power generation such as thermal generators or energy storage systems. Because of the negative environmental impact, supporting renewable energy sources with thermal generators is no longer a viable option for many countries. Instead, energy storage systems are becoming an increasingly popular choice for providing firm capacity to variable renewable energy (VRE) sources. However, the amount of storage needed to support a firm capacity for a VRE source like solar will change depending on factors such as the size of the solar power plant, the amount of power being generated, and the duration of the firm capacity. Generally, larger solar power plants will require more storage to support their firm capacity because they generate more power, and thus more storage is needed to store excess power when it is not being used.

The optimal size of an energy storage system (ESS) is crucial for ensuring maximum firmness of a hybrid system that is supported by variable renewable energy sources (VRE). The firmness needs to be maintained on an hourly basis for an extended period of time, such as a year, in order to transition to 100% renewables. To achieve this, a mathematical model has been developed to determine the optimal size of the ESS, taking into account the duration of the required firm capacity. This methodology can be applied to any grid, providing valuable insights into the transition to renewable energy sources.

This paper presents a mathematical model that aims to maximize the firmness factor of a hybrid system by determining the optimal size and type of solar, wind and energy storage systems while minimizing the investment cost. The optimization problem aims to maximize the firmness factor of a hybrid system while minimizing the investment cost of the energy storage system. The solution involves selecting an appropriate size and type of solar and storage systems and optimizing their operation to meet the hourly power demand of the system, all while satisfying the capacity constraints.

The methodology presented in this context requires only one parameter, which is hourly renewable generation data for a year. The model has two variables: (i) the firmness factors of each month and (ii) the hourly State-of-Energy of the ESS. The State-of-Energy refers to the amount of energy stored in the system at a given time, which can be expressed in different forms depending on the type of energy storage system. A metric calculator function is used to process the output of the mathematical model and provide metrics related to the size of the ESS needed to support a VRE system and achieve the desired firmness factor at a specific location.The diagram of methodology for optimal ESS capacity selection is shown in Figure 26.

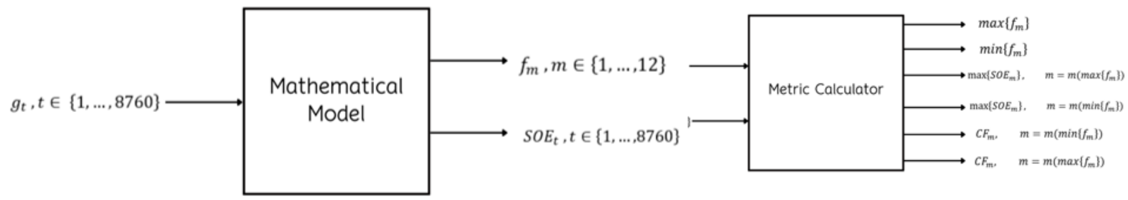

Figure 26: Methodology for optimal ESS capacity selection

5.1 Mathematical Model

A hybrid system, which includes a variable renewable energy sources (VRE) and an energy storage system (ESS) connected to the grid via a single interconnection, is analyzed in this model. The hourly generation dataset of a renewable generator, represented by (g_t) where t= 1,. . . ,T, is considered, with T being the number of hours in a year (8,760). This allows the model to account for seasonal variability. The energy generated can be used to either charge the ESS (c_t) or contribute to the firmness factor (p_t) according to Eq.2. However, the ESS has a maximum power capacity N, and cannot charge and discharge simultaneously. By introducing a binary variable (u_t $\epsilon\{0, 1\}$, $\forall t$) in the model, the ESS can either discharge (d_t) or charge (c_t) at time t, as shown in Eqs.3 and 4. The ESS must be charged for a certain period of time before it can begin discharging to support the firm capacity output. Therefore, the ESS is prohibited from discharging for a certain time period (t_c) by ensuring it is in discharge mode during the initial hours, as specified in Eq.5.

The round-trip efficiency of any ESS is modeled as the product of its charging efficiency and discharging efficiency, denoted as μ_c and μ_d, respectively. The ESS's state-of-energy (SoE) at time t (SoE_t) can be calculated by adding the charge or discharge amount in hour t to the previous hour's SoE, as shown in Eq.6. However, this equation is not valid for the first hour because there is no previous hour. Therefore, an initial SoE value, denoted as SoE^{ini} in Eq.7, must be specified. The SoE is subject to minimum and maximum limits, as shown in Eq.8. The firmness factor of the hybrid system, denoted as f_t, is the sum of the VRE's contribution to the firmness factor (p_t) and the ESS's contribution to the firmness factor, i.e., the discharge power (d_t), as given in Eq.9. The illustration of the model with the names of the variables and parameters is given in Figure 27.

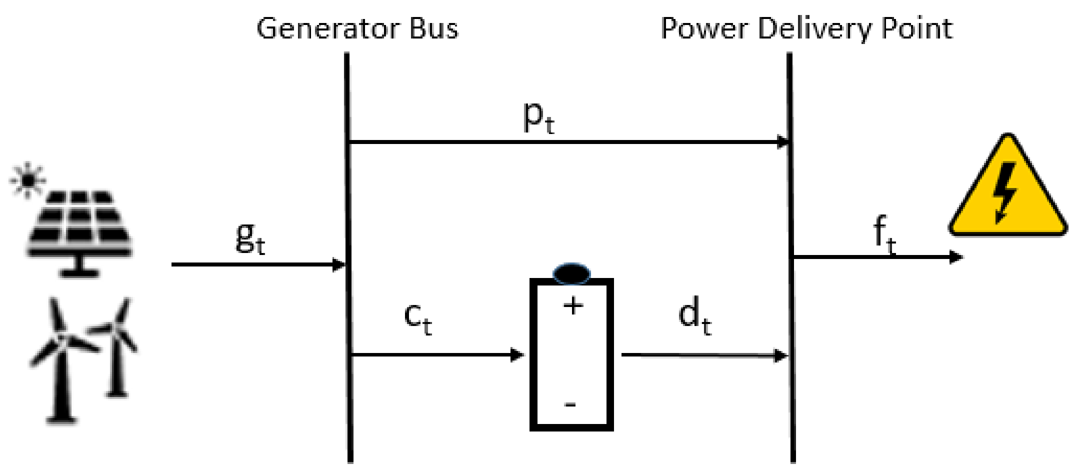

Figure 27: Illustration of the modeling for the hybrid system

The variability in the firmness of a renewable energy resource can be attributed to various factors such as weather patterns, daylight hours, and other factors that influence the availability of the resource. For example, solar power production is typically higher in the summer months when there are longer daylight hours and clear skies. By considering the degree of variability in the firmness of the resource over a period of time, it is possible to account for these seasonal fluctuations. To obtain a more precise estimation of the hybrid system's overall firmness factor and its seasonal variations, the firmness factor can be computed on a monthly basis using Equation 10.

The aim of this model is to maximize the firmness factor of a hybrid renewable energy system while minimizing the capacity of the energy storage system (ESS) in order to reduce the overall investment cost. The objective function is expressed in Eq.1 in Figure 28 , and the constraints are formulated to ensure the maximum firmness factor is achieved from the hybrid project. By minimizing the energy storage system (ESS) capacity while maintaining a high level of firmness, the model searches to find an optimal balance between energy storage and renewable generation.

$$\text{minimize } SoE^{max} \tag{1}$$

subject to

$$g_t = c_t + p_t \quad ,\forall t \tag{2}$$

$$c_t \leq N u_t \quad ,\forall t \tag{3}$$

$$d_t \leq N(1 - u_t) \quad ,\forall t \tag{4}$$

$$u_t = 1 \quad ,\forall t < t_c \tag{5}$$

$$SoE_t = SoE_{t-1} + \mu_c c_t - \frac{d_t}{\mu_d} \quad ,\forall t > 1 \tag{6}$$

$$SoE_t = SoE^{ini} \quad ,t = 1 \tag{7}$$

$$SoE^{min} \leq SoE_t \leq SoE^{max} \quad ,\forall t \tag{8}$$

$$f_t = p_t + d_t \quad ,\forall t \tag{9}$$

$$f_t = f_{t-1} \quad ,\forall t \geq t_c \tag{10}$$

Figure 28: Equations

The mathematical model gives two significant outputs that offer important information on the hybrid energy system's efficiency and dependability. These outputs are the hybrid system's firmness factor and the battery's state of energy, which provide valuable insights into the system's performance and reliability.

The firmness factor is a crucial metric that represents the reliability and predictability of a hybrid energy system, taking into account the variability of the renewable energy resource over the course of a year. By calculating the firmness factor on a monthly basis, a more accurate picture of the hybrid system's overall reliability can be obtained, accounting for seasonal changes in weather patterns and other factors that may affect the availability of the resource. This information is essential for stakeholders and investors in the renewable energy sector to understand the stability and predictability of the system. Sample outputs of firmness factors using locational solar generation data are illustrated in Figure 29 (a) for Şanlıurfa in Turkey and in Figure 29 (b) for Trabzon in Turkey.

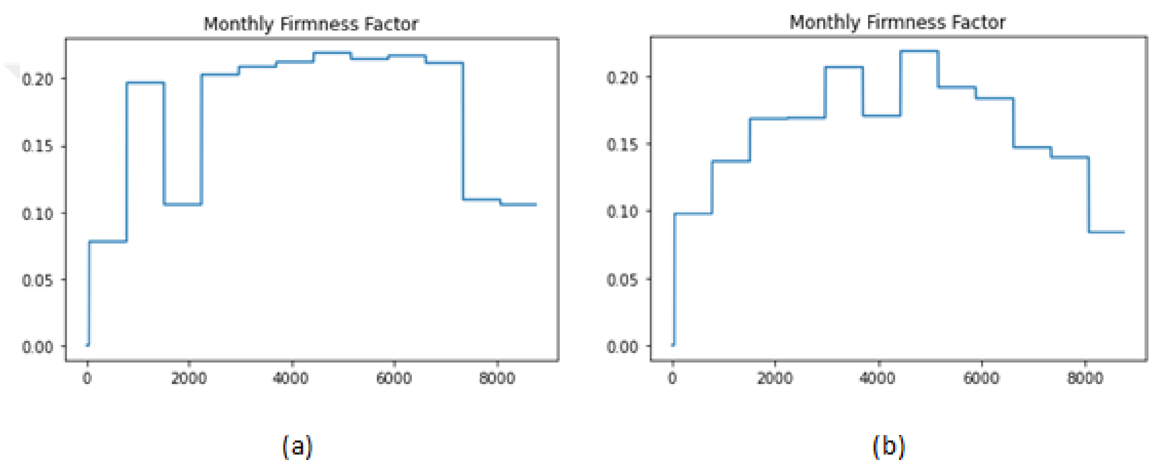

Figure 29: Monthly Firmness Factor (a) Şanlıurfa, Turkey, (b) Trabzon, Turkey

The second output of the model is the state of energy (SoE) of the battery, which provides very important information for understanding the performance of the battery energy storage system (BESS). Unlike the state of charge (SoC), which is commonly used to describe the battery charge level in percentage, state of energy (SoE) measures the actual energy stored in the battery. In this study, state of energy (SoE) is tracked to determine the maximum capacity required for the battery energy storage system (BESS) in kWh. The hourly dataset of optimal state of energy (SoE) for a year provides valuable insights into the behavior of the battery, and the maximum value in this dataset represents the required battery energy storage system (BESS) capacity to achieve the optimal firmness factor.A sample output from Sanliurfa's firmness factors using solar generation is illustrated in Figure 30 (a) for Şanlıurfa and another sample is illustrated in Figure 30 (b) for Trabzon, Turkey. The state of energy (SoE) of the battery energy storage system (BESS) changes with respect to charging or discharging decisions of the battery.

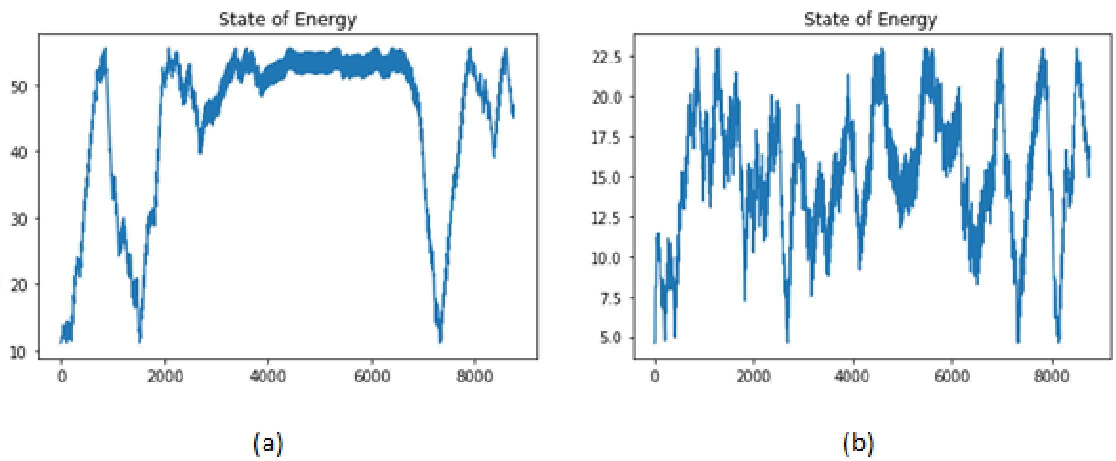

Figure 30: Hourly optimal SoE of the BESS (a) Şanlıurfa, Turkey, (b) Trabzon, Turkey

5.2 Metric Calculator

This section details the second stage of the methodology, which involves the use of a metric calculator. This calculator takes the outputs generated by the mathematical model and uses them to generate five additional outputs, which are described in detail in Section 5.2.1. These outputs are designed to provide valuable information on the performance and reliability of the hybrid energy system, including the capacity requirement of the battery energy storage system, the energy generated and consumed by the system, the net energy output of the system, and the greenhouse gas emissions associated with the system's operation. By analyzing these outputs, stakeholders in the renewable energy sector can gain a deeper understanding of the potential benefits and drawbacks of investing in hybrid energy systems.

To begin the operation of the metric calculator, it first identifies the minimum and maximum firmness factors among the 12 months of firmness factors that are inputted into the calculator. After this initial step, the calculator proceeds to calculate two additional metrics by identifying the maximum state of energy (SoE) of the battery during the month with the highest firmness factor, as well as during the month with the lowest firmness factor. An example of this process can be seen in Figure 31, which displays the results of the metric calculator using solar generation data from (a) Şanlıurfa, Turkey and (b) Trabzon, Turkey. The red shaded area represents the month with the maximum firmness factor, while the green shaded area represents the month with the minimum firmness factor. The maximum SoE values for these two months are shown with arrows in the Figure 31.

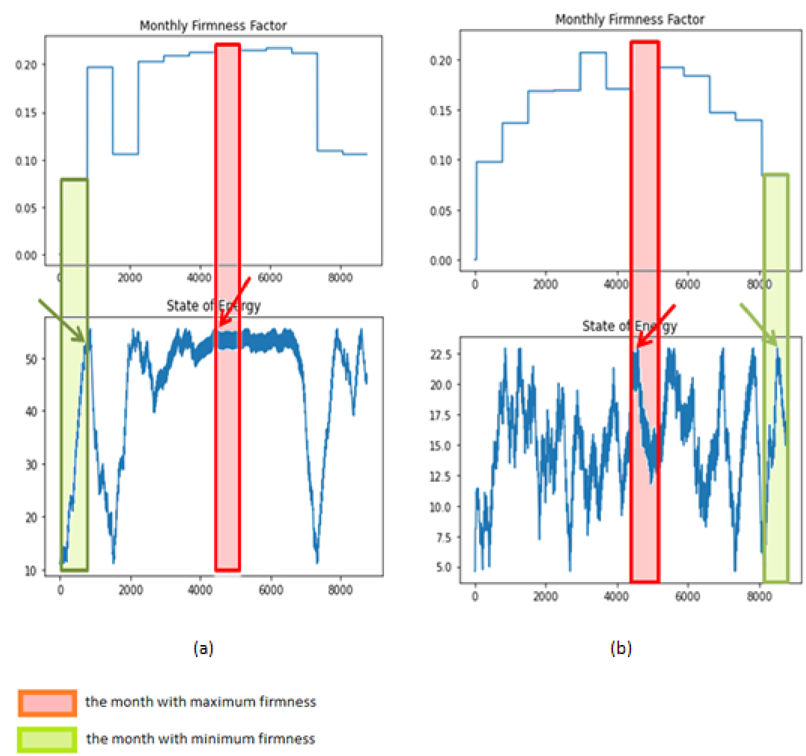

Figure 31: (a) Firmness and SOE Selection of Şanlıurfa (b) Firmness and SOE Selection of Trabzon

Another metric that can be calculated with the solar and wind generation data is the capacity factor.It represents the percentage of the total time that a power plant or system is operating at its full capacity over a given time period. A capacity factor of

100% would mean that the system is generating electricity at its maximum capacity continuously. The capacity factor is calculated by dividing the total electricity generated during the time period by the multiplying of the system's maximum capacity and the number of hours in the time period as given in Equation 11.

$$Capacity\ Factor_m = \frac{Actual\ Energy\ Generated\ in\ Month_m(MWh)}{Capacity(MW)\ x\ Total\ Hours\ in\ Month_m(h)},\ m\ \epsilon\{1, ..., 12\} \qquad (11)$$

After determining the months with maximum and minimum firmness, the capacity factors for both months are calculated by summing the solar generation of that month and dividing it by the number of hours multiplied by the capacity which is 1MW in this study in that month. The same calculation has also been done using wind energy data.

CHAPTER VI

RESULTS AND DISCUSSIONS

6.1 Case Study and Results

This section explains the case study done using the methodology detailed in Sections 5.1 and 5.2 and its results. In order to present a case study, wind and solar generation data of 10 different locations from the Turkey are selected. To consider different aspects of the regions, locations were selected from South to North and are given in Table 1.

Table 1: Locations Used in Case Study

	Location	Region
1	Şanlıurfa	Southeastern Anatolia
2	Mardin	Southeastern Anatolia
3	Diyarbakır	Southeastern Anatolia
4	Malatya	Eastern Anatolia
5	Elazığ	Eastern Anatolia
6	Erzincan	Eastern Anatolia
7	Bayburt	Black Sea
8	Gümüşhane	Black Sea
9	Trabzon	Black Sea
10	Rize	Black Sea

6.1.1 Solar Energy

To broaden the scope of the study, solar data from 10 locations around the Turkey were utilized as inputs. The methodology presented in Section 5.2 was applied to obtain the maximum and minimum firmness values.For every location, two firmness factors which are maximum, and minimum are shown in Figure 32.

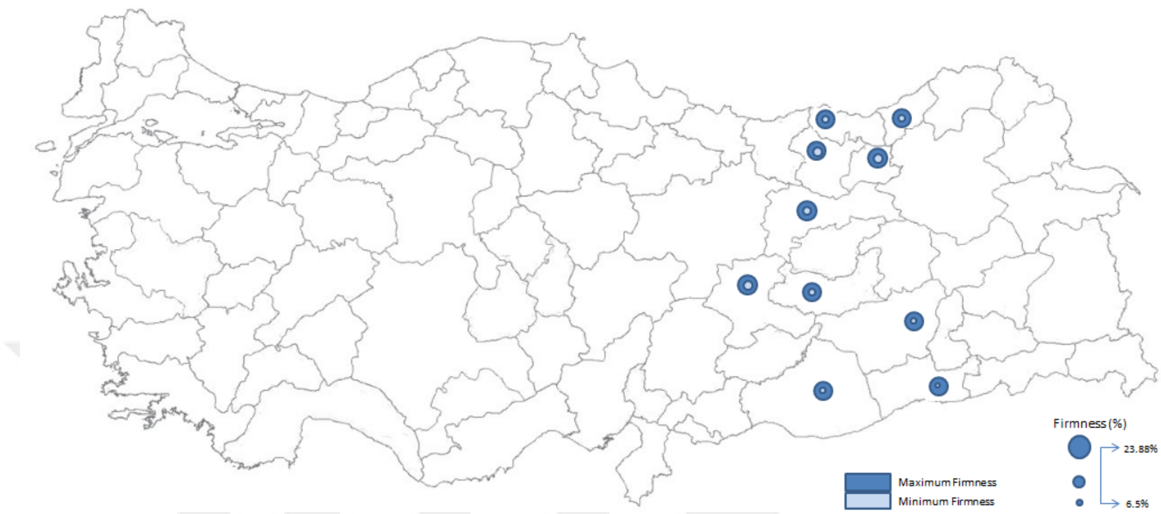

Figure 32: Maximum and Minimum Firmness Factors of Selected Locations for Solar Energy

Among these locations, a maximum of 23.88% firmness is calculated using the solar generation of Erzincan while a minimum firmness of 6.5% was calculated at Mardin. Erzincan has the maximum monthly capacity of 23.88% to provide certain electricity that is generated from solar power for a year. Further details of the results are stated in Table 2.

It can be observed from the analysis that the capacity factor and firmness factor are strongly correlated, with a linear relationship between them. The locations with higher firmness factors have higher capacity factors, while those with lower firmness factors have lower capacity factors. The relationship between these two factors is showed in Figure 33, where the capacity factor and firmness factor of each location are plotted. It can be seen that there is a positive correlation between the two factors, with locations with higher firmness factors having higher capacity factors, and vice versa. This information can be useful for investors in the renewable energy sector, as it provides insight into the performance of different locations for solar and wind

Table 2: Results Obtained from Solar Data

	Results (Firmness)	Region	Hour	Month	FF (%)	SOE	CF (%)
Şanlıurfa	Max. Min.	S.E.A.	4429 - 5158 49 - 778	7 1	21.9 7.77	55.53 52.7	23.95 13.93
Mardin	Max. Min.	S.E.A.	2969 - 3698 8079 - 8760	5 12	22.57 6.5	46.48 46.48	23.76 11.92
Diyarbakır	Max. Min.	S.E.A.	2969 - 3698 49 - 778	5 1	22.87 8.13	44.98 42.39	24.02 12.98
Malatya	Max. Min.	E. A.	5159 - 5888 8079 - 8760	8 12	23.3 11.12	20.58 19.25	24.13 12.27
Elazığ	Max. Min.	E. A.	2969 - 3698 49 - 778	5 1	23.14 8.9	41.02 38.7	24.2 13.3
Erzincan	Max. Min.	E. A.	2969 - 3698 8079 - 8760	5 12	23.88 11.66	24.15 25.49	24.14 14.73
Bayburt	Max. Min.	B.S.	4429 - 5158 8079 - 8760	7 12	23.8 11.74	26.55 26.55	25.57 15.18
Gümüşhane	Max. Min.	B.S.	4429 - 5158 8079 - 8760	7 12	22.8 11.3	24.89 25.99	24.67 14.37
Trabzon	Max. Min.	B.S.	4429 - 5158 8079 - 8760	7 12	21.86 8.39	22.98 22.98	23.09 10.73
Rize	Max. Min.	B.S.	4429 - 5158 8079 - 8760	7 12	22.2 9.19	25.43 25.43	23.36 12.26
S.E.A. : SouthEastern Anatolia, E. A. : Eastern Anatolia, B.S. : Black Sea, FF : Firmness Factor, CF : Capacity Factor							

power generation.

Adding a trendline to the scatter plot of capacity factor and firmness values gives Equation 12, which represents the linear relationship between these two metrics.For the selected month with minimum and maximum firmness, the firmness can be roughly estimated by multiplying the capacity factor of the selected month by 1.2081 and subtracting 6.3615 from this value, as given in Equation 12. m is month of a year starting from January (1) and ending at December (12) in Equation 12.

$$Firmness_{solar,m}(\%) = 1.2081\, x\, Capacity\ Factor_{solar,m}(\%) - 6.3615 \qquad (12)$$

Using the method explained in Section 5.2, the maximum and minimum firmness values were calculated for various locations around the Turkey, and the maximum SOE values for those months were determined. While most of the locations showed similar

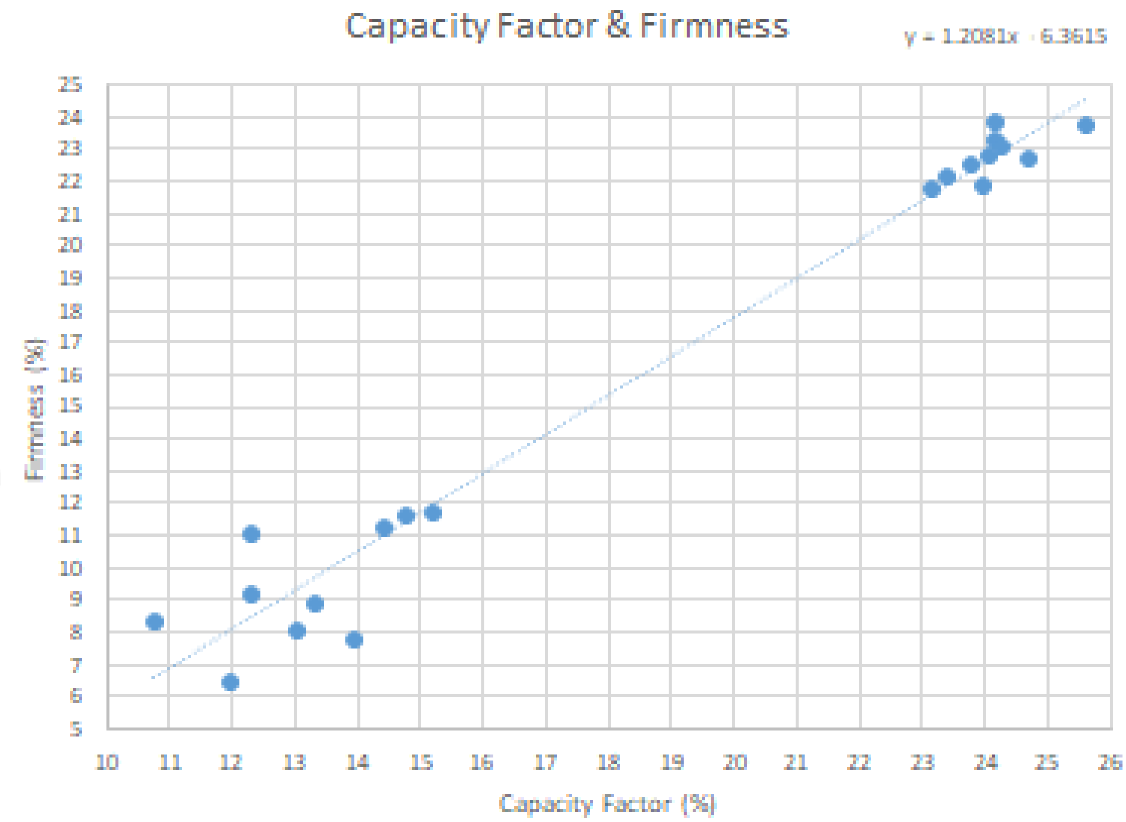

Figure 33: Linear Relation Between the Capacity Factor and Firmness Factor for Solar Energy

or close maximum SOE values for the months with the highest and lowest firmness values, there were some cases where there was a significant difference between the required battery size for the minimum and maximum firmness values. For example, in Şanlıurfa, as shown in Figure 34, the required battery size was found to be 52.7 MWh for the month with the minimum firmness factor, but for the month with the maximum firmness factor, the required battery size was 55.53 MWh.

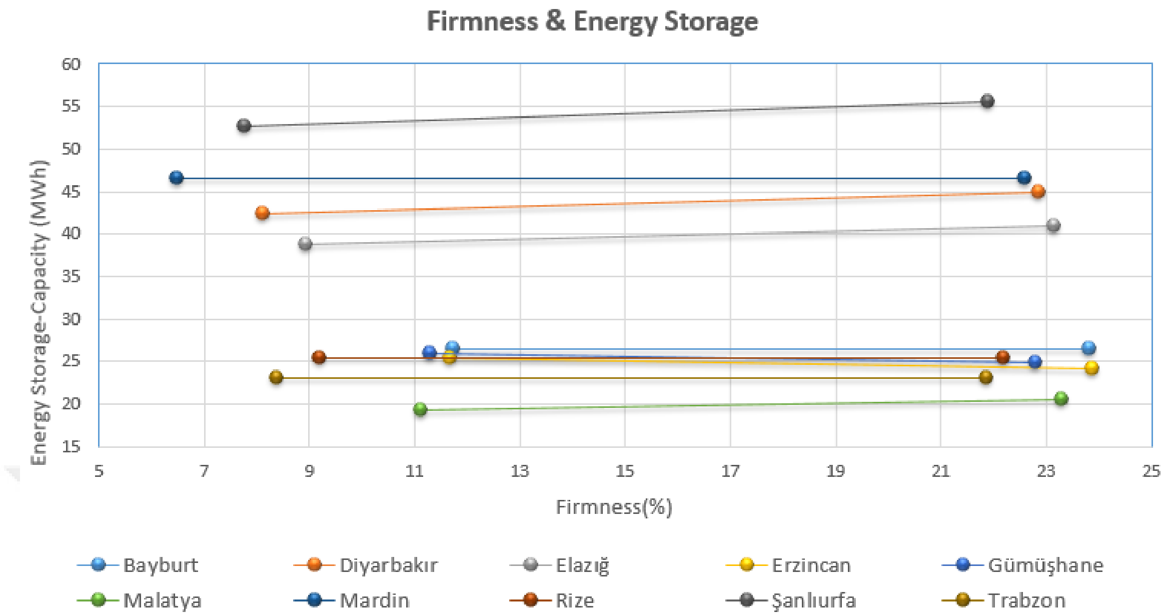

Figure 34: Firmness Factors vs. SOE of Selected Locations for Solar Energy

According to Figure 34, different locations in different regions have various behaviors. Therefore, it is not possible to make generalization. However, a better and more accurate estimate can be made with more data.

6.1.2 Wind Energy

Figure 35 shows the maximum and minimum firmness values for wind energry obtained for the selected locations after applying the same methodology as in solar energy.

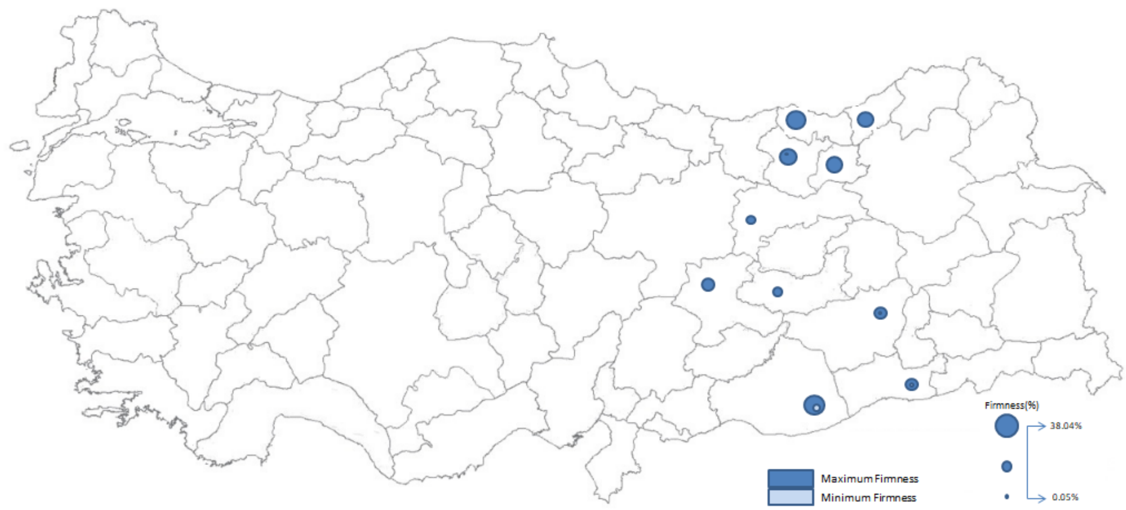

Figure 35: Maximum and Minimum Firmness Factors of Selected Locations for Wind Energy

It is noticeable that there is a significant difference between the maximum and minimum firmness values of wind and solar as both sources are influenced by different factors.The minimum firmness factor belongs to Rize with 0.05%, and the maximum firmness factors for Şanlıurfa is 38.04% when data on wind generation is used.Although wind power has the advantage of being able to generate electricity even at night or in cloudy weather, its output is highly dependent on wind speed. As a result, there may be large variations in the maximum and minimum firmness factors of wind power in different locations. For example, in Trabzon, the maximum and minimum firmness factors are significantly different due to the variability of wind speed.In many locations there could be months with very low capacity to provide a certain output whereas there also could be some months with very high capacity. A detailed summary of the results can be found in Table 3.

In both solar and wind cases, the relations between capacity factor and firmness factor are found to be linear but with different slopes. A scatter graph is used to illustrate the relationships between capacity factor and firmness in Figure 36.

Adding a trendline to the scatter plot of capacity factor and firmness values

Table 3: Results Obtained from Wind Data

	Results (Firmness)	Region	Hour	Month	FF (%)	SOE	CF (%)
Şanlıurfa	Max.	S.E.A.	4429 - 5158	7	38.04	50.68	34.96
	Min.		2239 - 2968	4	12.2	37.19	13.6
Mardin	Max.	S.E.A.	4429 - 5158	7	23.13	35.6	21.31
	Min.		2239 - 2968	4	6.62	38.97	10.31
Diyarbakır	Max.	S.E.A.	4429 - 5158	7	23.79	40.94	21.4
	Min.		2239 - 2968	4	4.88	29.81	6.92
Malatya	Max.	E. A.	4429 - 5158	7	24.44	49.29	21.46
	Min.		6619 - 7348	10	2.7	40.58	7.26
Elazığ	Max.	E. A.	4429 - 5158	7	18.19	40.03	15.52
	Min.		6619 - 7348	10	2.7	42.16	6.12
Erzincan	Max.	E. A.	49 - 778	1	16.82	56.65	20.61
	Min.		7349 - 8078	11	0.07	56.65	4.33
Bayburt	Max.	B.S.	49 - 778	1	30.76	54.62	31.72
	Min.		7349 - 8078	11	1.3	63.67	8.66
Gümüşhane	Max.	B.S.	49 - 778	1	31.9	59.72	34.66
	Min.		7349 - 8078	11	3.69	67.33	11.76
Trabzon	Max.	B.S.	49 - 778	1	36.22	57.51	41.07
	Min.		5889 - 6618	9	0.08	65.85	5.21
Rize	Max.	B.S.	49 - 778	1	29.53	57.17	34.8
	Min.		5889 - 6618	9	0.05	64.6	4.32

S.E.A. : SouthEastern Anatolia, E. A. : Eastern Anatolia, B.S. : Black Sea,
FF : Firmness Factor, CF : Capacity Factor

gives Equation 13, which represents the linear relationship between these two metrics.For the selected month with minimum and maximum firmness, the firmness can be roughly estimated by multiplying the capacity factor of the selected month by 1.0873 and subtracting 4.0041 from this value, as given in Equation 13. m is month of a year starting from January (1) and ending at December (12) in Equation 13.

$$Firmness_{solar,m}(\%) = 1.0873\, x\, Capacity\ Factor_{solar,m}(\%)\ - 4.0041 \quad (13)$$

The maximum SOE values of the months with minimum and maximum firmness are chosen among the results obtained from the wind data. The outcomes showed that because of the various locations with various wind speeds, the size of the battery changes almost in every location as illustrated in Figure 37.

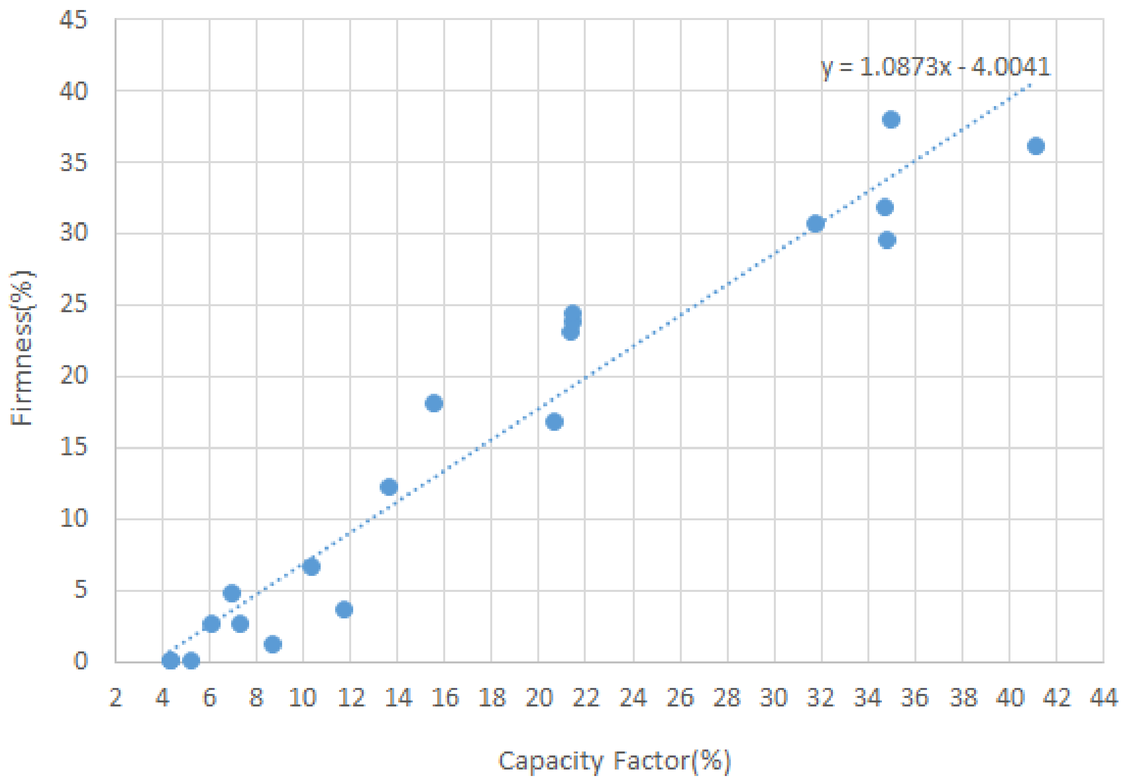

Figure 36: Linear Relation Between the Capacity Factor and Firmness Factor for Wind Energy

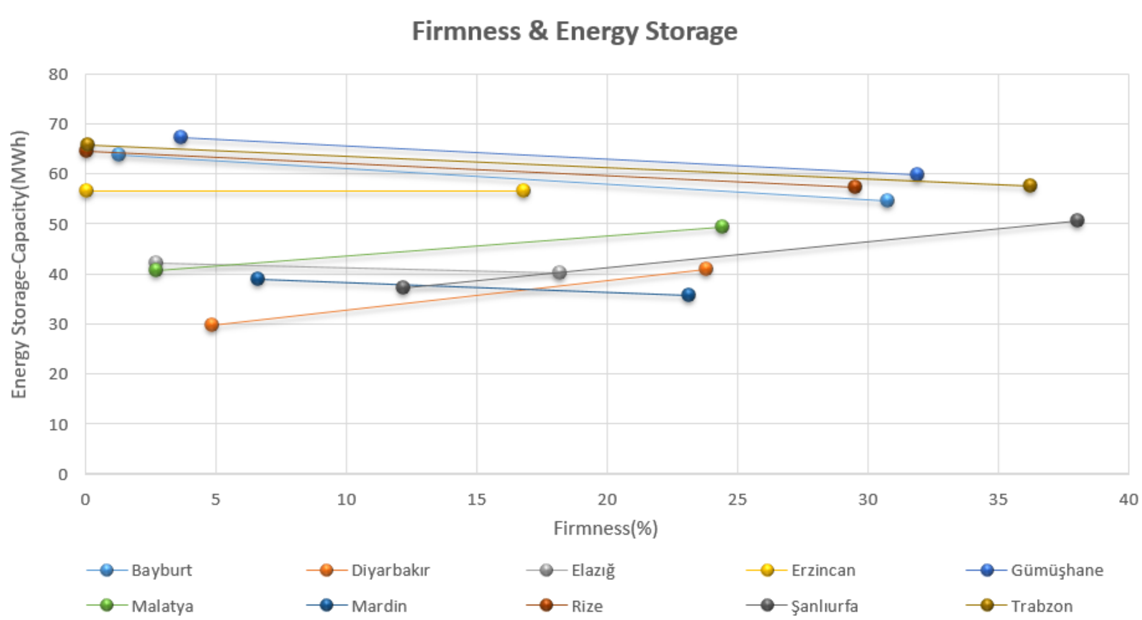

Figure 37: Firmness Factors vs. SOE of Selected Locations for Wind Energy

When the results of the firmness factors and SOE values of solar and wind are compared, the amount of storage needed for wind generation is very large compared to solar. In the solar case, the maximum storage is 55.53MWh where in the case of wind the maximum storage is 67.33MWh. Similarly, the firmness factor of solar is around 23.8% where the firmness factor of wind is around 38%. In Figure 38, the amount of solar storage and firmness that covers the wind storage and firmness is shown by the red lined area.

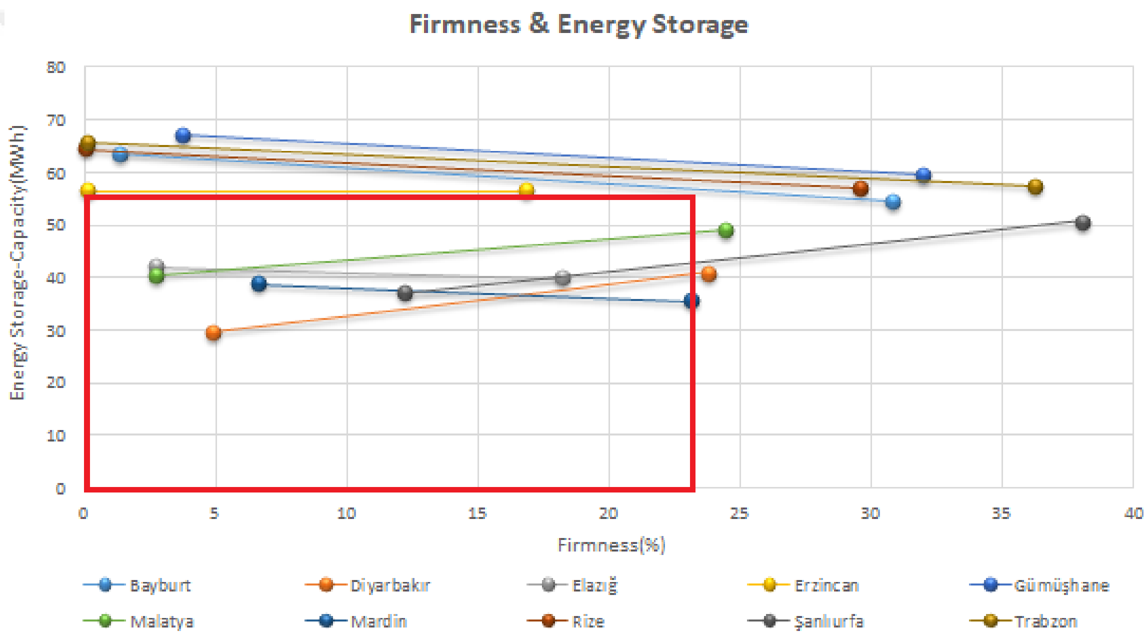

Figure 38: The Amount of Solar Storage and Firmness That Meets the Wind Storage and Firmness

6.2 Discussion

There has been a growing interest in the use of renewable and storage systems to replace thermal generators in power systems in recent years. This trend is motivated by several factors, including the need to reduce greenhouse gas emissions, the affordability of renewable energy technologies, and the expanding role of distributed energy resources in the power system.

Shifting from thermal generator capacity to renewable and storage systems in power systems has several benefits, one of which is the potential to mitigate the effects of climate change by reducing greenhouse gas emissions. Thermal generators, like coal and natural gas power plants, are significant contributors to greenhouse gas emissions, and replacing them with renewable and storage systems can lead to a reduction in emissions. This transition can help to address the urgent need to reduce carbon emissions and limit global warming.

Replacing thermal generator capacity with renewable and storage systems offers the advantage of reducing the overall cost of electricity. Incorporating cost-competitive renewable energy technologies like solar and wind into the power system can lower the cost of electricity for consumers. Additionally, storage systems like batteries can help to mitigate the variability of renewable energy sources, thus increasing their reliability and reducing the overall cost of electricity.

However, there are several obstacles that come with the replacement of thermal generator capacity with renewable and storage systems. One of the major obstacle is the need to guarantee the reliability and stability of the power system. Renewable energy sources like solar and wind are unreliable and can't supply power consistently, while storage systems such as batteries have limited capacity and may not provide electricity for extended periods. Therefore, it's critical to carefully plan and manage the incorporation of renewable and storage systems into the power system to ensure its reliability and stability.

Another obstacle for the integration of renewable energy sources with energy storage systems is the high initial investment required. Energy storage systems are expensive, which may make it difficult for companies to justify the investment. Additionally, energy storage systems have limited lifespans and require frequent maintenance, which increases their overall cost. Therefore, it is essential to carefully evaluate the financial aspects of integrating renewable energy sources with energy storage systems to ensure that the benefits outweigh the costs.

The results of this paper provide an insight on transition from thermal systems to VRE+ESS hybrid systems and on the subject of firm capacity that hybrid systems can deliver. The required capacity of energy storage system to deliver a firm capacity can help researchers in the field of capacity expansion studies.

CHAPTER VII

CONCLUSIONS

Hybrid systems are power systems that combine a renewable resource and an energy storage system. The renewable resource, which can be solar, wind, or another non-fossil fuel source, provides energy without emitting greenhouse gases. The energy storage system, such as a battery, can store the excess energy generated by the renewable resource for use when needed. By combining the two, hybrid systems can provide reliable and sustainable power generation while reducing carbon emissions.

A hybrid system integrates both renewable and non-renewable sources of power generation, making it a versatile and reliable energy source.This allows the system to take advantage of the benefits of both types of power generation. For example, a hybrid system can use the renewable resource to generate power when conditions are favorable, and then use the storage system to provide power when the renewable resource is not available.

The primary objective of this study is to determine the required size of an energy storage system (ESS) in a hybrid power system consisting of either 1 MW solar or 1 MW wind capacity that can replace a diesel generator or any other thermal system that can deliver a firm capacity. A linear programming model is developed minimizing the capacity of the ESS and thus the capital cost of investment with a constraint set including the technical modeling of a VRE and an ESS. One of the important parameters in the model is the maximum firmness factor of the hybrid system. Firmness is a critical aspect in renewable energy since it influences the reliability and stability of the power grid. In general, firm power refers to power that is continuously available, irrespective of weather or other conditions, and is usually supplied by non-renewable sources such as natural gas or coal. Conversely, non-firm power is power that is only accessible when the conditions are favorable, such as when the sun is shining or the wind is blowing. Non-firm power sources, such as solar and wind, are subject to variability in power output based on weather and environmental conditions. This can present challenges to maintaining a stable and reliable power grid, particularly for weak or small grids such as those found on remote islands that are isolated from larger power systems.

To ensure the stability and reliability of power grids that rely heavily on renewable energy sources, it is necessary to have a backup source of firm power generation, such as thermal generators or battery storage systems. Renewable sources, like solar and wind, are subject to fluctuations in output due to changing weather and environmental conditions, which can cause instability on the power grid. The inclusion of firm power generation sources can provide consistent power supply and help to balance the variability of renewable sources, ensuring a stable and reliable power grid.

This paper has established that there is a direct correlation between the firmness factor and capacity factor of solar and wind systems for the chosen locations, as per the linear programming model. The firmness factor serves as an additional criterion that investors can utilize to calculate the energy storage system capacity for delivering firm power output as an alternative to thermal power generation.

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