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RENEWABLE ENERGY

Guru Prasad Das School of Interdisciplinary and Vocational Studies
Krishna Kanta Handiqui State Open University

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COURSE INTRODUCTION

Renewable Energy course is an Ability Enhancement Course (AEC) designed to provide learners with a basic understanding of different energy resources, their applications, and the importance of sustainable energy systems. The main objective of this course is to develop awareness about conventional and renewable sources of energy and their role in meeting the growing global and national energy demands. This course familiarizes the learner with the principles, technologies, and applications of renewable energy systems and explains the environmental and economic aspects associated with energy production and utilization.

The course introduces the limitations of conventional energy resources and discusses the need for renewable energy in the context of energy security, sustainability, and climate change mitigation. It explains various renewable energy technologies such as solar, wind, hydro, bioenergy, ocean, tidal, and geothermal energy systems. The course also discusses energy storage technologies, hybrid renewable energy systems, energy economics, energy auditing, and renewable energy policies at national and international levels. Further, it introduces environmental issues related to energy production and future trends such as AI/ML applications in renewable energy optimization and smart charging systems.

After completing this course, the learner develops an understanding of the principles and applications of renewable energy technologies and gains knowledge about energy conservation, sustainability, and environmental protection. The learner also acquires basic ideas about energy economics, policy frameworks, energy auditing, and emerging technologies in the renewable energy sector.

There are fifteen units in this course.

The **first unit** introduces conventional sources of energy, including fossil fuels and nuclear energy, and discusses their formation, extraction, distribution, strategic importance, applications, and environmental impacts.

The **second unit** introduces renewable sources of energy and explains the need for renewable energy in the global and Indian energy scenario. It also discusses the classification of energy sources, energy security, and sustainability.

The **third unit** discusses solar energy, solar radiation, solar thermal systems, different types of solar collectors, and applications such as solar distillation, solar cookers, solar cooling, and solar greenhouses.

The **fourth unit** introduces solar photovoltaic systems, including solar cell technologies, PV system components, equivalent circuit models, grid-connected and off-grid systems, rooftop PV systems, and maintenance of solar power plants.

The **fifth unit** discusses wind energy, characteristics of wind power, wind turbines, aerodynamics of wind turbines, grid integration, and challenges associated with wind energy technology.

The **sixth unit** introduces hydro energy, hydropower resources, components of hydropower systems, hydro technologies, hydro turbines, pumped hydro energy storage, and environmental impacts of hydropower applications.

The **seventh unit** discusses bioenergy, including biomass and biofuels, sources and potential of bioenergy, characteristics of bioenergy fuels, and their environmental and economic aspects.

The **eighth unit** introduces ocean energy and discusses wave energy devices, ocean thermal energy conversion (OTEC), osmotic power, and their applications.

The **ninth unit** discusses tidal energy, wave energy devices, and different tidal energy technologies.

The **tenth unit** introduces geothermal energy, geothermal resources, geothermal technologies, and their applications.

The **eleventh unit** discusses energy storage devices and hybrid renewable energy systems, including batteries, hybrid system classifications, the role of storage systems, and hybrid systems for electric vehicle charging.

The **twelfth unit** explains energy economics and auditing, including energy saving schemes, investment analysis methods, energy audits of different sectors, lifecycle assessment, and socio-economic aspects of energy transition.

The **thirteenth** unit discusses renewable energy policies at national and international levels and explains policy implementation programmes such as KUSUM, PM Surya Ghar: MuftBijliYojana, and Green Energy Corridors.

The **fourteenth** unit explains the relationship between renewable energy and the environment, including greenhouse gas emissions, global warming, climate change mitigation, international agreements, and carbon pricing systems.

The **fifteenth** unit introduces future trends in renewable energy, including the role of artificial intelligence and machine learning in renewable energy optimization and smart charging technologies such as V2V, V2G, and V2X systems.

While going through the units, the learner will notice some boxes containing additional information that help in understanding important or unfamiliar terms. Sections titled “ACTIVITY” provide opportunities for the learner to apply knowledge through questions related to the topic. Some useful concepts are also provided under the heading “LET US KNOW”. At the end of each section, “CHECK YOUR PROGRESS” questions are included to help the learner assess understanding of the topic. Attempting these questions and comparing the responses with the “ANSWERS TO CHECK YOUR PROGRESS” given at the end of each unit helps the learner evaluate progress in the course.

UNIT 1: CONVENTIONAL SOURCES OF ENERGY

UNIT STRUCTURE

1.1 Learning Objectives
1.2 Introduction
1.3 Overview of Conventional Energy Sources
1.4 Types of Conventional Sources
1.5 Fossil Fuels
1.5.1 Limitations
1.5.2 Formation
1.5.3 Extraction of Conventional Energy Sources
1.6 Nuclear Energy
1.7 Global and National Distribution of Reserves
1.8 Strategic Importance of Conventional Energy Resources
1.9 Uses and Applications: Environmental Impacts
1.10 Let us Sum Up
1.11 Answers to Check Your Progress
1.12 Further Reading
1.13 Model Questions

1.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- define conventional energy sources and their key characteristics
- differentiate the major types of conventional energy sources
- describe fossile fuels, their formation, and their limitations
- explain the principles of nuclear energy and its role as a conventional energy source
- illustrate the distribution of conventional energy reserves
- evaluate the uses, applications, and environmental impacts of conventional energy sources.

1.2 INTRODUCTION

This is the first unit of the course on Renewable Energy. This unit introduces the concept of conventional energy sources and their significance in meeting global and national energy demands. In this unit you will learn about the characteristics and different types of conventional energy sources, including fossil fuels and nuclear energy. The unit explains how fossil fuels are formed, their limitations and their extraction method. You will also explore the principles of nuclear energy and its role in power generation. In addition, the unit covers the global and India-focused distribution of conventional energy reserves. By the end of this unit you will provide the uses, applications, and environmental impacts of conventional energy sources.

1.3 OVERVIEW OF CONVENTIONAL ENERGY SOURCES

Renewable energy is the type of energy that is captured or generated from an energy resource which is rapidly replaced or renewed by a natural process, such as power generated from sunlight or wind. Renewable energy sources are also known as Alternative Energy sources and are commonly called Non-conventional sources of energy. However, it should be noted that large-scale hydropower is an exception. Although hydropower is a renewable source of energy because it is continuously replenished by the natural water cycle, it is traditionally classified as a conventional source of energy due to its long history of commercial use and well-established technology. Contrary to the Non-conventional energy, most conventional sources of energy are non-renewable by any natural process within a human timescale.

Before learning about the need of renewable energy, you have to learn what the conventional energy sources are and why there is need for renewable energy sources.

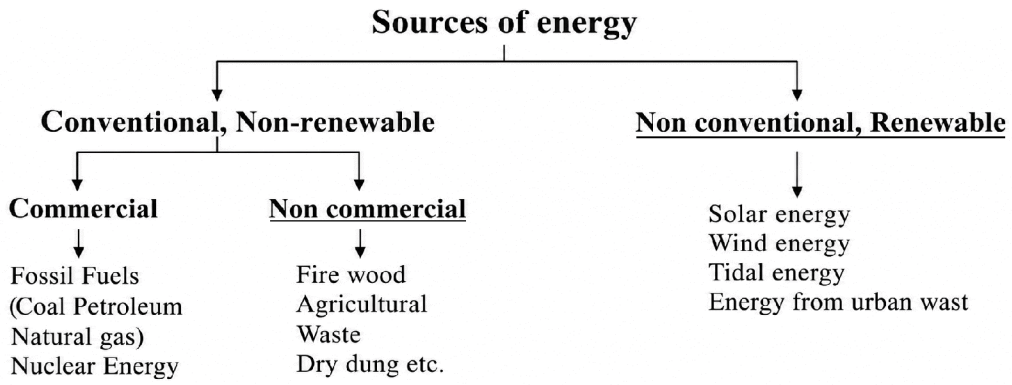
Energy is the capacity or ability to do work or cause change. To carry out works, man obtains energy from various sources. In the pre-industrialization era, wood was the primary source of energy. Coal, petroleum oil, natural gas, nuclear energy and hydroelectric are commonly known as conventional energy sources. However, world's energy supply mainly comes from fossil fuels such as coal, petroleum oil, and natural gas.

Conventional energy sources have played a fundamental role in supporting industrialization, economic development, and technological advancement for more than a century. Currently, fossil fuels account for a significant share of the global energy supply due to their high energy density, established infrastructure, and ease of extraction, transportation, and storage.

Despite their widespread use, conventional energy sources have significant limitations. Fossil fuels are finite, non-renewable resources that are being depleted through continuous consumption. Their extraction and combustion release greenhouse gases and other pollutants which causes air pollution, global warming, and climate change. Although nuclear energy is a low-carbon source of electricity, it presents challenges related to radioactive waste management and operational safety. Because of these limitations of conventional energy sources, the study of renewable energy systems has become essential.

1.4 TYPES OF CONVENTIONAL ENERGY SOURCES

Most conventional energy sources are non-renewable, which means they exist in limited quantities and have been used extensively for many years. They are commonly referred to as "traditional" or "commercial" energy sources because they serve as the primary fuels for electricity generation, transportation, and industrial activities. However, some conventional energy sources are also classified as non-commercial, particularly those used locally for domestic purposes. The classification of sources of energy is shown below.



Conventional energy sources are of the following types.

Fossil fuels: These are the most widely used conventional sources of energy, formed over millions of years from the buried remains of ancient plants and animals. Examples are coal, petroleum oil and natural gas.

Nuclear energy: Energy produced by the nuclear fission of radioactive elements like uranium in nuclear reactors, which is considered a significant conventional source.

Hydroelectric Energy (Hydropower): This energy is generated from the flow or fall of water. It is the only major renewable energy source that is traditionally classified as a conventional energy source.

Non-Commercial Energy Sources:

Non-commercial energy sources are traditional fuels that are generally collected from nature or produced locally and are not bought or sold in the commercial market. They are commonly used for cooking, heating, and small-scale domestic activities, particularly in rural areas.

Some common non-commercial energy sources include:

- **Firewood:** Wood collected from forests or plantations and used as fuel for cooking and heating.
- **Agricultural Waste:** Crop residues such as rice husk, wheat straw, sugarcane bagasse, and coconut shells that are used as fuel after harvesting.
- **Dry Dung:** Dried animal dung, mainly from cattle, shaped into cakes and used as a cooking and heating fuel in many rural households.

Although these energy sources are inexpensive and locally available, their excessive use can contribute to deforestation, indoor air pollution, and health problems. Therefore, they are gradually being replaced by cleaner and more efficient energy sources.

1.5 FOSSIL FUELS

Fossil Fuels are non-renewable energy resources formed over millions of years from the buried remains of organic matter (plants and animals). Under high temperature and pressure beneath the Earth's surface, this organic matter gradually transforms into fossil fuels. The three major fossil fuels are coal, petroleum, and natural gas.

Coal:
Coal is a black or brownish-black combustible sedimentary rock and one of the most important fossil fuels. It is rich in carbon and is formed from the buried remains of ancient plants through a slow process called carbonization over millions of years. Coal occurs in underground deposits and is extracted by mining. It is an important source of energy and is widely used for electricity generation, industrial heating, and the production of steel. Depending on its carbon content and heating value, coal is classified into four main types: peat, lignite, bituminous coal, and anthracite.

Petroleum:
Petroleum (crude oil) is a liquid fossil fuel formed mainly from the buried remains of microscopic marine organisms, such as plankton and algae, over millions of years under high temperature and pressure. It is refined by fractional distillation into various useful products (fractions), while some by-products are also obtained during the refining process. The major products include liquefied petroleum gas (LPG), gasoline (petrol), naphtha, kerosene, diesel, jet fuel, lubricants, paraffin wax, and bitumen (asphalt). Gasoline is used extensively in transportation. Petroleum is regarded as liquid gold and is one of the major energy sources. It also serves as an important raw material for the petrochemical industry, where it is used to manufacture plastics, synthetic fibres, detergents, fertilizers, medicines, paints, and many other useful products.

Natural gas:
Natural gas is a mixture of hydrocarbon gases, primarily methane, along with smaller amounts of ethane, propane, butane, and other gases, used for heating and electricity generation. It is also widely used as a domestic cooking fuel, an industrial fuel, and as a fuel for vehicles in the form of Compressed Natural Gas (CNG). Compared with coal and petroleum, natural gas burns more cleanly and produces lower emissions of smoke, sulphur compounds, and carbon dioxide, making it a relatively cleaner fossil fuel.

1.5.1 Limitations

It is true that generating energy from the conventional sources have various advantages. It is technologically simple and cost-effective. These have energy efficient calorific factor. Massive quantities of electricity can be generated in one location. Transporting fossil fuels like gas and oil is possible through pipelines which is simple to accomplish. Gas-powered power plants are extremely efficient. Construction of fossil fuel operated power stations is technologically simple.

Despite these advantages, conventional source of energy like fossil fuels have serious limitations. The following are some limitations of conventional sources of energy like fossil fuels.

- The conventional sources of energy are available in finite reserves in the world and cannot be replenished. Because these resources take millions of years to form.
- Due to increasing consumption of energy, these are rapidly depleting. So, these are going to be exhausted in future.
- The extraction of fossil fuels such as coal leads to the destruction of large areas of land and has damaging effect on the ecological balance.

- Extraction of fossil fuels is extremely difficult and is highly risky, sometimes leaving miners' lives at risk.
- During the use of conventional sources of fuel, there is always risk of fire and accidents.
- The conventional sources of fuel have a major drawback of great polluting effect on environments. In the process of combustion of fossil fuels, lots of harmful gases are released, causing pollution to the atmosphere. In case of coal, fly-ash is released, gases released include carbon dioxide, which traps the Sun's heat and contributes to global warming. In addition, sulphur dioxide is produced, which can create acid rain
- Transportation and distribution of conventional sources of fuel are very costly.
- Use of natural gas may cause unpleasant odours in nearby areas.

1.5.2 Formations

Fossil fuels are formed by nature. The Processes of formation of fossil fuel are almost similar. These are discussed here.

- **Coal:** Coal is a kind of sedimentary rock that was formed from over millions of years from the buried remains of plants, which are transformed in a process called carbonization. This process was the result of dense forests getting buried under soil due to natural processes like storm, floods, earthquakes etc. These plant materials accumulated in swampy environments and formed peat, i.e. partially decayed plant material. As this peat was buried under layers of sediment, it is subjected to increasing temperature and pressure, causing it to undergo chemical changes and become coal. The process of formation of coal from dead vegetation is called carbonization and the time period is called CARBONIFEROUS ERA. Most coal deposits were formed during the Carboniferous Period (about 359–299 million years ago), which is part of the Paleozoic Era.
- **Petroleum and natural gas:** Petroleum is a fossil fuel created from organic matters of ancient time, transformed by geological forces deep within the Earth. The formation process includes
  - i) Organic accumulation: Petroleum forms over millions of years from the anaerobic decomposition of organic matter (like algae and plankton) which die and sink to the bottom of ancient seas and lakes.
  - ii) Burial and sedimentation: These decomposed organic matters were buried under layers of sediment in the floors of ocean.
  - iii) Anaerobic condition: The lack of oxygen (anaerobic) prevents complete decay, preserving the organic material.
  - iv) Heat and Pressure (Catagenesis): As burial depth increases, immense heat and pressure from the Earth's core transforms the organic matter into kerogen, a waxy solid.
  - v) Hydrocarbon generation: Further heat and pressure break down the kerogen into liquid petroleum (crude oil) and natural gas.
  - vi) Migration and Trapping: The lighter oil and gas migrate through porous rocks (reservoir rocks) until they are blocked by impermeable layers (cap rocks), forming underground reservoirs.

- **Natural gas** is often found associated with oil, but can also exist in non-associated form (dry gas), or trapped within shale (shale gas) or coal beds (coalbed methane). Natural gas is about 70-90% methane.
- **Petroleum Gas and Liquefied Petroleum Gas (LPG):** Petroleum gas is a mixture of ethane, propane and butane, but the major component is butane. Petroleum gas can be liquefied under high pressure and the pure Liquefied Petroleum Gas (LPG) is a colourless, odourless gas. A strong smelling compound called **ethyl mercaptan (C2H5SH)** is added to LPG for its detection in the case of any leakage. Both fuel require oxygen for combustion.

1.5.3 Extraction of Conventional Energy Sources

The extraction of fossil fuels involves various methods depending on the type of fuel and its location:

- **Extraction of Coal :** In general, coal is found as deposits close to the surface of earth or deep down. Coal is extracted by mining. There are two methods of mining of coal – **opencast mining** and **underground mining** Opencast mining is also called strip mining or surface mining. This method is used when the deposits of coal are near the surface of the earth. Underground or deep mining is used when coal deposits lie deep down the earth's surface. Extraction of coal by strip mining is a more economical process than deep mining. Besides these two widely used methods, rat-hole mining is a type of underground mining method in which coal is extracted through narrow vertical shafts and horizontal tunnels (called rat holes). It is mainly adopted for mining thin coal seams but is associated with significant safety and environmental challenges.
- **Extraction of Petroleum :** After formation, petroleum migrated from the source rock to be entrapped in large underground reservoirs beneath impermeable rocks. It is often present as floating over a layer of water and is held in this position under the pressure of a layer of natural gas over it. Petroleum is obtained by drilling wells into trapped underground reservoirs beneath impermeable rocks.
  Refining: Various components of petroleum are separated from one another by a process, which is known as the refining of petroleum. This is done by a process called fractional distillation. Fractional distillation is based on the fact that the different components of petroleum have distinctly different boiling points.
- **Extraction of Natural Gas :** Natural Gas is generally present as associated with petroleum deposits and is obtained from well, dug in the oil bearing regions. When Natural gas occurs along with petroleum in oil wells, it is called 'Wet Gas'. Wet gas contains gaseous hydrocarbons containing one carbon (C1) to four carbon (C4), i.e. methane, ethane, propane and butane. The Wet gas is then suitably treated to remove propane (C3), propene (C3), butene (C4) and butane (C4). The mixture of C3 to C4 components is liquefied and used as Liquefied Petroleum Gas (LPG).
  On the other hand, when the gas is associated with crude oil, it is called 'Dry Gas' and consists almost entirely of methane, ethane, with small concentration of impurities such as CO2, CO, H2S, N2 and inert gases.
  Before use, the natural gas is purified to remove objectionable ingredients such as water, dust, grit, H2S, CO2, N2 and heavier liquefiable hydrocarbons. The

approximate composition of natural gas is: CH4 = 70-90%, C2H6 = 5-10%, H2 = 3%, CO + CO2 = rest. The calorific value varies from 12000 to 14000 kcal/m^3. It is an excellent domestic fuel and is conveyed over very large distance in pipelines.

1.6 NUCLEAR ENERGY

Nuclear energy is generated from radioactive element, like uranium, mined from the Earth. Since uranium or other radioactive elements are available in finite amounts in earth, nuclear energy is considered non-renewable resources.

Nuclear energy is produced by a process called nuclear fission. Nuclear fission is a reaction where the nucleus of an atom splits into two or more smaller nuclei, while releasing energy. For example, if the nucleus of an atom of uranium-235 (an isotope of uranium) is hit by a neutron, the nucleus of uranium atom splits into two smaller nuclei, viz., a barium nucleus and a krypton nucleus and two or three neutrons. These extra neutrons will hit other nearby uranium-235 atoms, which will also split and generate additional neutrons in a multiplying effect. The process generates a chain reaction in a fraction of a second.

Another nuclear process is called nuclear fusion. In nuclear fusion, two light atomic nuclei, such as isotopes of hydrogen, combine to form a heavier nucleus, releasing a very large amount of energy. Nuclear fusion is the process by which the Sun and other stars produce energy. However, controlled nuclear fusion is still under development and is not yet widely used for commercial electricity generation. Each time the reaction occurs, there is a release of energy in the form of heat and radiation. The heat can be converted into electricity in a nuclear power plant, in a similar manner to the generation of electricity from the heat from fossil fuels such as coal, gas and oil.

Inside nuclear power plants, nuclear reactors and other equipment contain and control the chain reactions, most commonly generated by the fission of uranium-235, to produce heat. The heat is used to produce steam. The steam is then passed to spin turbines, activating an electric generator to create low-carbon electricity.

1.7 GLOBAL AND NATIONAL DISTRIBUTION OF RESERVES

India stands at eleventh position in the world in energy production by producing 2.4% of world energy. But India accounts for 3.5 % of total energy consumption and holds the sixth position in energy consumption. The wide gap between energy production and energy consumption calls for the need to increase the energy production.

Coal:

The proven global coal reserve was estimated to be 9,84,453 million tonnes by end of 2003. The USA had the largest share of the global reserve (25.4%) followed by Russia (15.9%), China (11.6%). India was 4th in the list with 8.6%.

Coal deposits in India are 148790 million tonnes. Coal deposits of India are mainly found in Orissa, Bihar, Bengal and Madhya Pradesh. According to an estimate, coal reserves in India would last about 130 years. With 7% of the world's coal, India possesses fourth largest coal reserve in the world. For its energy needs, India heavily relies on coal, which is one of the dirtiest hydrocarbon fuels.

Petroleum oil

As per an estimate of 2025, there is approximately 1.77 trillion barrels of proven oil reserves in the earth, which are expected to last roughly 47 years at current consumption rates. (One barrel of oil is approximately 160 litres). These reserves are found as highly concentrated in Venezuela followed by Saudi Arabia and Canada.Top 3 countries as holders of highest reserves of petroleum are Venezuela: ~303 billion barrels, Saudi Arabia: ~267–297 billion barrels and Canada: ~168 billion barrels.

Although Venezuela has the largest amount oil reserves, most of its oil is found offshore or deep underground and is dense. For this reason, the cost of extracting the oil in Venezuela's reserves using the currently available technology is very high and so is not profitable.

Saudi Arabia's oil reserves, on the other hand, are close to the surface and on land, which makes the oil much more accessible and the extraction processes are mostly cost-effective. For this, Saudi Arabia's oil sector is significantly more profitable.

In India, oil was first found at Makum in Assam in 1867. The oil fields of Assam were the only source of petroleum in our country until about 40 years ago. Some other places where oil wells have been dug are

(i) Ankleshwar and Kalol in Gujarat,
(ii) Offshore areas west of Mumbai, and
(iii) Offshore deltas of the Godavari and Kaveri rivers

Government agencies engaged in exploring and producing crude oil are i) Oil and Natural Gas Commission (ONGC) and ii) Oil India Limited (OIL). Also extraction of crude now a days are outsourced to private companies like Schlumberger. Among many refineries the larger refineries of India are at Jamnagar, Mathura, Bharuch, Digboi, Haldia and Barauni. The resources of oil are small in India.

Gas

The global proven gas reserve was estimated to be 176 trillion cubic metres by the end of 2003. The largest share of the natural gas reserve is with the Russian Federation.

In India, free gas is obtained from gas fields in Assam, Gujarat and Andhra Pradesh.

Nuclear Power Supply

Nuclear Power contributes to about 2.4 per cent of electricity generated in India. India has ten nuclear power reactors at five nuclear power stations producing electricity. More nuclear reactors have also been approved for construction.

1.8 STRATEGIC IMPORTANCE OF CONVENTIONAL ENERGY RESOURCES

Conventional energy resources are the basis of global energy supplies, Despite the present day transition to renewable energy sources, conventional energy resources still have their strategic importance. Their importance lies in their ability to provide reliable, high-density, and scalable power required for industrial growth and national security.

Their strategic importance may be analysed from different viewpoints.

- **Reliability in baseload power:** Conventional sources of energy provide the baseload power. It is the constant, minimum, continuous and reliable level of electricity demand required on a power grid that must be supplied 24/7. Coal, petroleum oil and gas and nuclear plants can operate continuously, regardless of

weather conditions. On the other hand, solar and wind are intermittent. Fossil fuels and nuclear fuel produce massive amounts of energy per unit, making them essential for heavy industries (steel, cement) and manufacturing.

- **National Energy Security and Stability:** Nations having large domestic reserves of coal, gas, or uranium have greater energy independence which in turn makes them geopolitically self-reliant. Because domestic control over energy resources allows governments to manage energy costs for citizens and businesses. A steady and affordable supply of conventional energy is a priority for national security.
- **Transportation and Industrial Infrastructure:** Petroleum-based fuels (gasoline, diesel, jet fuel) are the primary driver of transport sector. Heavy industries are still reliant on conventional energy sources. Because the energy required for high-temperature processes in such industries cannot be managed by renewable energy sources. In many industries like manufacturing fertilizers, plastics, and chemicals, natural gas does not serve as energy, but serves a raw material (feedstock), which has direct impact on food security and industrial production.
- **Established Infrastructure and Lower Immediate Costs:** The existing global infrastructure for conventional energy (pipelines, power plants, refineries) have been built with huge investments. For introduction of new renewable energy sources, it requires fresh investments for replacement. But utilizing the existing infrastructure for conventional energy makes them cost effective and accessible in short term.
- **Role in the Energy Transition:** It is highlighted that conventional energy needs to be replaced by renewable energy, but it seems to be paradoxical that, conventional energy resources are even functional for supporting the growth of renewable energy sources.
- **As Backup Power:** As renewable energy capacity increases, gas-fired power plants are essential as a "backup" to support in case of interruption. In situations where renewable energy generation drops (e.g., a "dunkelflaute" - a period of low wind and low sun), conventional power stations serve as a backup to prevent power blackouts. These backup plants ensure that the solar of wind power operated grids do not fail when the sun is not shining or the wind is not blowing.
- **Bridging Fuel:** In the transition from conventional to renewable energy infrastructure, natural gas acts as a cleaner "bridging fuel" compared to coal, reducing carbon emissions.

1.9 USES AND APPLICATIONS: ENVIRONMENTAL IMPACTS

Conventional energy is used in many ways to improve the standard of living of mankind. The energy consumption of a nation can be broadly divided into the following sectors depending on energy-related activities. These can be further subdivided into subsectors:

- Domestic sector (houses and offices including commercial buildings)
- Transportation sector
- Agriculture sector
- Industry sector

The ways of applications of conventional energy are as follows.

- **Electricity Generation:** Fossil fuels (coal, natural gas, oil) and nuclear power fuel thermal power plants, while hydropower uses dams to generate electricity.
- **Transportation:** Oil (gasoline, diesel) powers most cars, trucks, planes, and ships. Natural gas (Compressed Natural Gas) is used in some vehicles.
- **Heating and Cooking:** Firewood, coal, oil, and natural gas are used for residential and industrial heating.
- **Industrial Processes:** These are used for fuelling machinery, producing materials, and providing energy for manufacturing.

Environmental impacts

Despite their tremendous importance, conventional energy sources are known for their adverse environmental impact. It is important to understand the environmental impact of fossil fuels for developing sustainable energy solutions and mitigating adverse ecological effects.

Various environmental problems from mining, transport, storage and energy generation from fossil fuels are:

1. **Air Pollution and Climate Change**
   - Acid Rain and Smog: Combustion of coal releases sulphur dioxide, nitrogen oxides, and volatile organic compounds (VOCs), forming smog and acid rain, damaging forests and buildings and triggering respiratory problems in humans.
   - Greenhouse Gases (GHGs): Burning fossil fuels releases massive amounts of greenhouse gases e.g. carbon dioxide and methane, causing global warming. Increased average temperatures due to global warming affects weather patterns and sea level which in turn, results in more frequent and severe weather events such as hurricanes, droughts, and floods. Over the period of time, these pollution causes climate change.
   - Particulate matters: Coal and oil combustion release fine particulate matter, that can enter into the lungs, causing respiratory and cardiovascular diseases.
2. **Water Pollution and Ecosystem Damage**
   - Acid Mine Drainage: Coal mining leaches heavy metals and acid into groundwater and rivers.
   - Oil Spills: Tanker accidents and pipeline leaks contaminate oceans and coastlines, killing marine life and birds.
   - Thermal Pollution: Power plants discharge hot water, altering aquatic ecosystems.
   - Habitat Loss: Mining, drilling (like oil sands), and dam construction destroy wetlands, forests, and other habitats.
   - Loss of Biodiversity: Decline in species populations affects ecosystem services and livelihoods dependent on them.
3. **Land Degradation and Waste**
   - Mining: Coal mining causes soil erosion, land subsidence, and leaves behind toxic waste (fly ash and sulphur).

- Nuclear Waste: Nuclear power produces long-lived radioactive waste requiring secure, long-term storage, before it can be economically dismantled and in turn disposed of as waste.

4. Resource Depletion and Extraction Impacts

- Non-Renewable: Fossil fuels are finite, and extraction becomes more difficult and environmentally damaging over time.
- Extraction Pollution: Extraction processes (fracking, oil sands) disturb land and contaminate soil and water.

5. Ocean Acidification

Carbon dioxide (CO_2) emissions are absorbed by the world's oceans, leading to ocean acidification. This process affects marine life, particularly organisms with shells and skeletons which are made up of calcium carbonate, such as corals and shellfish, disrupting marine ecosystems and food chains.

6. Risk of Accidents

In nuclear power plants, there is a catastrophic risk potential if containment fails, due to accidental overheated fuels melting and releasing large quantities of fission products into the environment..

CHECK YOUR PROGRESS

Q1: What are the different types of fossil fuel?
Q2: What nuclear reaction is used in nuclear power plant to generate energy?
Q3: Whatisthemainconstituentin natural gas?
Q4: What are the main constituents in Liquefied Petroleum Gas?
Q5: Name the three countries that are top reservoir of petroleum.
Q6: Mention three major limitations of using fossil fuels.

1.10 LET US SUM UP

- Conventional energy sources are traditional energy resources used for large-scale energy production and consumption.
- Commercial type conventional energy sources include coal, petroleum, natural gas and nuclear energy.
- Fossil fuels are the dominant global energy sources due to their high energy density and established infrastructure.
- Fossil fuels are formed over millions of years from organic matter under heat and pressure.
- Extraction methods include mining (coal), drilling (oil and gas), and related industrial processes.
- Fossil fuels significant limitations such as depletion of reserves and environmental pollution.
- Nuclear energy provides large-scale electricity generation with low greenhouse Gas emissions during operation.
- Conventional energy reserves are unevenly distributed across different regions globally and within India.

- Transitioning to renewable energy is essential for sustain development.
- The use of conventional energy sources leads to environmental impacts such as air pollution, global warming, and climate change, highlighting the need for sustainable alternatives.

1.11 ANSWER TO CHECK YOUR PROGRESS

Ans to Q1: Coal, Petroleum and Natural Gas
Ans to Q2: Nuclear Fission
Ans to Q3: Methane
Ans to Q4: Ethane, Propane and Butane
Ans to Q5: Venezuela, Saudi Arabia and Canada
Ans to Q6: No-renewable, Limited availability and Highly polluting

1.12 FURTHER READING

- M VR Koteswara Rao, Energy Resources: Conventional & Non-Conventional, B S Publications, 2019
- Anthony Benvenuto, Chemistry and Energy: From Conventional to Renewable, De Gruyter, 2022

1.13 MODEL QUESTIONS

Q1: How was coal formed in ancient era?
Q2: What are the major sectors, in which fossil fuels are used extensively?
Q3: What are the environmental hazards associated with fossil fuel extraction?
Q4: What are the adverse environmental impacts of use of fossil fuels?
Q5: How do fossil fuels contribute to climate change?
Q6: How does ocean acidification affect marine life?
Q7: What are the risk factors in a nuclear power plant?

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UNIT 2: RENEWABLE SOURCES OF ENERGY

UNIT STRUCTURE

2.1 Learning Objectives
2.2 Introduction
2.3 Introduction to Renewable Energy
2.4 Need for Renewable Energy
2.5 Energy Scenario
    2.5.1 Global Context
    2.5.2 Indian Context
2.6 Classification of Energy Sources
2.7 Energy Security and Sustainability
2.8 Let us Sum Up
2.9 Answers to Check Your Progress
2.10 Further Reading
2.11 Model Questions

2.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- describe the basics and importance of renewable energy
- explain the need for renewable energy and its benefits
- analyze the global and Indian energy scenarios
- classify renewable and non-renewable energy sources
- evaluate energy security and sustainable energy practices.

2.2 INTRODUCTION

In the previous unit, you studied conventional energy sources and their characteristics. This unit introduces the fundamentals of renewable energy and its significance. It explains the need for renewable energy and its benefits. In this unit learners will analyze the global and Indian energy scenarios. The unit also covers the classification of energy sources and the concepts of energy security and sustainability.

2.3 INTRODUCTION TO RENEWABLE ENERGY

Before discussing about renewable energy, let us discuss, very shortly about energy. Energy is the ability to do work or produce change. Energy is a fundamental physical quantity responsible for all physical and biological processes. It is required to carry out almost all activities in our daily lives such as transportation, agriculture, sports, lighting, communication, physical and physiological activities. Energy cannot be created or destroyed; it can only be converted from one form to another. Energy is required for any activities that are required to be carried out for the betterment of human life. Energy can be of various types. Here we will discuss about Renewable Energy and its importance.

The demand for energy has been increasing in the world and therefore the need for newer sources of energy must be met with efficiency and sustainability. One of the newer sources of energy is the renewable energy. The renewable energy referred to energy which can be obtained from natural resources that can be renewed over a short span of time. There are various forms of renewable energy such as solar energy, wind energy, hydel power energy, biomass energy, tidal energy etc. Even though the sources of renewable energy are not high to meet the world primary energy target yet their usage has definitely grown over the past decade. Therefore, it can be said that renewable energy plays an important role in providing various forms of clean energy to sustain ourselves and also helps in mitigating climate change.

Various definitions have been proposed for defining renewable energy. The International Renewable Energy Agency (IRENA) has provided a statutory definition, which has been ratified as on February 2013 by 108 members (107 states and the European Union), which is “renewable energy includes all the forms of energy which are produced from renewable sources in a sustainable manner which includes geothermal energy, bioenergy, hydropower, wind energy, solar energy and ocean energy”. The International Energy Agency (IEA) defines renewable energy resources as those which are “derived from natural processes” and “those which are replenished at a faster rate than they are consumed”. The major advantage of renewable energy sources is that they produce much lower pollutant and greenhouse gas emissions than fossil fuels.



Figure 2.1: Pictorial representation of the various forms of renewable energy being used.

2.4 NEED FOR RENEWABLE ENERGY

The most commonly used energy all over the world are energy derived from oil, coal, natural gas and nuclear power. However a major limitation is that the sources of all these forms of energy are non-renewable and therefore there is always a possibility of exhaustion of these forms of energy from repeated uses. Therefore it is very important for us to explore newer forms of energy and particularly renewable forms of energy which can provide us with various forms of energy for the generations to come. The Intergovernmental Panel on Climate Change (IPCC) along with various other international organizations have been demanding the reduction of greenhouse gas emissions to minimize the effects of climate change. Therefore there is a need of renewable energy sources to minimize climate change effects. There are various advantages of renewable energy, which can be stated as follows:

(i) Role in environment protection: Renewable energy sources are cleaner sources of energy which if used judiciously can minimize environmental impact. They help in mitigating greenhouse gas emissions and reduction of global warming thus helping to mitigate climate change.

(ii) Reusable resources: One of the major limitations of the conventional forms of fuel like fossil fuel is their limitation. However, renewable sources of energy are reusable as their sources are never ending and available continuously if managed sustainably.

(iii) Self-dependence: Dependence on conventional fuel has a lot of constraints. To overcome such constraints, renewable sources of energy can be used with proper technological tools so that the nations become self-sufficient in energy production and its dependence on imported fossil fuels is minimized.

(iv) Economic development: The use of renewable energy shall require initial investment which has the potential for economic development of the region. Although the initial investment is high, renewable energy systems have relatively low operating and maintenance costs in the long run. It shall also lead to generation of employment.

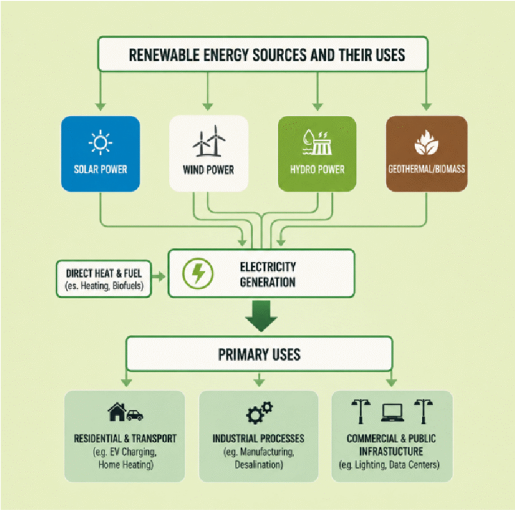


Figure 2.2: Flowchart showing the various renewable energy sources and their uses.

2.5 ENERGY SCENARIO

The requirement of energy all over the world is different. Here in we shall see the energy scenario both in terms of the world and India.

2.5.1 Global Contexts

In the global context, the last decade saw a reduction of 2% in case of fossil fuels. In the year 2013, there was 82% usage while it fell to 80% in 2023. Although the demand for energy increased by 15% yet 40% of this demand was met by renewable forms of energy. While in the last decade, the overall energy demand, in advanced economies declined by 0.5% every year. From the usage of different sources of energy, it has been observed that, coal, natural gas and nuclear energy has declined along with the use of oil, yet there is an increase of 3% use of renewable energy every year since 2013. In case of emerging market and developing economies, where 85% of the population strives, there has been anincrease in energy demand of 2.6% every year since the last decade. This increase has been fuelled by the increase in the population of around 720 million, 50 % rise in the economy and 40% increase in industrial output. According to the United Nations, the global energy demand is estimated to grow by 28% from 2017 to 2040. In terms of investment, in 2024, global investments reached USD 728 billion, a 8% increase from the previous year. China led the global renewable energy investments in between 2015-2024 with investments of 290 billion USD in 2024, while the European Union and the United Kingdom invested about 114 billion USD while the USA invested around 97 billion USD.

2.5.2 Indian Context

The development of the economy of India relies on energy. The per capita energy consumption in India increased by 25% in the last 10 years from 14,682 Mega Joule/ person in 2014-15 to 18,410 Mega Joule/ person in 2023-24. For meeting most of the domestic demand, India requires to import crude oil, coal and natural gas. In 2023-24, the net import of coal reached by 11.2% reaching a total of 262.99 million tonnes, while in case of crude oil it rose from 232.70 Million tonnes to 234.26 Million tonnes. The import of natural gas increased by about 21% amounting to 31.8 BCM (Billion cubic metre) in 2023-24. In the Indian context, energy requirements must be balanced with climate goals to ensure an efficient and sustainable economy. As of October 2024, India has installed approximately 223 GW of renewable energy capacity. India also reduced the emission intensity of its GDP by 33% (from 2005-2019) to meet its goal of meeting the Nationally Determined Contributions (NDC) targets by the year 2030. According to this, India aims to achieve 50% non-fossil fuel capacity by 2030. India has managed to be a global power in terms of use of renewable energy resources ranking 4th in terms of installed renewable energy capacity.

Of the renewable energy being used in India, Solar power encompasses 45%, followed by hydro and wind, each with 23% and biopower and small hydro at 6% and 3% respectively. Since, 2014, the solar power capacity has grown 39 times reaching 135.81 GW by December 2025. Of these 103.24 GW (76%) is ground mounted, 23.62 GW (17%) rooftop (grid connected) installed and 3.36 GW (2-3%) hybrid and 5.59 GW (4%) off-grid solar components. The government of India launched the PM Surya

GharMuftBijliYojana on February 2024 to accelerate top roof solar installations in the residential households. It aims to install top roof solar capacity in one crore households with a financial outlay of 75,021 crores. Various other central and state government initiatives have been launched to enhance self reliance and sustainable development in this sector. Some more initiatives in this sector is the Production Linked Initiative (PLI) to make India a global leader in solar industry and it aligns with the vision of AtmaNirbhar Bharat. Further, India also stands 4th globally in the area of cumulative wind capacity with an installed capacity of 51.3 GW until June 2025. India's Hydro capacity grew from 35.8 GW to 48 GW, as of June 2025, with plans to expand further.

Nuclear energy contributes about 8.8 GW to India's non-fossil fuel capacity and supports the country's clean energy goals. It offers reliable base-load power with low emissions, complementing variable renewables. The biomass energy capacity has grown from 8.1 GW to 11.6 GW, including expanded biogas and waste-to-energy projects. Biomass supports rural energy needs and utilizes agricultural and organic waste. The Government of India plans to bid for 50 GW of renewable energy capacity annually from 2023-2028. This is the strategy of the government to achieve 500 GW of non fossil fuel electricity capacity by 2030.

Besides, India's electricity production has been witnessing an average annual growth of about 5% since 2017. The major share of electricity generation comes from coal, accounting for around 74.7%. This is followed by renewable energy at approximately 20.8%, nuclear energy at 2.7%, and the remaining about 1.8% from oil and gas.

As of March 31, 2024, in case of coal, the reserves stood at 389.42 billion tonnes. The states sharing this reserve are Odisha (25.47%), Jharkhand (23.58%), Chattisgarh (21.23%), West Bengal (8.72%) and Madhya Pradesh (8.43%). In terms of reserves for crude oil, it was found to be 671.40 Million tonnes of which the western offshore accounted for 32%, Assam (21.66%), Rajasthan (19.59%) and Gujarat (17.70%). The reserves for natural gases in 2023-24 were found to be 1094.19 BCM of which the western offshore accounted for 31.28%, Eastern offshore at 24.07% and Assam at 15.03%.

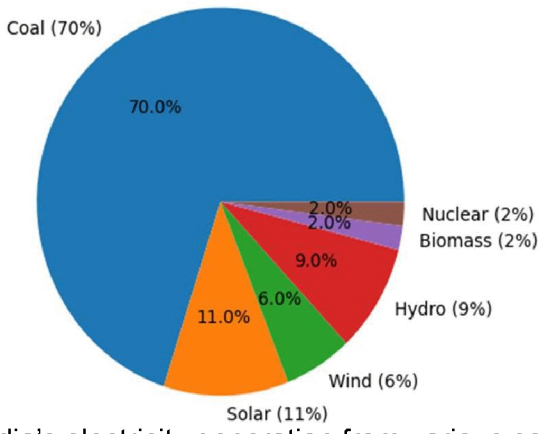


Figure 2.3: India's electricity generation from various sources in 2025

India, as a part of the effort towards sustainable development and climate action, has started focusing towards renewable forms of energy. The total estimated potential for renewable power generation in India stood at 2,109,655 MW in the year 2023-24. This potential amount comes from a variety of renewable sources such as solar, wind, biomass, smaller hydro units and co-generation from bagasse.

2.6 CLASSIFICATION OF ENERGY SOURCES

Energy sources can be classified into several types based upon the following criteria:

i. Conventional and Non-conventional energy sources: The conventional sources of energy are those which have been in use for a long period of time such as fossil fuel, nuclear and hydro resources. The non-conventional sources of energy are solar energy, wind energy and biomass energy.

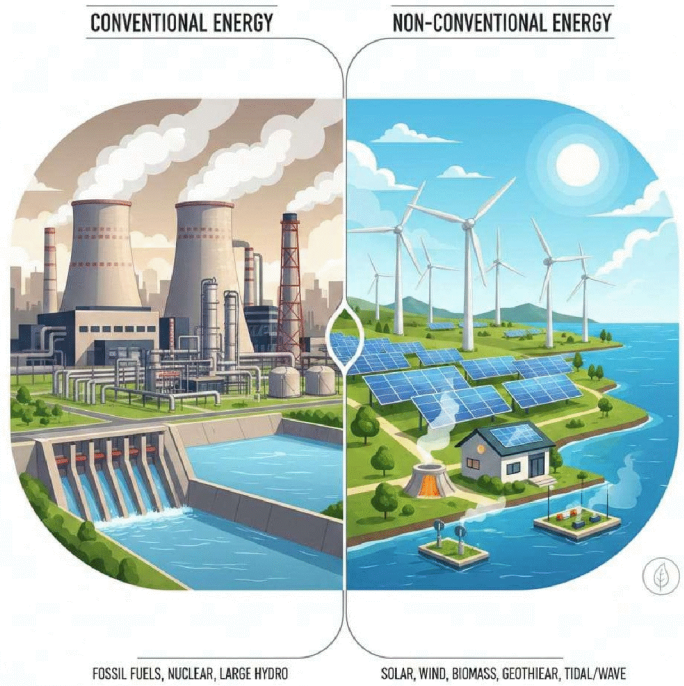


Figure 2.4: Pictorial representation showing the various conventional and non-conventional energy sources

ii. Renewable and Non renewable energy sources: The renewable energy sources which are widely used are solar power, wind power, tidal power, hydroelectric power and geothermal power. In case of non renewable energy sources, they are mostly the conventional fuels used are the fossil fuels such as oil, coal and gas.

iii. Primary and Secondary energy sources: The primary energy sources are either stored or found in nature such as coal, oil, biomass and natural gas. The secondary form of energy can be found in Petrol, Diesel, Hydrogen and electricity. For the requirement in industry or commercial activities, primary energy can be converted into secondary energy.

2.7 ENERGY SECURITY AND SUSTAINABILITY

Energy is one of the most vital components of our lives. For any human activity, energy is required. Humans rely on energy for making their lives easier and comfortable and to meet all ends. Therefore, it becomes imperative that there is a constant supply of energy in our lives for our disposal so that we can carry out all our activities promptly and lead our lives comfortably. As such energy security is very important for us. According to the International Energy Agency (IEA), energy security can be defined as the uninterrupted availability of various energy sources at an affordable price. Energy security has a short and a long term consideration. The short term consideration is based on the ability to react promptly to sudden changes in demand and supply. The long term aspect can be related to investments which are done timely for ensuring energy supplies. In international terms, energy security can be stated as the relationship between the requirements of the major nations which are consumers and the producing nations which offer the supplies to the consumers. Earlier the major consumers were the United States of America and the European nations, however with the emergence of India and China as the emerging economies, there is a tilt in the consumers. This alteration in the consuming nations is a major concern for energy security. Therefore in terms of energy security it is mostly focused upon affordability and availability as these are the dimensions for standard evaluations of energy security and that these two dimensions are considered as they can have tremendous impact on other dimensions. A major example, of ensuring energy security can be observed in Europe where to make energy available at reasonable prices, Europe has excluded energy from sanctions and are focusing on more coal consumption to decrease their dependency on other nations. It is observed that in case of developed nations, the relationship between energy consumption and economic growth is no longer directly proportional as it was historically although the relationship remains proportional in developing nations. As a measure to limit the risks of energy security various options are being looked into, one of which is renewable energy. Renewable energy such as solar and wind energy are the keys to future energy security related issues worldwide. A major advantage of the renewable energy is that they can provide a secure and stable alternative to the use of fossil fuels. Fossil fuels also bear the impact of price volatility and conflicts which can raise various geopolitical risks. Further due to high prices of fossil fuels and interruptions in their supply can lead to decrease in energy security and therefore there is a need to focus on renewable energy. Various nations gradually shifted their focus to renewable energy. China, in 2008, announced that 15% of its energy requirements shall be generated from renewable sources by 2020. Use of renewable energy got further boost with the adoption of the Paris Agreement in 2015 which called for the committed nations to reduce their greenhouse gas emissions and limit global warming, which paved the way for focusing more on renewable energy resources and reduce the dependencies on fossil fuels and thus improve energy security.

The United Nations in 2017, adopted the Sustainable Development Goals which included more usage of renewable energy resources. A major issue of energy security was observed during the Covid-19 pandemic where supplies and production were disrupted. This further stressed the requirement of renewable energy sources, which are less vulnerable to disruptions in fuel supply and international energy markets.

Another major energy security was observed in the recent Russia-Ukraine war which again focused on the need of renewable energy sources.

CHECK YOUR PROGRESS

Q1: What is renewable energy?
Q2: What are the various forms of renewable energy?
Q3: How can renewable energy be defined?
Q4: State the advantages of renewable energy.
Q5: Write short notes on
(i) PM Surya GharMuftBijliYojana
(ii) Production Linked Initiative
(iii) AtmaNirbhar Bharat
Q6: Classify the energy resources.
Q7: What is energy security?

2.8 LET US SUM UP

- Renewable energy is obtained from naturally replenishing resources such as solar, wind, hydropower, biomass, geothermal, and ocean energy. It provides a sustainable alternative to conventional fossil fuels.
- The growing demand for energy, depletion of fossil fuels, and concerns over climate change have increased the importance of renewable energy for environmental protection, energy security, and sustainable development.
- The global energy scenario shows a gradual shift towards renewable energy through increased investments, technological advancements, and international efforts to reduce greenhouse gas emissions.
- India has made significant progress in renewable energy by expanding solar, wind, hydropower, and biomass capacity, supported by government initiatives such as the PM Surya GharMuftBijliYojana and the Production Linked Incentive (PLI) Scheme.
- Energy sources can be classified as conventional and non-conventional, renewable and non-renewable, and primary and secondary energy sources based on their origin and usage.
- Renewable energy plays a vital role in ensuring energy security, reducing dependence on fossil fuel imports, supporting economic growth, creating employment opportunities, and contributing to a cleaner and more sustainable future.

2.9 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Renewable energy is the source of energy which can be derived from natural resources that can be renewed over a short span of time.

Ans to Q2: Biomass energy, tidal energy, solar energy, wind energy, hydel power energy etc.

Ans to Q3: Renewable energy can be defined as the form of energy which includes all the forms of energy that are produced from renewable sources in a sustainable manner which includes geothermal energy, bioenergy, hydropower, wind energy, solar energy and ocean energy.

Ans to Q4: The advantages of renewable energy can be stated as below

(i) Help in protection of the environment
(ii) Self dependency
(iii) Reusable
(iv) Economic development

Ans to Q5:

(i) PM Surya GharMuftBijliYojana: PM Surya GharMuftBijliYojana was launched in February 2024 to promote rooftop solar installations in residential households across India. The scheme aims to provide free electricity through solar power to one crore households. With a financial outlay of ₹75,021 crore, it supports subsidies for rooftop solar systems, reducing electricity bills and encouraging clean energy adoption. The scheme also promotes sustainable development and reducesdependence on fossil fuels while strengthening India's renewable energy capacity.

(ii) Production Linked Initiative: The Production Linked Incentive (PLI) Scheme is a government initiative to boost domestic manufacturing in key sectors, including solar energy. It provides financial incentives to companies based on increased production and performance. In the renewable energy sector, PLI aims to strengthen solar panel manufacturing, reduce imports, and make India a global leader in clean energy technology.

(iii) AtmaNirbhar Bharat: AtmaNirbhar Bharat, meaning "Self-Reliant India," was launched in 2020 to promote economic self-sufficiency. It focuses on strengthening domestic industries, encouraging innovation, and reducing dependence on imports. In the renewable energy sector, it supports local manufacturing of solar equipment and clean technologies, contributing to sustainable growth and national development.

Ans to Q6: The energy resources can be classified as

(i) Conventional and Non conventional energy sources
(ii) Renewable and Non Renewable energy sources
(iii) Primary and Secondary energy sources

Ans to Q7: Energy security refers to the uninterrupted availability of energy sources at an affordable price, as defined by the International Energy Agency (IEA).

2.10 FURTHER READING

- https://www.ireda.in/images/HTMLfiles/23.pdf
- https://mospi.gov.in/sites/default/files/publication_reports/Energy_Statistics_2025/Energy%20Statistics%20India%202025_27032025.pdf http://static.pib.gov.in/WriteReadData/specificdocs/2025/doc2025622575501.pdf
- https://beeindia.gov.in/sites/default/files/BEE_India_Energy_Scenario_Report-2024_web_version-rev2.pdf
- https://beeindia.gov.in/sites/default/files/1Ch1.pdf
- Foss, M. (2022), The impact of renewable on energy security, Canadian Foreign Policy Journal, Vol 28 (3), 234-248, https://doi.org/10.1080/11926422.2022.2118138.
- Khan, K. et al (2024),Does renewable energy development enhance energy security, UtilitiesPolicy, Vol 87, , 101725, https://doi.org/10.1016/j.jup.2024.101725.

2.11 MODEL QUESTIONS

A. Very Short Answer Questions

1. Define renewable energy.
2. Give two examples of renewable energy sources.
3. What is the difference between renewable and non-renewable energy?
4. What is biomass energy?
5. What is meant by solar photovoltaic (PV) system?
6. Name two advantages of wind energy.
7. What is geothermal energy?
8. What is the main source of hydroelectric power?
9. State one limitation of tidal energy.
10. Why is renewable energy important for sustainable development?

B. Short Answer Questions

1. Explain the need for renewable energy in India.
2. Differentiate between renewable and non-renewable energy sources with examples.
3. Describe the working principle of a solar water heater.
4. Explain the advantages and disadvantages of wind energy.
5. Discuss the role of biomass in rural energy supply.
6. What are the environmental benefits of renewable energy sources?
7. Describe the basic components of a solar PV system.
8. Explain how hydroelectric power is generated.

C. Long Answer/ Descriptive Questions

1. Discuss the importance of renewable energy in the global energy scenario.
2. Explain various types of renewable energy sources with suitable examples.
3. Analyze the role of renewable energy in reducing greenhouse gas emissions.

4. Discuss the challenges faced in the implementation of renewable energy projects in India.
5. Compare solar, wind, and hydro energy in terms of efficiency, cost, and environmental impact.

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UNIT 3: SOLAR ENERGY

UNIT STRUCTURE

3.1 Learning Objectives
3.2 Introduction
3.3 Introduction to Solar Energy
3.3.1 Importance of Solar Energy
3.3.2 Solar Radiation and Measurements
3.4 Solar Radiation Geometry
3.5 Solar Thermal System
3.6 Classification of Solar Thermal Collectors
3.6.1 Non Concentrating and Concentrating Collectors
3.6.2 Flat Plate Collector
3.7 Concept of Solar Thermal for Power Generation and Process Heating
3.8 Solar Thermal Application
3.8.1 Solar Distillation
3.8.2 Solar Cooker
3.8.3 Solar Cooling
3.8.4 Solar Greenhouses
3.9 Let Us Sum Up
3.10 Answers to Check Your Progress
3.11 Further Reading
3.12 Model Questions

3.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- explain the fundamental principles of solar energy and its measurement techniques
- analyze solar radiation geometry and its impact on solar energy collection
- describe the working principles and components of solar thermal systems
- classify different types of solar thermal collectors
- discuss the application of solar thermal energy for power generation and process heating
- identify and elaborate on various solar thermal applications such as distillation, cooking, cooling, and greenhouse heating.

3.2 INTRODUCTION

In the previous unit we discussed about the renewable sources of energy. In this unit you will be introduced to one of the most promising and abundant renewable energy sources that is solar energy. This unit provides you the

importance of solar energy as a key renewable energy resource. You will also study the solar radiation and its measurement, along with the geometry of solar radiation that influences energy availability. The unit further covers solar thermal systems and the classification of solar thermal collectors that include non-concentrating and concentrating types such as flat plate collectors. It also explains the application of solar thermal energy in power generation and process heating. Finally, learners will explore various practical applications of solar energy such as solar distillation, cooking, cooling, and greenhouse systems.

3.3 INTRODUCTION TO SOLAR ENERGY

Solar energy is the light and heat that come from the Sun. It is used to produce electricity and heat through technologies such as solar panels, solar heating systems, solar thermal plants, and other advanced methods. Solar energy is a renewable source of power because it is naturally available and does not run out. It is also environmental friendly, producing little to no pollution compared to fossil fuels, which cause greenhouse gas emissions and air pollution.

The Sun, a colossal fusion reactor at the center of our solar system, bombards Earth with an immense flux of energy—approximately 173,000 terawatts continuously, dwarfing humanity's total energy consumption by orders of magnitude. This energy arrives primarily as electromagnetic radiation, spanning ultraviolet, visible, and infrared spectra. On a clear day, the Earth's surface can receive up to 1,000 W/m² of solar energy, although this varies with location, time, weather, and season. Unlike non-renewable fossil fuels, solar energy is continuously available and will not be depleted over human lifetimes.

Historically, solar energy utilization dates back millennia. Ancient civilizations, such as the Greeks and Romans, used passive solar design by orienting buildings to capture sunlight for natural heating. In the 19th century, innovations such as Augustin Mouchot's solar-powered steam engine laid the foundation for modern solar energy technologies. The discovery of the photovoltaic effect by Alexandre-Edmond Becquerel in 1839 marked the beginning of solar electricity. Later, in 1954, Bell Labs developed the first practical silicon solar cell which made modern solar technology possible. Since 2010, the cost of solar photovoltaic (PV) systems has fallen by more than 89%, and global solar capacity has grown rapidly. By 2022, the world's installed solar capacity had exceeded 1 terawatt (TW).

The key technologies that define solar energy systems are the following-

1. **Solar Photovoltaics:** Solar cells made from semiconductors convert sunlight directly into electricity using the photovoltaic effect. Crystalline silicon is the most commonly used material, while thin-film and perovskite cells offer the potential for higher efficiency and lower costs. Solar PV systems are used in homes, power grids, and satellites.
2. **Solar Thermal Energy:** Solar collectors absorb sunlight to heat fluids. This heat is used for hot water, space heating, and power generation. Flat-plate and evacuated-tube collectors are used for low to medium temperatures, while parabolic troughs and solar towers are used for high temperatures to produce electricity.

3. **Passive Solar Architecture**: Building design maximizes natural light and heat gain through orientation, insulation, thermal mass, and glazing, reducing energy needs without mechanical systems.

4. **Concentrating Solar Power**: Mirrors focus sunlight onto receivers, heating fluids to drive turbines. Molten salt storage enables dispatchable power and helps reduce intermittency.
5. **Emerging Innovations:** Artificial photosynthesis mimics plants to produce hydrogen or fuels, while space-based solar power transmits energy wirelessly to Earth.

Overall, solar energy is a clean, reliable, and sustainable solution for meeting future energy needs.

3.3.1 Importance of Solar Energy

The importance of solar energy stems from several key factors are discussed below.

- **Environmental Sustainability:** Solar energy production does not emit greenhouse gases or other pollutants which make it an important solution for reducing climate change and air pollution.
- **Abundance and Renewability:** The sun is an inexhaustible energy source, providing more energy to Earth in one hour than humanity consumes in a year.
- **Energy Security:** Utilizing solar energy reduces reliance on finite and politically volatile fossil fuel resources and strengthens national energy independence.
- **Economic Benefits:** The solar industry creates jobs in manufacturing, installation, and maintenance. Reduced electricity bills for consumers and businesses also contribute to economic savings.
- **Decentralization:** Solar panels can be installed on rooftops or in remote areas to generate electricity, even where there is no access to a central power grid. This helps improve energy access.
- **Low Operating Costs:** Once installed, solar energy systems have very low operating and maintenance costs.

3.3.2 Solar Radiation and Measurements

Solar radiation is the electromagnetic radiation emitted by the Sun. It is the primary energy input for all solar energy systems. Understanding its characteristics and accurate measurement is fundamental for designing efficient solar technologies.
Characteristics of Solar Radiation:

Solar Constant (GSC): The solar constant is the amount of solar energy received per unit area, measured outside Earth's atmosphere when Earth is at its average distance from the Sun. Its value is about 1361 W/m².
Spectral Distribution: Solar radiation contains different wavelengths, including ultraviolet, visible light, and infrared. Most of the energy is in the visible range. Dust, air particles, and altitude can change the spectrum, with high-altitude areas receiving more UV light, useful for disinfection and solar technologies like perovskite cells.

Solar radiation has three main parts: direct, diffuse, and global.

Direct Radiation: Direct solar radiation travels in a straight line from the Sun without being scattered. It has high intensity and is used in concentrating solar systems like parabolic troughs. It is measured as direct normal irradiance and makes up most of the solar energy on clear days (about 70–90% of the total).

Diffuse Radiation: Diffuse solar radiation is sunlight that is scattered by clouds, dust, water vapor, and other particles in the atmosphere. Its amount varies widely depending on how clear or polluted the sky is. This scattering happens through Rayleigh scattering (from small particles) and Mie scattering (from larger particles). A blue sky is an example of Rayleigh scattering ($\propto 1/\lambda^4$), where shorter wavelengths (blue light) are scattered more.

Global Radiation (G): Global radiation is the total solar energy received on a surface. It includes direct sunlight, diffuse sunlight, and reflected light. On a horizontal surface, it is the sum of direct radiation (adjusted by angle) and diffuse radiation. On average, the Earth receives about 3–5 kWh/m²/day, while desert regions can receive up to 7–8 kWh/m²/day.

The amount of global radiation varies significantly based on:

- Solar Altitude: The sun's angle in the sky; intensity is highest at solar noon and lowest at sunrise/sunset.
- Atmospheric Conditions: Cloud cover, water vapor, and aerosols (like pollution or dust) can reduce direct radiation by up to 100% on overcast days.
- Latitude and Season: Locations closer to the equator receive more consistent radiation year-round. In higher latitudes, summer totals are significantly higher than winter totals.

In summary, solar radiation is fairly consistent and has different components which makes it predictable and versatile. This supports more than 1 TW of installed solar capacity, while better forecasting helps manage its variability.

Measurement of Solar Radiation:
Various instruments are used to measure solar radiation:

- **Pyranometer:** Measures global (total) solar radiation on a planar surface (usually horizontal). It responds to both direct and diffuse radiation.
- **Pyrheliometer:** Measures direct normal irradiance, which is the solar radiation received from the sun directly on a surface perpendicular to the sun's rays. It must track the sun's movement.
- **Pyrgeometer:** Measures net infrared radiation (long-wave radiation).
- **Sunshine Recorder:** Measures the duration of bright sunshine.

3.4 SOLAR RADIATION GEOMETRY

Solar radiation geometry describes the relationships between the sun, the earth, and a receiving surface. These relationships determine the amount and angle of solar

radiation incident on a surface at any given time and location. The major geometric parameters include:

Solar Declination (δ): This is the angular position of the sun at solar noon with respect to the plane of the equator. Due to the Earth's 23.45° axial tilt, varies seasonally between (summer solstice in the Northern Hemisphere) and (winter solstice). It follows an approximately sinusoidal pattern, calculated as

$$= 23.45^{0} \sin(360^{0} \frac{284+n}{365})$$

where *n* is the day of the year. Accurate δ values are essential for predicting daily solar paths and optimizing collector orientations.

Latitude (ϕ): It is defined as the angular location of a site north or south of the equator, ranging from 0° at the equator to 90°at the poles. Latitude fundamentally influences the sun's maximum altitude and path across the sky, directly affecting annual insolation. For instance, higher latitudes experience greater seasonal variations in solar availability.

Hour Angle (HA): The hour angle (HA) measures the angular distance of a celestial body (like the sun or a star) westward along the celestial equator from an observer's meridian, indicating time since the last transit. It is commonly expressed in degrees. Example- 15^0 per hour. The hour angle is negative in the morning, and positive in the afternoon.

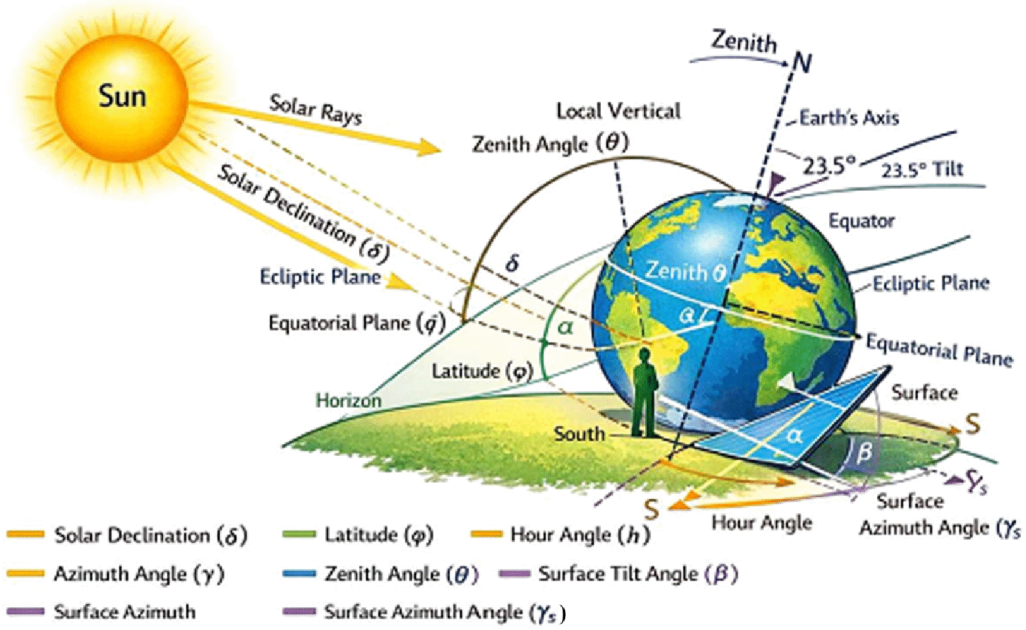


Figure 3.1: Schematic diagram to depict the solar radiation geometry

Altitude Angle(α): The angle between the sun's rays and the horizontal plane, indicating how high the sun appears in the sky. Values near 90° maximize direct radiation on horizontal surfaces.

Zenith Angle(θ): Complementary to altitude, it measures the angle between the sun's rays and the vertical (zenith). Minimum θ (ideally 0°) yields maximum perpendicular incidence, minimizing cosine losses in radiation calculations.
Azimuth Angle (γ): The azimuth angle is measured clockwise from true north to the horizontal projection of the sun's rays. It varies from east at sunrise to west at sunset, influencing shading and tracker designs.
Surface Tilt Angle(β): The permanent inclination of a receiving surface from horizontal, typically optimized annually. It enhances winter capture in the north by aligning closer to the lower sun path.
Surface Azimuth Angle(γ_s): The deviation of the surface normal's horizontal projection from true south or north, ideally 0° or 180° for maximum exposure. γSallows seasonal adjustments, such as south-facing in winter.
These parameters interrelate via spherical trigonometry to compute the incident angle maximizes energy yield, critical for collector efficiency. Software like SAM or TRNSYS automates these for site-specific designs, accounting for atmospheric refraction and equation of time. Understanding this geometry underpins shading analysis, tracking strategies (single- or dual-axis), and hybrid systems, enabling precise forecasting and optimization in solar thermal and PV applications.

3.5 SOLAR THERMAL SYSTEM

A solar thermal system is designed to convert sunlight into thermal energy (heat). This heat can then be used for various applications such as water heating, space heating, industrial process heat, or even power generation. The basic components of a typical solar thermal system as depicted in the Figure 3.2. include:

- **Solar Collector:** The device that absorbs solar radiation and converts it into heat.
- **Heat Transfer Fluid:** A fluid (e.g., water, anti-freeze solution, air, or oil) that circulates through the collector to pick up the absorbed heat.
- **Heat Exchanger:** Used to transfer heat from the heat transfer fluid to another medium (e.g., potable water).
- **Storage Tank:** Stores the heated fluid for later use.
- **Piping and Insulation:** Connects components and minimizes heat loss.
- **Control System:** Regulates fluid flow and temperature.

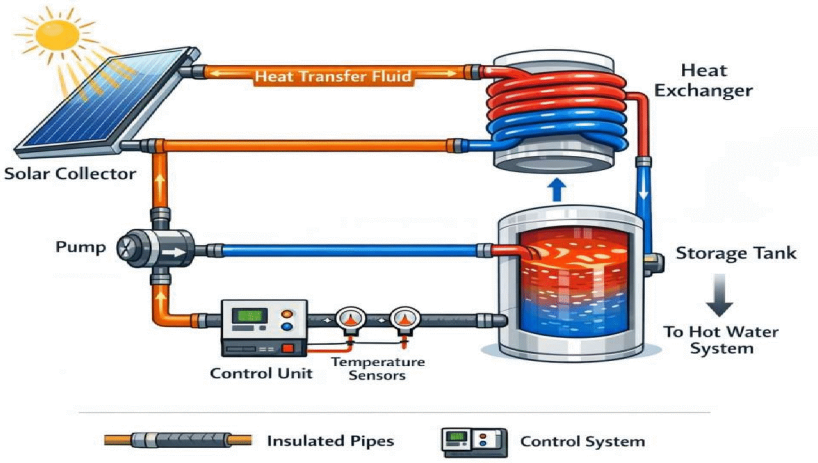


Figure 3.2: Schematic diagram of a typical solar thermal system

3.6 CLASSIFICATION OF SOLAR THERMAL COLLECTORS

Solar thermal collectors are broadly classified based on their ability to concentrate sunlight. The details of the classifications of the solar thermal collectors are described below.

3.6.1 Non Concentrating and Concentrating Collectors

Non-Concentrating Collectors:

- These collectors have an aperture (area receiving solar radiation) equal to their absorber area.
- They collect both direct and diffuse solar radiation.
- Typically operate at lower temperatures (up to 100 ^{0}C).
- Examples: Flat plate collectors and evacuated tube collectors.
- They are used for domestic hot water, space heating, solar drying etc.

Concentrating Collectors:

- These collectors use reflective surfaces (mirrors) to concentrate direct solar radiation onto a smaller absorber area.
- They primarily collect direct radiation, require sun tracking mechanisms.
- They can achieve much higher temperatures (from 100 ^{0}C to 1000 ^{0}C).
- Examples are parabolic trough collectors, parabolic dish collectors, central receiver systems (solar power towers) and fresnel reflectors.
- They are used for power generation, industrial process heating, solar cooling etc.

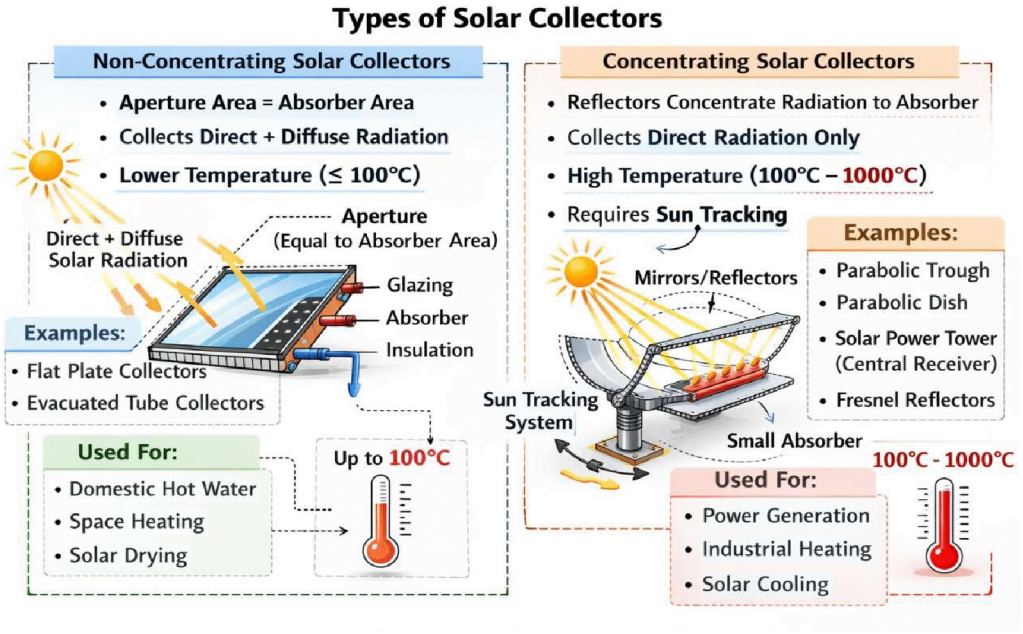


Figure 3.3: Schematic diagram of differentiating Non-Concentrating and Concentrating Solar collector

3.6.2 Flat Plate Collector

The flat plate collector is the most common type of non-concentrating solar thermal collector. It is relatively simple in design and widely used for domestic and commercial hot water applications.

Components of a Flat Plate Collector:

- **Absorber Plate:** A dark metal plate, usually made of copper or aluminum, coated to absorb maximum solar energy and reduce heat loss. Fluid channels are typically integrated into or attached to this plate that carry the heat transfer fluid.
- **Transparent Cover:** One or more layers of glass or plastic placed above the absorber plate. It allows solar radiation to pass through while trapping infrared radiation re-emitted by the absorber (greenhouse effect) and reducing convective heat loss.
- **Insulation:** Placed on the back and sides of the absorber plate to minimize heat loss to the ambient environment.
- **Casing/Enclosure:** A weatherproof box that protects the components and holds them together.
- **Working Principle:** Solar radiation passes through the transparent cover and is absorbed by the dark absorber plate, converting sunlight into heat. A heat transfer fluid (usually water or an anti-freeze mixture) flows through tubes attached to or integrated into the absorber plate, picking up this heat. The heated fluid then circulates to a storage tank or a heat exchanger for use.

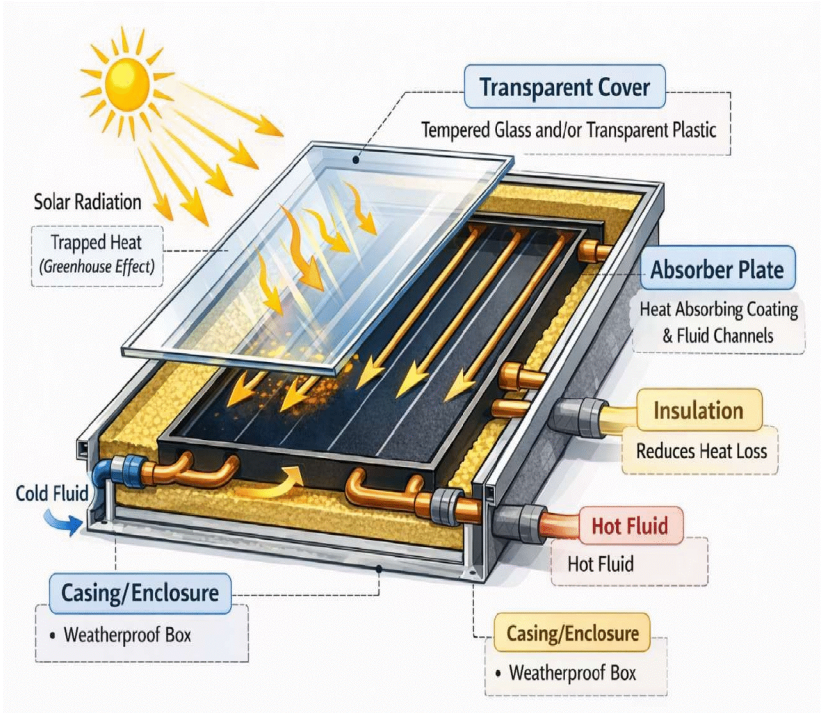


Figure 3.4: Schematic diagram elucidating the components and working principle of a flat plate collector

3.7 CONCEPT OF SOLAR THERMAL FOR POWER GENERATION AND PROCESS HEATING

Solar thermal energy plays a significant role in both generating electricity and providing heat for industrial processes.

Power Generation:

Concentrated Solar Power (CSP) generation systems use concentrating collectors to focus sunlight onto a receiver, heating a fluid to very high temperatures. This high-temperature fluid then drives a conventional steam turbine to generate electricity, similar to traditional thermal power plants. Common CSP technologies include:

- **Parabolic Troughs:** Long, parabolic mirrors focus sunlight onto a receiver tube running along the focal line.
- **Solar Power Towers:** A field of heliostats (tracking mirrors) reflects sunlight onto a central receiver mounted on a tower, heating a fluid (e.g., molten salt).
- **Parabolic Dishes:** Dish-shaped concentrators focus sunlight onto a receiver at their focal point, often coupled with a stirling engine.
- **Linear Fresnel Reflectors:** A series of long, shallow mirrors focus sunlight onto elevated receiver tubes.

Many CSP plants use thermal energy storage, such as molten salt systems, to produce electricity even after sunset or during cloudy conditions.

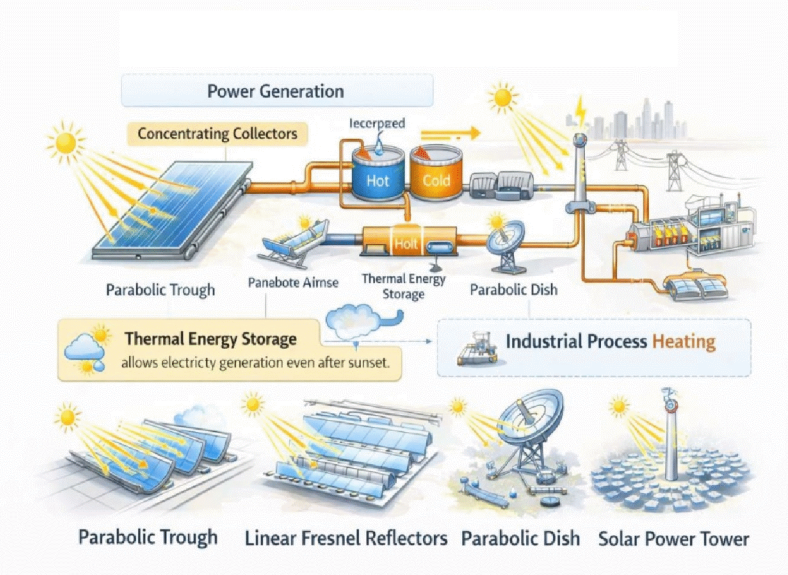


Figure 3.5: Schematic diagram depicting a concentrated solar power generation system for different industrial process heating

Process Heating:

Industrial processes require significant amounts of heat for various operations like drying, distillation, sterilization, and chemical reactions. Solar thermal systems can supply this heat, reducing reliance on fossil fuels. The required temperature range dictates the type of solar collector used:

- **Low-temperature heat (below 100 ^{0}C):** Typically supplied by flat plate or evacuated tube collectors for applications like water preheating, laundries, or food processing.
- **Medium-temperature heat (100^{0}C - 250^{0}C):** Often uses parabolic troughs or compound parabolic concentrators for processes like steam generation, drying, and distillation in industries such as textiles, chemicals, and food and beverage.
- **High-temperature heat (above 250 ^{0}C):** Achieved with parabolic dishes or central receiver systems for very specific industrial applications or for generating high-pressure steam.

3.8 SOLAR THERMAL APPLICATIONS

Solar thermal technology finds a wide array of applications beyond just electricity generation and large-scale industrial heating.

3.8.1 Solar Distillation

Solar distillation (or solar desalination) is a process that uses solar energy to purify water by evaporating and condensing it. A solar still typically consists of a basin of saline or brackish water covered by a transparent glass cover. Sunlight passes through the cover, heats the water, causing it to evaporate. The water vapor then rises, condenses on the cooler underside of the glass cover, and trickles down into a collection trough as distilled, potable water. This method is particularly useful in remote areas with abundant sunshine but limited access to fresh water.

3.8.2 Solar Cooker

A solar cooker is a device that harnesses sunlight for cooking, pasteurization, and drying. It typically uses reflective surfaces to concentrate sunlight onto a dark cooking pot.

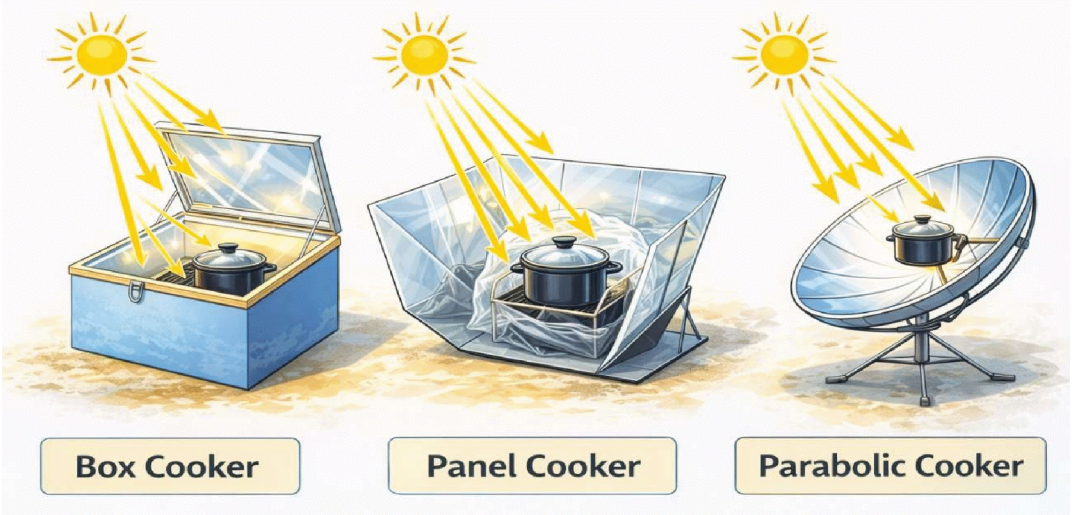


Figure 3.6: Different types of solar cookers

The three main types of solar cooker are:

- **Box Cookers:** Simple, insulated boxes with a transparent lid and sometimes reflectors to direct more sunlight inside. They cook slowly at moderate temperatures.
- **Panel Cookers:** Use reflective panels to direct sunlight onto a cooking pot, often inside a heat-resistant bag. They are lightweight and portable.
- **Parabolic Cookers:** Use a parabolic dish to concentrate sunlight intensely onto a focal point, achieving high temperatures rapidly. They are more efficient but require frequent adjustment to track the sun.

  Solar cookers are an eco-friendly alternative to traditional cooking methods, especially in regions facing fuel wood scarcity and indoor air pollution.

3.8.3 Solar Cooling

Solar cooling systems use solar thermal energy to drive refrigeration or air conditioning cycles.

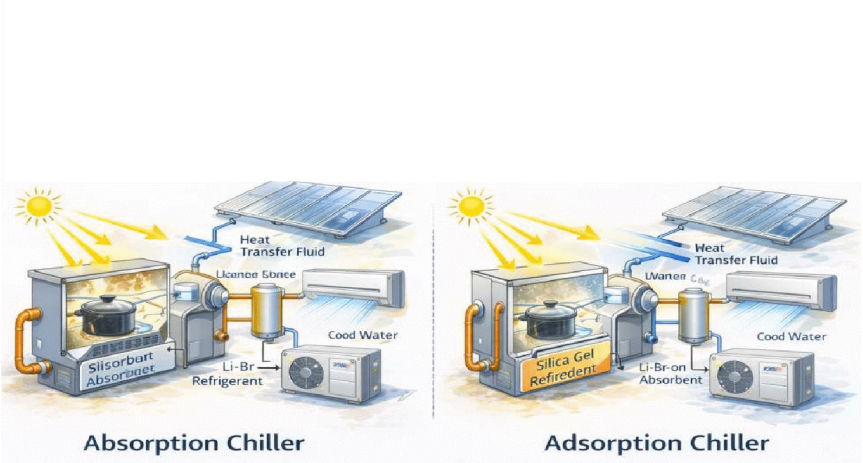


Figure 3.7: Schematic diagram depicting two different types of solar coolers

Instead of using electricity to power a compressor (as in conventional vapor-compression systems), solar cooling typically employs:

- **Absorption Chillers:** These systems use a heat source (solar thermal energy) to drive a thermochemical process involving a refrigerant (e.g., water) and an absorbent (e.g., lithium bromide) to produce a cooling effect.
- **Adsorption Chillers:** Similar to absorption chillers, but they use a solid adsorbent material (e.g., silica gel) to absorb the refrigerant.

Solar cooling is attractive because cooling demand often coincides with peak solar radiation, making it an efficient way to reduce peak electricity loads and operating costs.

3.8.4 Solar Greenhouses

Solar greenhouses are designed to maximize solar energy capture for heating and lighting, creating an optimal environment for plant growth, particularly in colder climates. Key features often include:

- **Orientation:** Typically oriented towards the equator to receive maximum winter sunlight.
- **Glazing:** Transparent materials (glass or polycarbonate) to allow sunlight penetration.
- **Thermal Mass:** Materials like water barrels, concrete, or stone within the greenhouse absorb and store solar heat during the day, slowly releasing it at night to maintain stable temperatures.
- **Insulation:** Well-insulated north walls (in the northern hemisphere) and foundations to minimize heat loss.
- **Ventilation:** Passive or active ventilation systems to manage temperature and humidity.

Solar greenhouses reduce or eliminate the need for fossil fuel heating, extending growing seasons and enabling the cultivation of diverse crops.

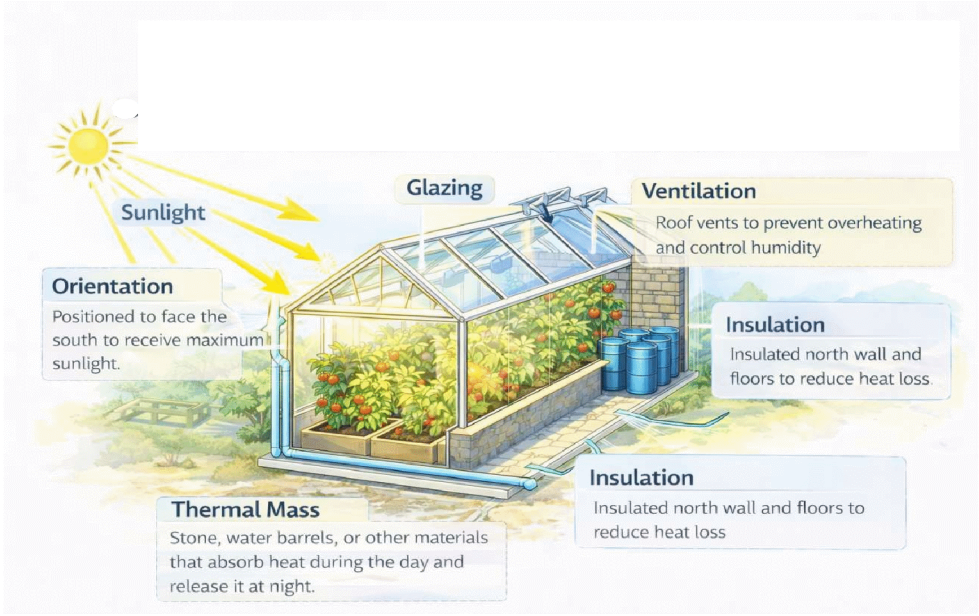


Figure: 3.8 Schematic diagram of a Solar Greenhouse arrangement

CHECK YOUR PROGRESS

Q1: List three reasons why solar energy is considered an important renewable energy source.
Q2: Differentiate between direct and diffuse solar radiation.
Q3: Name two instruments used for measuring solar radiation.
Q4: What is the primary function of the transparent cover in a flat plate collector?
Q5: What do you mean by solar distillation?

3.9 LET US SUM UP

- Solar energy is a clean, renewable, and sustainable source of energy with significant environmental and economic benefits.
- Solar radiation and its measurement are essential for understanding and designing efficient solar energy systems.
- Solar radiation geometry determines the amount of solar energy received by a surface and influences system performance.
- Solar thermal systems convert solar radiation into heat energy using various components and collectors, including flat plate collectors.
- Solar thermal energy is used for electricity generation and industrial process heating through different solar thermal technologies.
- Solar thermal applications include solar distillation, solar cookers, solar cooling, and solar greenhouses for sustainable energy utilization.

3.10 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Solar energy is considered as an important renewable energy source primarily because of the following reasons

1. Clean and Environmentally Friendly
2. Renewable and Abundant
3. Reduces Energy Costs Over Time

Ans to Q2: Direct solar radiation is the sunlight that reaches the Earth's surface directly from the sun without scattering. It is strong and produces clear shadows.

Diffuse solar radiation is sunlight that is scattered by clouds, dust, and gases in the atmosphere before reaching the Earth. It is weaker and produces soft or no shadows

Ans to Q3: Two instruments used for measuring solar radiation are:

1. Pyranometer – Measures total solar radiation (both direct and diffuse radiation) falling on a surface.
2. Pyrheliometer – Measures direct solar radiation coming straight from the sun. These are commonly used in meteorology and solar energy studies.

Ans to Q4: The transparent cover in a flat plate collector allows solar radiation to enter and reduces heat loss by trapping heat inside the collector.

Ans to Q5: Solar distillation is a process in which solar energy is used to evaporate water, and the water vapor is then condensed to obtain pure water, leaving impurities behind.

3.11 FURTHER READING

- Duffie, J. A., & Beckman, W. A..*Solar Engineering of Thermal Processes*. John Wiley & Sons.
- Goswami, D. Y., Kreith, F., &Kreider, J. F..*Principles of Solar Engineering.* CRC Press.

- Kalogirou, S. A..*Solar Energy Engineering: Processes and Systems*. Academic Press.
- Renewable Energy Handbooks and Journals (e.g., *Solar Energy* journal, publications by IRENA or IEA)

3.12 MODEL QUESTIONS

Q1: What are the components and working principle of a flat plate solar collector
Q2: How do CSP systems generate electricity, and what are the main CSP types?
Q3: Which geometric factors affect solar radiation on a surface?
Q4: How do non-concentrating and concentrating solar thermal collectors differ in use and temperature range?
Q5: What are three applications of solar thermal technology and how do they work?

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UNIT 4: SOLAR PHOTOVOLTAICS SYSTEM

UNIT STRUCTURE

4.1 Learning Objectives
4.2 Introduction
4.3 Introduction to Photovoltaics
  4.3.1 Characteristics of PV Systems
  4.3.2 Different Solar Cell technologies
4.4 PV System Components
4.5 PV Models
  4.5.1 Equivalent Circuits
4.6 PV System Applications
  4.6.1 Off Grid and Grid connected PV Systems
  4.6.2 Rooftop PV Systems
4.7 Operation and Maintenance of Solar Power Plants
4.8 Sun Tracking System
4.9 Let Us Sum Up
4.10 Answers to Check Your Progress
4.11 Further Reading
4.12 Model Questions

4.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- describe the basics and characteristics of photovoltaic (PV) systems
- explain different solar cell technologies
- identify PV system components
- analyze PV models and equivalent circuits.
- examine PV system applications, including off-grid, grid-connected, and rooftop systems.
- evaluate operation, maintenance, and sun tracking systems in solar power plants

4.2 INTRODUCTION

In the previous unit, we discussed the solar energy. In this unit, you will learn the fundamentals of photovoltaic (PV) systems, including their key characteristics and working principles. You will also explore different solar cell technologies. The unit covers PV modeling and its equivalent circuits. It also includes various applications of PV systems, such as off-grid, grid-connected, and rooftop installations. In addition, you will study the role of sun tracking systems in improving energy generation efficiency.

4.3 INTRODUCTION TO PHOTOVOLTAICS

Photovoltaics (PV) is a technology used to convert sunlight directly into electricity by means of semiconductor materials. The word “photovoltaic” is derived from two terms: “photo,” meaning light, and “voltaic,” referring to electricity. This process is based on

the photovoltaic effect, in which certain materials generate an electric current when exposed to sunlight. The basic unit of a photovoltaic system is the solar cell. A solar cell is usually made of semiconductor materials such as silicon, which is the most commonly used material due to its abundance, stability, and efficiency. A solar cell consists of two layers of semiconductor material: the p-type layer and the n-type layer. These two layers form a p-n junction, which creates an internal electric field. When sunlight in the form of photons strikes the surface of the solar cell, the energy of the photons excites electrons, causing them to move freely and create electron-hole pairs. The internal electric field at the p-n junction separates these charges, resulting in the flow of direct current (DC) electricity.

Since a single solar cell produces only a small amount of voltage and current, multiple cells are connected together to form a solar module or solar panel. Several modules can be combined to form a photovoltaic array capable of producing larger amounts of electricity suitable for residential, commercial, and industrial applications. The electricity generated by solar panels is usually DC, which is converted into alternating current (AC) using an inverter so that it can be used for household appliances and supplied to the electrical grid.

Photovoltaic systems are classified into different types based on their application. Off-grid systems operate independently and are commonly used in remote areas where utility grid access is unavailable. These systems often include batteries for energy storage. Grid-connected systems are directly linked to the utility grid and are widely used in urban and industrial areas. Rooftop PV systems installed on homes, offices, and factories are becoming increasingly popular because they help reduce electricity bills and support distributed power generation.

4.3.1 Characteristics of PV Systems

Figure 4.1 shows the schematic diagram of a basic solar cell (PV) structure detailing all major components generally used.

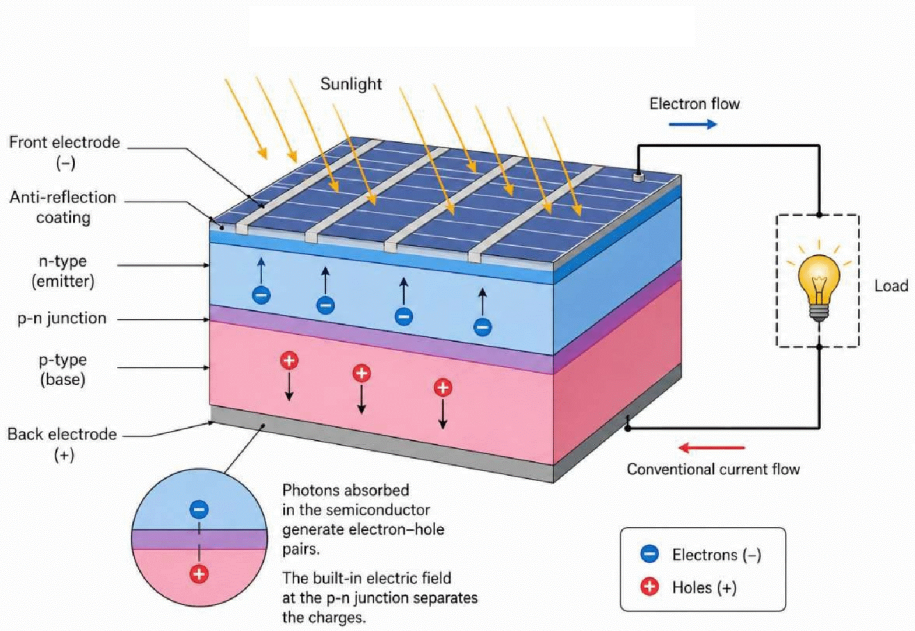


Figure 4.1: Basic structure of a solar cell

The most important characteristics of a PV cell can usually be understood studying the current-voltage (I–V) and power-voltage (P–V) curves of a PV device as shown in the Figure 4.2.

Some of the important parameters associated with a PV Cell are as follows:

(a) Short Circuit Current (Isc): It is the current produced when output terminals are shorted.

(b) Open Circuit Voltage: It is the voltage produced when no load is connected.

(c) Maximum Power Point (MPP): The operating point where maximum power is delivered is called the maximum power point (MPP).

(d) Fill Factor (FF): The fill factor indicates the, "squareness" of the solar cell, determining its usable power and is given as

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

Where, V_{mp} and I_{mp} are the Voltage and current at maximum power point respectively. Maximum Power Voltage (V_{mp}) is the voltage at which a solar cell or PV module delivers its maximum output power. Likewise, Maximum Power Current (I_{mp}) is the current produced by a solar cell or PV module when operating at its maximum power point.

(e) Efficiency: The efficiency of a solar cell or a photovoltaic cell is calculated as the ratio of maximum power output to incident solar power, influenced by materials, design, and light management. Mathematically,

$$\eta = \frac{P_{max}}{P_{in}} \times 100\% = \frac{FF \times V_{OC} \times I_{SC}}{P_{in}} \times 100\%$$

Where P_{in} is the incident solar power (W)

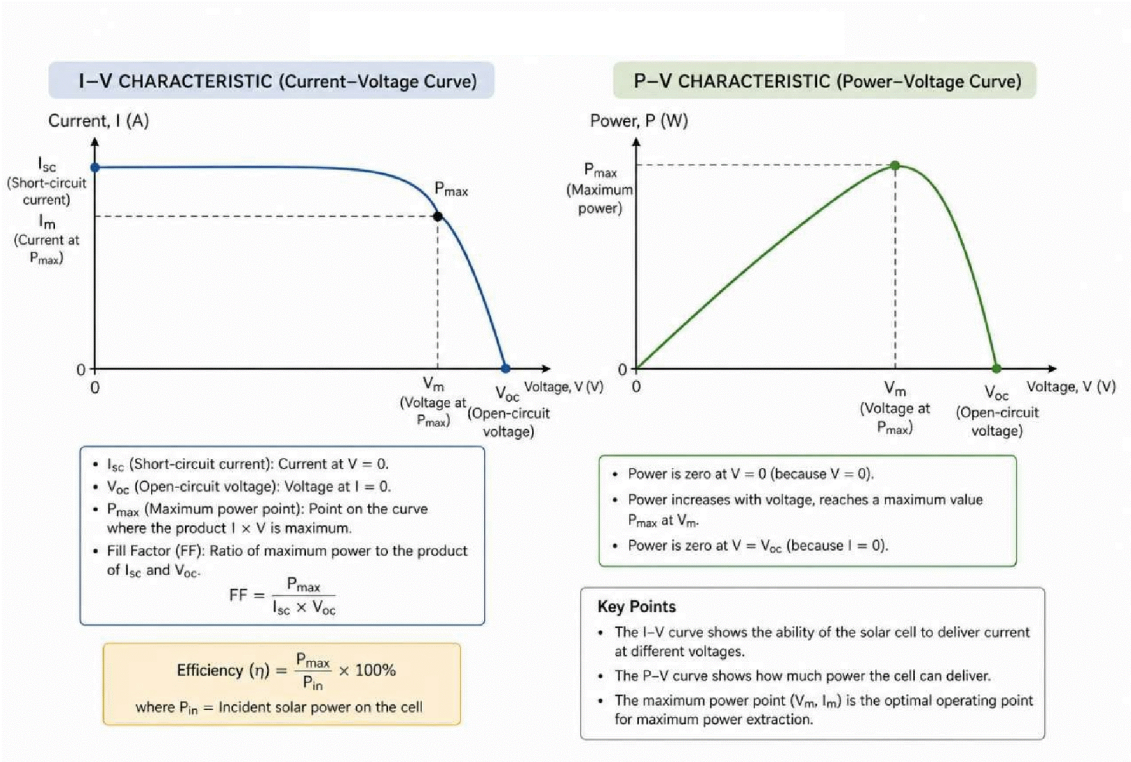


Figure 4.2: I-V and P-V Characteristic curves for a PV Solar Cell

4.3.2 Different Solar Cell Technologies

There are several types of solar cell technologies. It includes monocrystalline silicon, polycrystalline silicon, and thin-film solar cells. Monocrystalline cells offer high efficiency and longer lifespan but are relatively expensive. Polycrystalline cells are more affordable with slightly lower efficiency. Thin-film cells are lightweight and flexible but generally have lower efficiency. Recent advancements include bifacial modules, perovskite solar cells, and tandem solar cells, which promise higher performance and lower costs in the future.

Based on material and manufacturing technology, solar cells are classified into three types.

(a) Monocrystalline Silicon Solar Cell: Monocrystalline silicon solar cells are one of the most efficient and widely used types of photovoltaic (PV) cells. They are made from a single continuous crystal structure of pure silicon, which allows electrons to move more freely and results in higher efficiency compared to other solar cell technologies. These cells are easily recognized by their uniform dark black color and rounded edges.

The word "monocrystalline" means that the entire solar cell is made from one single crystal of silicon. This high-purity silicon structure improves the movement of charge carriers and reduces energy losses, making these cells highly suitable for applications where maximum power output is required in limited space.

Characteristics:

(a) High Efficiency: Monocrystalline solar cells have high conversion efficiency, typically ranging from 18% to 24%, and in advanced technologies even higher.

(b) Long Lifespan: They generally have a service life of 25 years or more with minimal degradation.

(c) Space Efficient: Because of their high efficiency, fewer panels are required to produce the same amount of electricity compared to other technologies.

(d) Better Performance: They perform better under low-light conditions and high-temperature environments compared to many alternatives.

(b) Polycrystalline Silicon: Polycrystalline solar cells, also known as multicrystalline solar cells, are a widely used type of photovoltaic (PV) cell made from multiple silicon crystal fragments melted together to form a single wafer. Unlike monocrystalline solar cells, which are made from a single crystal structure, polycrystalline cells contain many small silicon crystals. This gives them a characteristic blue color and a grainy, textured appearance.

Polycrystalline solar cells are popular because they offer a good balance between performance and cost. Although their efficiency is slightly lower than monocrystalline cells, they are less expensive to manufacture and are suitable for many residential, commercial, and industrial solar applications.

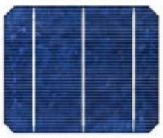
Characteristics:

(a) Moderate Efficiency: Polycrystalline solar cells typically have an efficiency range of 15% to 18%, which is slightly lower than monocrystalline cells due to grain boundaries that restrict electron movement.

(b) Lower Cost: They are cheaper to manufacture because the production process is simpler and less silicon is wasted.
(c) Good Durability: These cells also have a long service life, usually around 20–25 years.
(d) Larger Area Requirement: Because of lower efficiency, more panels may be needed to generate the same power as monocrystalline systems.

Table 1: Comparison between polycrystalline and Monocrystalline solar cells

Comparison of Polycrystalline and Monocrystalline Solar Cells

Parameter	Polycrystalline Solar Cell	Monocrystalline Solar Cell
Efficiency	Moderate (15% – 18%)	Higher (18% – 24% or more)
Cost	Lower	Higher
Appearance	Blue 	Black 
Lifespan	Slightly lower (20 – 25 years)	Longer (25 years or more)
Space Requirement	More (Larger area required for the same power output)	Less (Less area required for the same power output)

(c) Thin Film Solar Cells: Thin-film solar cells are a type of photovoltaic (PV) technology in which very thin layers of semiconductor material are deposited onto a substrate such as glass, plastic, or metal. Unlike conventional crystalline silicon solar cells, which use thick silicon wafers, thin-film cells require only a small amount of active material, making them lightweight, flexible, and often less expensive to manufacture.

The thickness of the semiconductor layer in thin-film solar cells is usually only a few micrometers, which is much thinner than traditional silicon cells. These cells are designed to absorb sunlight efficiently despite their thin structure. Because of their flexibility and low weight, they are widely used in applications where conventional rigid panels are not suitable.

Types of Thin-Film Solar Cells

1. Amorphous Silicon (a-Si): Amorphous silicon solar cells use non-crystalline silicon as the semiconductor material. The most important features include: low manufacturing cost, flexibility, lightweight nature and better performance in low light conditions. However, these solar cells suffer from lower efficiency (6–10%). Major applications are in calculators, small electronic devices and building-integrated photovoltaics (BIPV)
2. Cadmium Telluride (CdTe): CdTe solar cells are one of the most commercially successful thin-film technologies. Primary features comprise of low production cost, good large-scale manufacturing capability and moderate efficiency (15–18%). The

major limitations arise from the fact that Cadmium is toxic and hence recycling and disposal requires care. These thin film solar cells find applications in utility-scale solar farms.

3. Copper Indium Gallium Selenide (CIGS): CIGS solar cells use a compound semiconductor made of copper, indium, gallium, and selenium. The main features of these kinds of solar cells are higher efficiency among thin-film cells (15–20%), flexibility and lightweight nature and better temperature performance. These solar cells find applications in portable solar chargers, space applications and flexible solar panels.

4.4 PV SYSTEM COMPONENTS

A photovoltaic (PV) system as depicted in Figure 4.3, consists of several essential components that work together to convert solar energy into usable electrical energy. These components ensure the efficient generation, storage, control, conversion, and distribution of solar power. Depending on the type of PV system—such as off-grid, grid-connected, or hybrid—the configuration may vary, but the basic components remain largely the same.

1. **PV Modules (Solar Panels):** PV modules are the most important part of a photovoltaic system. They consist of multiple solar cells connected in series and parallel to produce the required voltage and current.
   Solar cells convert sunlight directly into direct current (DC) electricity through the photovoltaic effect. Multiple modules connected together form a PV array, which increases power output. Their major functions are tocapture and convert solar radiation into DC electricity and provide the primary power source of the system

2. **Inverter:** The inverter is a critical component that converts direct current (DC) generated by the solar panels into alternating current (AC), which is required for household appliances and grid supply. Inverters are generally found in several configurations such as:string inverter, central inverter, micro inverter and hybrid inverter. Their major functions include DC to AC conversion, grid synchronization power quality improvement along with system monitoring and protection.

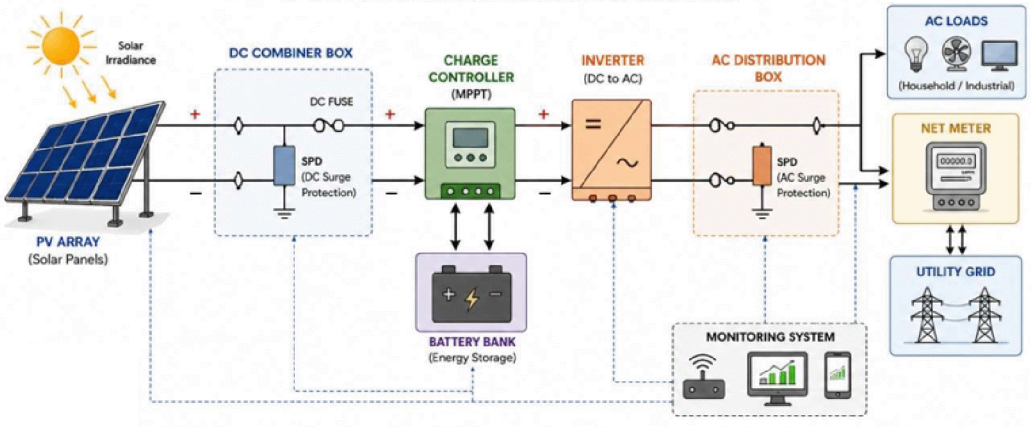


Figure 4.3: Photo-Voltaic System Components

3. **Battery Storage System:** Batteries are mainly used in off-grid and hybrid PV systems to store excess electricity generated during sunny periods for use during

night or cloudy conditions. The common battery types used are Lead-acid batteries, Lithium-ion batteries, gel batteries and flow batteries. Their functions mainly include energy storage, backup power supply and improved reliability.

4. **Charge Controller:** The charge controller regulates the charging and discharging of batteries to protect them from overcharging, deep discharge, and reverse current flow. It is mainly used in battery-based systems. PWM (Pulse Width Modulation) and MPPT (Maximum Power Point Tracking) are the main types of charge controller used. They function to protect batteries, regulate voltage, improve battery life and extract maximum power.
5. **Mounting Structure:** The mounting structure supports and secures the solar panels in the correct orientation and tilt angle to maximize sunlight absorption. These structures may be fixed or tracking-based. These structures provide mechanical support, maintain proper tilt angle and provide resistance against wind and weather. Basically the structural safety is ensured by these mounting systems.
6. **Cables and Connectors:** Proper electrical wiring is essential for safe and efficient energy transfer between system components. The cables and connectors facilitates power transmission, electrical interconnection and reduced transmission losses. One must ensure UV-resistant cables, proper insulation, weatherproof connectors and Safe cable routing during installation for higher efficiency.
7. **Protection Devices:** Protection devices ensure the safety of the PV system against faults such as short circuits, overloads, surges, and lightning. Common Protection Devices comprises of Fuse, Circuit breaker (MCB/MCCB), Surge Protection Device (SPD), Earthing system, Lightning arrestor, Isolator switches etc. These devices are meant for electrical safety, equipment protection, fire prevention and human safety.
8. **Net Meter (for Grid-Connected Systems):** A net meter is used in grid-connected PV systems to measure both imported and exported electricity. If excess electricity is generated, it is supplied to the utility grid and recorded through net metering. Their main functions are bidirectional energy measurement, billing adjustment and export-import tracking
9. **Monitoring System:** Modern PV systems include monitoring systems for performance analysis and fault detection. These systems may use digital displays, SCADA systems, mobile apps, or cloud-based platforms. The systems are required for real-time energy monitoring, fault identification, performance analysis and maintenance planning.

4.5 PV MODELS

Photovoltaic (PV) models are mathematical and electrical representations of solar cells, modules, or arrays used to predict their performance under different operating conditions. These models help engineers and researchers understand the behavior of PV systems without performing repeated physical experiments. PV modeling is used for performance prediction of solar cells and modules, system design and sizing, simulation of solar power plants, development of MPPT algorithms, fault detection and diagnosis, efficiency analysis and grid integration studies

Basic Principle of PV Modeling:

A solar cell behaves like a semiconductor p-n junction diode exposed to sunlight. When light falls on the cell, it generates a photocurrent. The electrical behavior can be

represented using equivalent circuits consisting of current sources, diodes, and resistances. The output current depends on:

- Solar radiation (irradiance)
- Cell temperature
- Load resistance
- Internal losses

Thus, PV models are developed to represent this behavior accurately.

Types of PV Models:

The most commonly used photovoltaic models are:

1. Ideal PV Model
2. Single-Diode Model
3. Double-Diode Model
4. Three-Diode Model
5. Empirical and Numerical Models

Among these, the Single-Diode Model is the most widely used because it provides a good balance between simplicity and accuracy.

1. **Ideal PV Model:** The ideal PV model is the simplest representation of a solar cell. It consists of a current source representing photocurrent and an ideal diode. This model ignores internal losses such as series and shunt resistances. The major limitation arises from the fact that it is too simple for practical applications because real solar cells always have internal resistive losses.
2. **Single-Diode Model:** The single-diode model is the most commonly used practical model for solar cell analysis. It includes a photocurrent source (***Iph***), one diode, series resistance (***Rs***), shunt resistance (***Rsh***). This model provides accurate results for most engineering applications.
3. **Double-Diode Model:** The double-diode model includes two diodes instead of one to improve accuracy. The second diode represents recombination losses inside the depletion region of the solar cell. Although they exhibit better accuracy and improved low-irradiance performance prediction but have more complex calculations
4. **Three-Diode Model:** This model uses three diodes to represent more detailed internal physical phenomena. It is mainly used for advanced research and high-precision simulations. This model is highly complex and requires extensive parameter estimation.
5. **Empirical and Numerical Models:** Empirical and Numerical Models are advanced approaches used to represent the performance and behavior of photovoltaic (PV) cells and modules beyond traditional equivalent circuit models. Empirical models are based on experimental observations and measured data rather than detailed physical representation of the solar cell. These models use mathematical equations obtained through curve fitting of actual I–V and P–V characteristics of solar cells. They are often called data-driven models.

   Numerical models, on the other hand are based on solving the physical semiconductor equations of solar cells using advanced mathematical techniques. These models provide highly accurate results and are widely used in research and detailed PV analysis. They are also called physics-based models. Numerical models are very highly accurate, perform detailed semiconductor analysis, suitable for research and advanced design and can predict behavior under extreme conditions.

4.5.1 Equivalent Circuits of PV Models

The Ideal PV Model is the simplest electrical representation of a photovoltaic (PV) cell. It is used to explain the basic working principle of solar energy conversion without considering internal losses such as resistive effects. In this model, the solar cell is represented by only two main elements: Photocurrent Source (***Iph***) and Ideal Diode (***D***). The photocurrent source represents the current generated when sunlight falls on the solar cell, while the diode represents the behaviour of the p-n junction of the semiconductor.

Assumptions of the Ideal Model:

The ideal PV model assumes: No series resistance (***Rs=0***) and infinite shunt resistance (***Rsh=∞)***, no leakage current and no internal power losses. Because of these assumptions, the model is simple but less accurate for practical systems. The equivalent circuit is shown in Fig. 4.4.

The output current of the ideal PV model is:

$$I = I_{ph} - I_D$$

where *I* = Output current

Iph = Photogenerated current

ID = Diode current

The diode current is given by:

$$I_D = I_0\left(e^{\frac{qV}{nKT}} - 1\right)$$

where:

I_0 = Reverse saturation current

q = Electron charge

V = Output voltage

n = Diode ideality factor

k = Boltzmann constant

T = Temperature in Kelvin

Thus,

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_0}(\frac{qv}{enKT} - \mathrm{I})$$

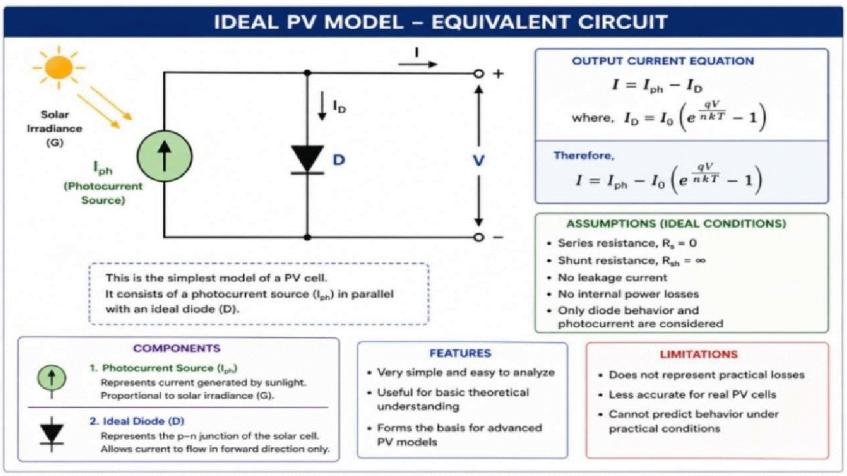


Figure 4.4: Equivalent circuit of an Ideal PV system

4.6 PV SYSTEM APPLICATIONS

Photovoltaic (PV) systems are widely used in various sectors because they provide clean, reliable, and sustainable electricity generation. Depending on the location, load requirements, and grid availability, PV systems can be designed for domestic, commercial, industrial, agricultural, and utility-scale applications.

The major applications of PV systems include:

- Rural electrification
- Water pumping systems
- Street lighting
- Telecom towers
- Railway signaling
- Residential buildings
- Commercial complexes
- Hospitals and schools
- Industrial power supply
- Electric vehicle charging stations
- Utility-scale solar power plants

Among these applications, the most common and important systems are Off-Grid and Grid-Connected PV Systems and Rooftop PV Systems.

4.6.1 Off-Grid and Grid Connected PV Systems

PV systems are mainly classified into two categories based on their connection with the utility grid:

1. Off-Grid PV System
2. Grid-Connected PV System

Both systems have different designs, operating principles, advantages, and applications.

1. Off-Grid PV System: An Off-Grid PV System operates independently without being connected to the utility electricity grid. It is mainly used in remote locations where grid supply is unavailable or unreliable. Since solar power is not available during night and cloudy weather, batteries are used for energy storage. The basic components of Off-Grid system are solar PV modules, charge controller, battery bank, inverter and Load.

During daytime the solar panels generate DC electricity, charge controller regulates charging, batteries store excess power and the inverter converts DC into AC for loads. During night time the batteries supply power to the load.

2. Grid-Connected PV System: A Grid-Connected PV System is directly connected to the utility grid. It supplies electricity to local loads and exports excess power to the grid through net metering. Battery storage is usually not required, which reduces system cost. The basic components of Grid-Connected system are solar PV modules, inverter, Net meter, utility grid and AC load.

During daytime solar panels generate DC electricity and the inverter converts DC to AC. The power is supplied to local loads and the excess power is exported to the grid. During low generation power is imported from the utility grid.

4.6.2 Rooftop PV Systems

A Rooftop PV Systemis a solar power system installed on the roof of residential, commercial, institutional, or industrial buildings. It uses available roof space to generate electricity and reduce dependence on conventional grid supply. Rooftop systems are one of the fastest-growing solar applications because they support decentralized power generation and reduce transmission losses.

Types of Rooftop PV Systems

1. **Grid-Connected Rooftop System:** These systems are connected to the utility grid through net metering. These are most common in urban residential and commercial buildings.
2. **Off-Grid Rooftop System:** These systems use batteries for storage and works independently of the grid and are suitable where power cuts are frequent.
3. **Hybrid Rooftop System:** These systems combine grid connection and battery backup, thereby providing uninterrupted power supply.

The main components of the Rooftop solar systems are solar PV panels, mounting structure, inverter, Net meter, Battery (optional), distribution board and protection devices.

The solar panels installed on rooftops capture sunlight and DC electricity is generated. Inverter converts DC into AC and the Electricity is used by household loads. Excess electricity is sent to the utility grid. The Figure 4.5 shows the rooftop PV system generally works.



Figure 4.5: Rooftop PV Systems

4.7 OPERATION AND MAINTENANCE OF SOLAR POWER PLANTS

Operation and Maintenance (O&M) of solar power plants is an essential activity to ensure reliable performance, maximum energy generation, long system life, and economic viability. Although solar photovoltaic (PV) plants have fewer moving parts compared to conventional power plants, regular maintenance is necessary to maintain efficiency and prevent performance degradation.

Proper O&M helps in reducing downtime, minimizing failures, improving plant performance ratio (PR), and extending the life of equipment such as solar modules, inverters, transformers, and switchgear.

Solar power plant maintenance is generally divided into:

1. Preventive Maintenance
2. Predictive Maintenance
3. Corrective Maintenance
4. Breakdown Maintenance

Objectives of Operation and Maintenance

The main objectives of O&M are to maximize power generation, improve plant availability, reduce operational losses, increase equipment lifespan, ensure personnel safety, minimize repair costs, maintain system efficiency and ensure compliance with standards.

Major O&M Activities

1. **Solar Module Cleaning:** Dust, bird droppings, leaves, and pollution reduce the amount of sunlight reaching the solar panels, thereby decreasing efficiency. Regular cleaning improves power output significantly. Most common methods used include manual cleaning using soft water and cloth, use of robotic cleaning systems and implementation of waterless dry cleaning methods
2. **Visual Inspection:** Routine inspection helps identify visible physical damage. Inspection helps to identify cracked modules, glass breakage, delamination, hot spots, corrosion, loose structures and damages caused by animal or bird. Early detection prevents larger failures.
3. **Electrical Inspection:** Electrical checks ensure safe and efficient plant operation. This includes checking cable condition, connector inspection, testing Junction box and insulation resistance, verification of earthing, continuity checks, Fuse and breaker inspection, etc. This helps prevent electrical faults and fire hazards.
4. **Inverter Maintenance:** The inverter is the heart of a solar power plant and requires regular monitoring. The major activities for proper maintenance of inverters include checking fault alarms, inspection of cooling fan inspection, cleaning of heat sink, software updates, monitoring performance log, DC and AC voltage/current verification, etc. Faulty inverters directly affect power generation.
5. **Transformer and Switchgear Maintenance:** For utility-scale plants, transformers and switchgear require periodic maintenance such as periodic checking of oil level, monitoring temperature, relay testing, breaker maintenance, inspection of busbar and periodic evaluation of protection coordination.
6. **Battery Maintenance (if available):** Battery systems are used in off-grid and hybrid plants. Maintenance of batteries are ensured by checking electrolyte level, cleaning terminals, testing specific gravity, monitoring Voltage and inspecting charge-discharge cycles. Proper battery care improves backup reliability.
7. **Vegetation Control:** Grass, bushes, and trees near the plant can cause shading and pest problems. These problems can be solved by grass cutting, trimming trees, removing weeds and employing pest control. This helps improve solar radiation availability.
8. **Mounting Structure Inspection:** The supporting structure must remain mechanically strong. Loose mounting structures can be dangerous. This can be ensured by bolt tightening, corrosion checking, tilt angle verification, wind damage inspection and foundation checking.
9. **Performance Monitoring:** Continuous monitoring helps identify underperforming components. Some of the Key Performance Indicators (KPIs) are

(a) Performance Ratio (PR)

measures actual performance compared to expected output.

$$\mathbf{PR} = \frac{\boldsymbol{Actual\ Energy\ Output}}{\boldsymbol{Theoritical\ Energy\ Output}} \mathbf{x100}$$

(b) **Capacity Utilization Factor (CUF)**

It measures how effectively plant capacity is utilized.

$$CUF = \frac{\text{Actual Energy Generated}}{\text{Installed Capacity x Total Time}} \text{x100}$$

4.8 SUN TRACKING SYSTEMS

A Sun Tracking System is a mechanical and control system used in solar power plants to continuously orient photovoltaic (PV) panels or solar collectors toward the sun throughout the day. The main objective of a sun tracking system is to maximize the amount of solar radiation received by the solar panels and thereby increase energy generation.

Since the position of the sun changes from morning to evening and also varies seasonally, fixed solar panels cannot always receive maximum sunlight. Sun tracking systems solve this problem by automatically adjusting the panel angle to follow the sun's movement. These systems are widely used in utility-scale solar plants, solar concentrators, and high-efficiency solar applications.

Solar panels produce maximum power when sunlight falls perpendicular (90°) to the panel surface. In fixed mounting systems, this ideal angle is available only for a short duration.

A tracking system helps by:

- Increasing solar energy capture
- Improving plant efficiency
- Enhancing daily power output
- Reducing mismatch losses
- Improving return on investment (ROI)

Tracking systems can increase energy generation by 15% to 40% depending on location and design.

The sun tracking system continuously monitors the position of the sun and adjusts the orientation of the PV panel using motors, sensors, and control units. The system uses: light sensors (LDRs) or solar sensors, microcontroller or PLC, DC/AC motors or actuators, mechanical support structure and feedback control system.

When sunlight intensity becomes unequal on the sensors, the controller sends signals to the motor to rotate the panel until both sensors receive equal sunlight, indicating correct alignment.

Types of Sun Tracking Systems

Sun tracking systems are mainly classified into:

1. **Single-Axis Tracking System:** A Single-Axis Tracker rotates the solar panel along one axis only, usually from east to west, following the daily movement of the sun. It is the most commonly used tracking system in large solar plants. The most common types of single Axis trackers include Horizontal Single-Axis Tracker (HSAT), Vertical Single-Axis Tracker (VSAT) and Tilted Single-Axis Tracker (TSAT).
2. **Dual-Axis Tracking System:** A Dual-Axis Tracker rotates the solar panel along two axes: azimuth angle (East-West movement) and elevation angle (Seasonal vertical movement). This allows the panel to remain perpendicular to sunlight

throughout the year. Dual axis trackers have certain advantages viz., maximum solar radiation capture, highest efficiency improvement and suitable for concentrated solar systems. However, higher installation costs, complex mechanical structure and higher maintenance requirements are major limitations.

Control Methods of Tracking Systems

1. **Passive Tracking:** This form of tracking uses thermal expansion of fluids to move the panel without electronic control. They are of simple design and require low maintenance. However, this system provides lower accuracy.
2. **Active Tracking:** Active tracking uses motors, sensors, and electronic controllers. This system is highly accurate and exhibit better performance but comes at a higher cost.
3. **Chronological Tracking:** Chronological tracking uses programmed sun position data based on time and location rather than sensors. This process has reliable operation and no sensor dependency.

CHECK YOUR PROGRESS

Q1: What is the photovoltaic effect? How a solar cell converts sunlight into electricity.

Q2: Define the following photovoltaic parameters:

a. Open-circuit voltage
b. Short-circuit current
c. Fill factor

Q3: Differentiate between mono and polycrystalline cells.

Q4: What are the major components of a photovoltaic (PV) system?

Q5: What is the purpose of PV models and equivalent circuits?

4.9 LET US SUM UP

- Photovoltaic (PV) technology converts sunlight directly into electricity using the photovoltaic effect.
- The performance of a solar cell is described by parameters such as I_{SC}, V_{OC}, FF, and efficiency.
- Monocrystalline, polycrystalline, thin-film, and emerging solar cells differ in efficiency, cost, and applications.
- A PV system consists of components such as PV modules, inverter, battery, charge controller, mounting structure, and protection devices.
- PV models and equivalent circuits are used to analyze and predict the performance of solar cells.
- PV systems are widely used in off-grid, grid-connected, and rooftop applications, with proper operation and maintenance ensuring reliable performance.

4.10 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: The photovoltaic effect is the process by which a solar cell converts sunlight directly into electricity. When sunlight falls on a semiconductor material, such as silicon, photons generate electron-hole pairs. The internal electric field at the p-n junction separates these charge carriers, producing a flow of direct current (DC) electricity.

Ans to Q2:

(a) Open-circuit voltage: The open-circuit voltage is the maximum voltage produced by a solar cell when no external load is connected and the output current is zero.

(b) Short-circuit current: The short-circuit current is the maximum current produced by a solar cell when its output terminals are short-circuited and the output voltage is zero.

(c) Fill Factor: The fill factor is the ratio of the maximum power output to the product of the open-circuit voltage and short-circuit current. It indicates the quality and power-producing capability of a solar cell.

Ans to Q3:

Parameter	Monocrystalline	Polycrystalline
Crystal Structure	Singlecrystal	Multiplecrystals
Efficiency	Higher	Moderate
Cost	Higher	Lower
Appearance	Black	Blue
Parameter	Monocrystalline	Polycrystalline
Lifespan	Longer	Slightly lower
Space Requirement	Less	More

Ans to Q4: The major components of a PV system include PV modules, inverter, battery, charge controller, mounting structure, cables and connectors, protection devices, net meter, and monitoring system.

Ans to Q5: PV models and equivalent circuits are used to predict and analyze the electrical performance of solar cells under different operating conditions. They help in system design, simulation, optimization, and performance evaluation.

4.11 FURTHER READING

- Messenger, R., and Ventre, J., *Photovoltaic Systems Engineering*
- Chetan Singh Solanki, *Solar Photovoltaics: Fundamentals, Technologies and Applications*
- S.P. Sukhatme, *Solar Energy: Principles of Thermal Collection and Storage*
- MNRE Guidelines on Solar PV Installations
- IEC Standards for PV Systems

4.12 MODEL QUESTIONS

Q1: Explain the working principle of a solar cell with neat diagram.
Q2: Discuss different solar cell technologies in detail.
Q3: Compare off-grid and grid-connected PV systems.
Q4: Describe operation and maintenance practices of solar power plants.
Q5: Explain sun tracking systems and their advantages.

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UNIT 5: WIND ENERGY

UNIT STRUCTURE

5.1 Learning Objectives
5.2 Introduction
5.3 Introduction to Wind Energy
5.4 Characteristics of Wind and Wind Power
5.5 Wind Turbines
5.5.1 Types of Wind Turbines
5.5.2 Components of Wind Turbines
5.6 Aerodynamics of Wind Turbine
5.6.1 Aerofoil
5.6.2 Lift and Drag Characteristics
5.7 Grid Integration of Wind Turbines
5.7.1 Power Electronic Interfaces
5.7.2 Grid Interconnection Topologies
5.8 Challenges of Wind Energy Technology
5.9 Let Us Sum Up
5.10 Answers to Check Your Progress
5.11 Further Reading
5.12 Model Questions

5.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- define wind energy and explain key wind characteristics
- explain different types of wind turbines and their components
- discuss basic aerodynamic concepts such as aerofoil, lift, and drag
- describe the working of wind turbines and methods of grid integration
- differentiate between various grid interconnection topologies
- assess the challenges associated with wind energy technology.

5.2 INTRODUCTION

In the previous unit, we discussed the solar photovoltaic system. In this unit, we will explore wind energy, beginning with the definition of wind energy and an explanation of its key characteristics. The unit will then cover different types of wind turbines along with their major components, followed by a discussion of basic aerodynamic concepts such as aerofoil, lift, and drag. It will also describe the working principles of wind turbines and the methods used for grid integration. Further, the unit will differentiate between various grid interconnection topologies and conclude with an assessment of the major challenges associated with wind energy technology.

5.3 INTRODUCTION TO WIND ENERGY

Wind energy is a clean, renewable, and environmentally sustainable source of energy obtained from the kinetic energy of moving air. It is one of the most rapidly developing renewable energy technologies and has become an important alternative to conventional fossil-fuel-based power generation. Wind is naturally produced due to uneven heating of the Earth's surface by solar radiation, which creates differences in atmospheric pressure and causes air to move from high-pressure regions to low-pressure regions.

The kinetic energy of moving wind is converted into electrical energy using wind turbines. When wind strikes the turbine blades, the rotor begins to rotate, converting the kinetic energy of wind into rotational energy. This rotational energy drives a generator connected to the turbine shaft, producing electricity. Wind energy systems can be installed as single turbines for small-scale applications or as large wind farms for utility-scale power generation. Modern wind power plants are developed in both onshore and offshore locations depending on wind availability and geographical conditions.

Wind energy provides several important advantages, including clean electricity generation without greenhouse gas emissions, low operating and maintenance costs, reduced dependence on fossil fuels, and sustainable long-term energy production. It is widely used for grid-connected electricity generation, rural electrification, water pumping, battery charging, and hybrid renewable energy systems. In addition, technological advancements in turbine design, control systems, and energy storage have significantly improved the efficiency and reliability of wind power systems.

However, wind energy also has certain limitations. The availability of wind is variable and depends on climatic and weather conditions, resulting in intermittent power generation. Large wind farms require considerable land area and suitable wind conditions, while issues such as noise generation, visual impact, and effects on birds and wildlife must also be considered. Despite these challenges, wind energy remains one of the most promising renewable energy resources for achieving sustainable development, energy security, and reduction of environmental pollution worldwide.

5.4 CHARACTERISTICS OF WIND AND WIND POWER

Wind is the movement of air produced by pressure differences in the atmosphere caused by unequal heating of the Earth's surface by solar radiation. The characteristics of wind play a vital role in determining the efficiency and performance of wind energy conversion systems. Important wind characteristics include wind speed, wind direction, air density, turbulence, and wind variation with height. These factors directly influence the amount of energy that can be extracted from the wind and converted into electrical power.

Among all wind characteristics, wind speed is the most significant because the power available in wind is proportional to the cube of wind velocity. This means that a small increase in wind speed results in a substantial increase in wind power generation. Wind

direction is also important, as wind turbines must be properly aligned with the wind to maximize energy capture. Air density affects the kinetic energy of wind, with higher air density providing greater power output. Wind speed generally increases with height above the ground due to reduced surface friction; therefore, wind turbines are mounted on tall towers to access stronger and more stable winds.

Wind power is the electrical power generated by converting the kinetic energy of moving air into mechanical energy through turbine blades and then into electrical energy using a generator. The power available in wind depends on air density, rotor swept area, and wind velocity. The theoretical wind power can be expressed as:

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

where P is the wind power, ρ is the air density, A is the swept area of the turbine blades, and v is the wind speed.

However, a wind turbine cannot extract all the available wind energy due to aerodynamic limitations. According to Betz's law, the maximum theoretical efficiency of a wind turbine is 59.3%. Practical wind turbines operate at lower efficiencies because of mechanical and electrical losses.

Wind power possesses several important characteristics. It is renewable, non-polluting, sustainable, and widely available. Wind energy systems have low operating costs and produce electricity without greenhouse gas emissions. However, wind power is intermittent and variable in nature because it depends on changing weather and climatic conditions. Therefore, efficient grid integration, forecasting methods, and energy storage systems are important for maintaining reliable electricity supply.

The analysis of wind characteristics is essential for wind resource assessment, turbine selection, site planning, and performance optimization. Proper understanding of wind behaviour improves the efficiency, reliability, and economic feasibility of wind energy systems, making wind power one of the most important renewable energy technologies for sustainable energy development.

5.5 WIND TURBINES

A wind turbine is a device used to convert the kinetic energy of wind into electrical energy. It operates by using aerodynamic blades that rotate when struck by moving air. The rotating blades drive a rotor connected to a generator, which converts mechanical energy into electrical energy. They are widely used in onshore and offshore wind farms for sustainable power production.

5.5.1 Types of Wind Turbines

A wind turbine consists of blades, rotor, nacelle, gearbox, generator, tower, and control system. Wind turbines are mainly classified into Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). Horizontal axis turbines are more commonly used because of their higher efficiency and suitability for large-scale power generation.

Horizontal Axis Wind Turbines are the most commonly used wind turbines for modern electricity generation. In these turbines, the rotor shaft is horizontal and parallel to the ground, while the blades rotate perpendicular to the wind direction. The turbine is mounted on a tall tower to capture stronger and more stable winds at higher altitudes. A yaw mechanism is used in wind turbines to rotate the nacelle and rotor so that they face the direction of the wind. This helps the turbine capture maximum wind energy and improve efficiency. The yaw mechanism usually consists of motors, gears, brakes, and control systems that automatically adjust the turbine's position according to changes in wind direction.
A VAWT consists of aerodynamic blades, rotor, hub, nacelle, gearbox, generator, tower, and control system. When wind strikes the blades, lift and drag force is produced, causing the rotor to rotate and drive the generator.

Here the rotor shaft is vertical and perpendicular to the ground. It works well in low speed wind conditions. It is suitable for urban areas and easy to maintain as its components can be placed near the ground.



HAWT VAWT

Figure 5.1: Types of Wind Turbine

5.5.2 Components of Wind Turbines

A wind turbine consists of several mechanical and electrical components that work together to convert the kinetic energy of wind into electrical energy. Each component performs a specific function to ensure efficient and reliable operation of the wind energy conversion system. Main components of wind turbines are listed below and shown in Figure 5.2.

1. Blades: The blades are the aerodynamic components of a wind turbine that capture the kinetic energy of wind. When wind flows over the blades, lift force is produced, causing the rotor to rotate.
2. Rotor: The rotor consists of the blades and hub assembly. It converts wind energy into rotational mechanical energy.
3. Hub: The hub connects the blades to the main shaft and transfers the rotational motion generated by the blades.
4. Nacelle: The nacelle is the housing mounted on top of the tower that contains important mechanical and electrical components such as the gearbox, generator, and brake system.
5. Gearbox: The gearbox increases the low rotational speed of the rotor to a higher speed suitable for driving the generator.
6. Generator: The generator converts the mechanical rotational energy from the turbine into electrical energy.
7. Tower: The tower supports the wind turbine and places the rotor at a greater height where wind speeds are stronger and more stable.
8. Yaw System: The yaw system rotates the nacelle so that the turbine faces the wind direction for maximum energy capture.
9. Pitch Control System: The pitch control system adjusts the angle of the blades to regulate rotor speed and protect the turbine during high wind conditions.
10. Brake System: The brake system is used to stop the rotor during maintenance or emergency situations for safe operation.

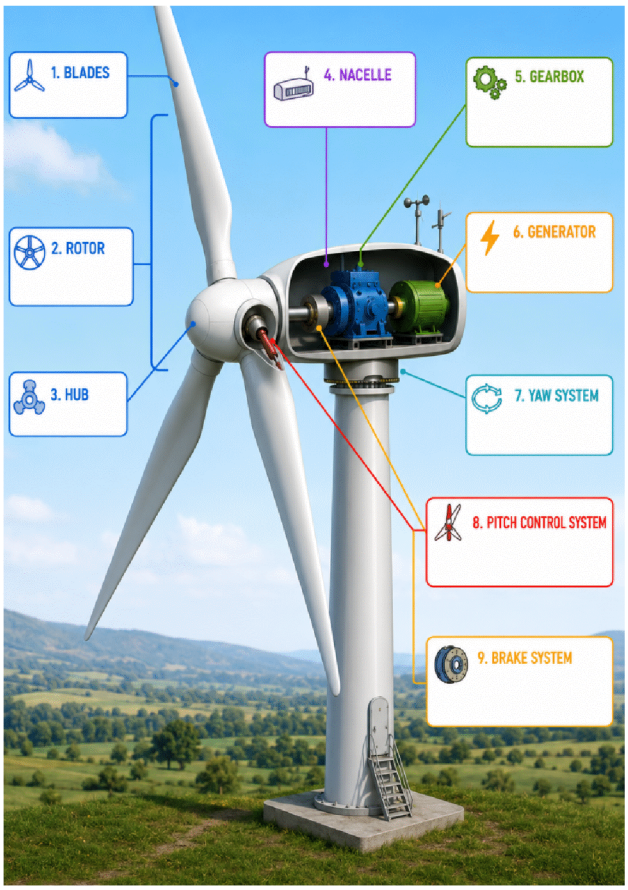


Figure 5.2: Components of Wind Turbine

5.6 AERODYNAMICS OF WIND TURBINE

Aerodynamics of a wind turbine is the study of how moving air (wind) interacts with turbine blades and produces forces that make the blades rotate. In a wind turbine, the energy of moving air is converted into mechanical energy through the rotation of blades, and this process is completely governed by aerodynamic principles. When wind approaches the rotor, it does not pass straight through; instead, its speed and direction change due to the presence of the blades. This interaction creates forces on the blades, mainly lift and drag, which together produce torque and cause rotation. Lift is the force that acts perpendicular to the direction of the wind and helps in rotating the turbine blades; it can be compared to the upward force experienced by a car when air flows over its body at high speed, slightly reducing its contact with the road. Drag is the force that acts in the same direction as the wind and opposes motion.

The basic theory of aerodynamics comes from fluid mechanics, where air is treated as a continuous flowing fluid. As wind flows around a blade, it follows curved paths called streamlines. The shape of the blade forces the air to move faster over the upper surface and relatively slower over the lower surface. According to fluid mechanics, when air moves faster, its pressure decreases. Therefore, the pressure above the blade becomes lower than the pressure below it. This pressure difference produces an upward force called lift. At the same time, due to friction and resistance, another force called drag acts in the direction of the wind.

The lift and drag forces acting on an aerofoil can be expressed using simple equations given in the book. The lift force is written as

$$L = \frac{1}{2}\rho V^2 c C_L$$

and the drag force is written as

$$D = \frac{1}{2}\rho V^2 c C_D$$

where ρ is the air density, V is the wind speed, c is the chord length of the blade, and C_L and C_D are the lift and drag coefficients respectively . C_L (lift coefficient) measures how effectively a blade produces lift, while C_D (drag coefficient) measures how much air resistance (drag) it experiences. These equations show that both lift and drag increase with the square of wind speed, meaning that even a small increase in wind speed can produce a large increase in force.

Aerodynamics is extremely important in wind turbines because it directly controls how much energy can be extracted from the wind. A good aerodynamic design increases lift and reduces drag, which improves efficiency. It also helps in designing blades that can operate safely under different wind conditions. Poor aerodynamics can lead to energy loss, vibration, noise, and even structural damage. Therefore, understanding aerodynamics is essential for designing efficient and reliable wind turbines. Figure 5.3 shows the airflow distribution over an aerofoil illustrating velocity and pressure differences, along with the resulting lift, drag, and resultant aerodynamic forces acting on the blade.

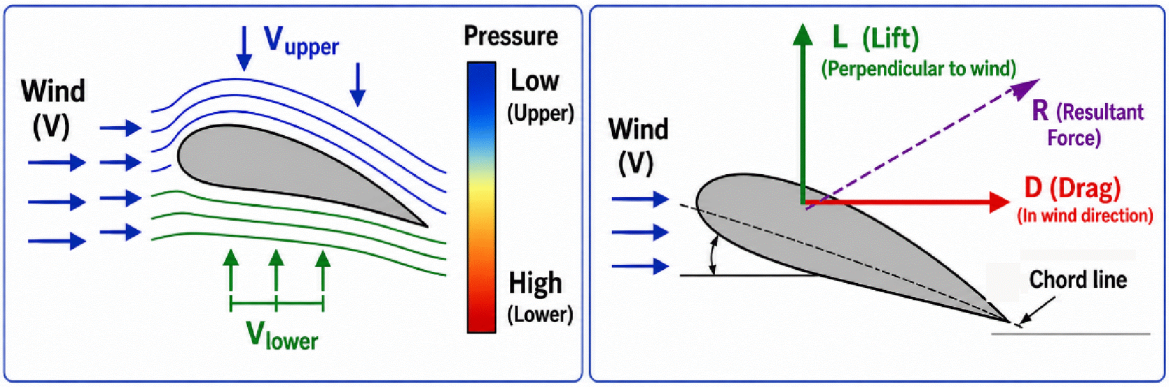


Figure 5.3: Aerofoil airflow, pressure distribution, and lift–drag forces.

5.6.1 AEROFOIL

An aerofoil is the cross-sectional shape of a wind turbine blade that is specially designed to produce lift when air flows over it. It is the most important part of the blade because its shape determines how effectively the blade can convert wind energy into motion. Instead of being flat, an aerofoil has a curved upper surface and a relatively flatter lower surface. This curved shape causes the air to move differently over the two surfaces, creating the pressure difference required for lift.

An aerofoil has several important parts. The front edge is called the leading edge, and the back edge is called the trailing edge. The straight line joining these two points is known as the chord line. The angle between this chord line and the direction of the incoming wind is called the angle of attackα. This angle is very important because it determines how much lift and drag will be produced. At small angles, the flow remains smooth, and lift increases steadily. At larger angles, the flow may separate from the surface, causing a sudden loss of lift. Figure 5.4 demonstrates the various part of an aerofoil.

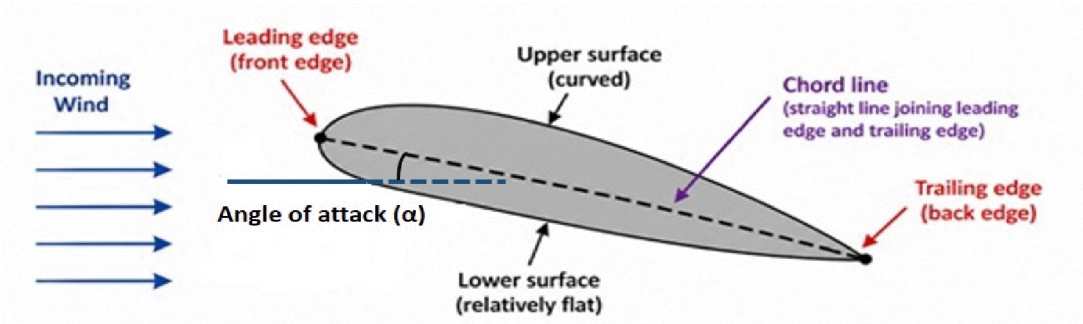


Figure 5.4: Aerofoil

Aerofoils are generally classified into symmetrical and cambered types. A symmetrical aerofoil has identical upper and lower surfaces and produces no lift at zero angle of attack. A cambered aerofoil has a curved upper surface and produces lift even at small angles, making it more suitable for wind turbines. The theory of aerofoils explains that lift is generated due to both pressure difference and the curvature of airflow around the blade. The air close to the surface forms a thin region called the boundary layer, which may be laminar (smooth) or turbulent (irregular). When the boundary layer separates

from the surface, the aerofoil experiences stall, which reduces its effectiveness. Figure 5.5 shows the comparison between a symmetrical aerofoil and a cambered aerofoil with airflow patterns at zero and small angles of attack. It illustrates that the symmetrical aerofoil produces no lift at zero angle, while the cambered aerofoil generates lift due to faster airflow over the upper surface and slower airflow over the lower surface.

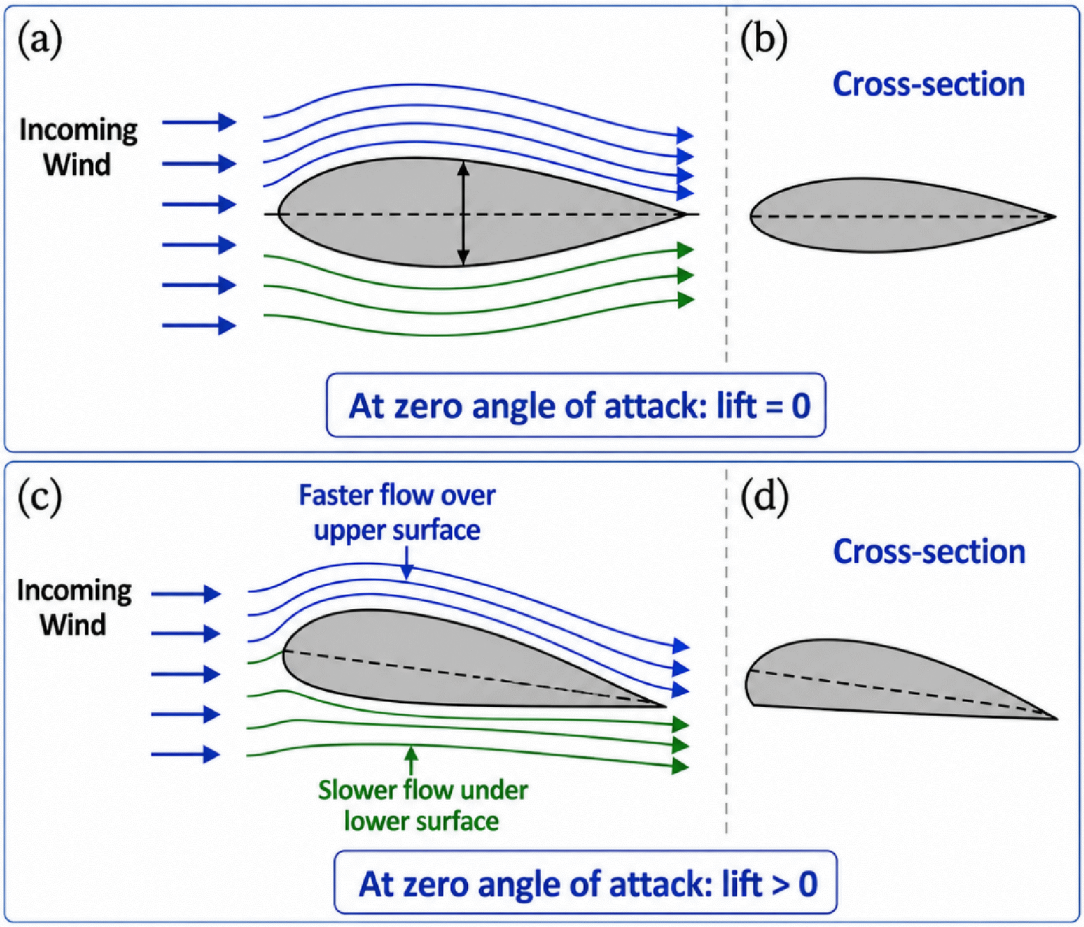


Figure 5.5: (a) Symmetrical aerofoil showing airflow distribution at zero angle of attack; (b) corresponding cross-section of the symmetrical aerofoil; (c) cambered aerofoil showing airflow pattern and pressure difference at zero angle of attack; (d) corresponding cross-section of the cambered aerofoil.

5.6.2 Lift and Drag Characteristics of Aerofoil

When air flows over an aerofoil, two main forces act on it-lift and drag. Lift acts perpendicular to the direction of the incoming wind and is responsible for rotating the turbine blades. Drag acts in the direction of the wind and opposes motion. For efficient operation, the lift should be as high as possible, while drag should be kept as low as possible.

The behaviour of lift and drag is usually studied using their coefficients, $C_L$andC_DThese coefficients depend mainly on the angle of attack and the shape of the aerofoil. At

small angles of attack, the lift coefficient increases almost linearly with angle. For many aerofoils, the lift increases at a nearly constant rate (about 2π per radian) until it reaches a maximum value. Beyond this point, the airflow starts separating from the surface, and lift suddenly decreases. This condition is called stall. The drag coefficient behaves differently. At small angles of attack, drag is very low because the airflow remains smooth and attached to the surface. However, as the angle increases, drag increases slowly at first and then rapidly after stall due to turbulence and flow separation. The total drag consists of skin friction drag, caused by air rubbing against the surface, and pressure drag, caused by differences in pressure around the aerofoil.
Figure 5.6 shows the variation of lift and drag coefficients with angle of attack for an aerofoil. The blue line represents the lift coefficient, which increases with angle of attack up to a maximum value and then decreases due to stall. The red line represents the drag coefficient, which remains low at small angles but increases rapidly at higher angles of attack.

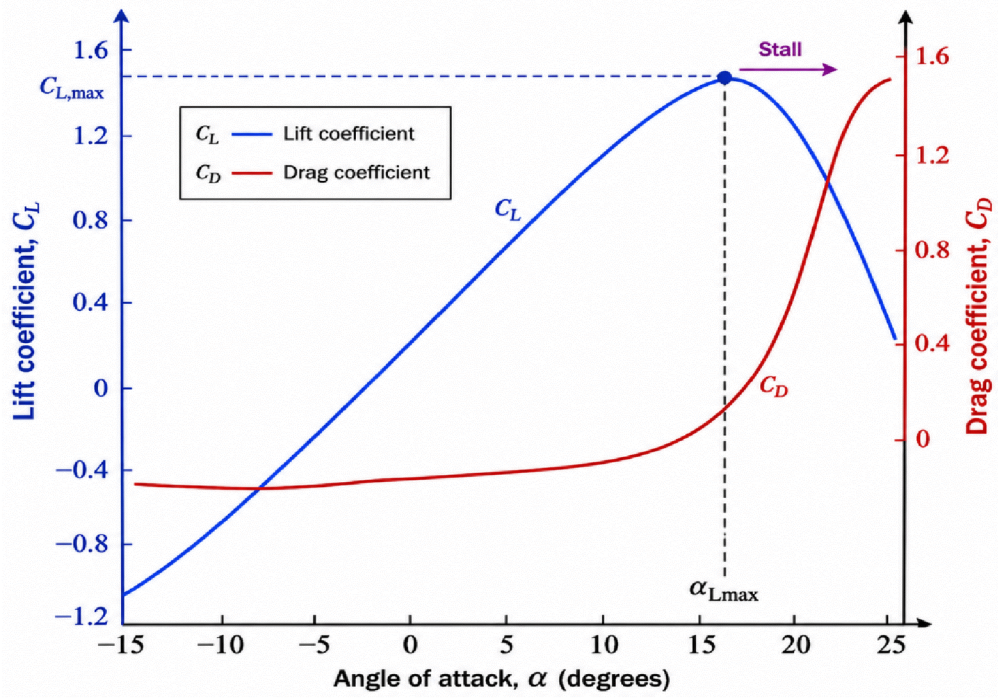


Figure 5.6: Variation of C_L and C_D with α

An important parameter in aerodynamics is the lift-to-drag ratio, written as $\frac{L}{D}$ .This ratio indicates how efficiently the aerofoil converts wind energy into useful motion. A higher value of $\frac{L}{D}$ means better performance. Wind turbine blades are designed to operate at angles where this ratio is maximum so that energy extraction is efficient.
Another important concept is Reynolds number, which is a measure of the flow condition and is given by

$$R_e = \frac{\rho V c}{\mu}$$

where μ is the dynamic viscosity of air , c is the characteristic length (in aerofoils, this is the chord length). This number helps determine whether the flow is laminar or turbulent and affects the lift and drag characteristics of the aerofoil.

In summary, the lift and drag characteristics of an aerofoil determine the overall performance of a wind turbine. By carefully selecting the aerofoil shape and operating conditions, engineers can maximize lift, minimize drag, and achieve high efficiency in energy conversion.

5.7 GRID INTEGRATION OF WIND TURBINES

Grid integration of wind turbines refers to the process of connecting wind-generated electrical power to the electrical grid (power system) so that it can be used by consumers. A power grid is a large interconnected network that delivers electricity from power plants to consumers through transmission lines, substations, and distribution systems, while maintaining a constant voltage and frequency (such as 50 Hz). In the case of wind energy, a wind turbine is connected to the electric grid through a step-wise process: first, the turbine converts wind energy into mechanical rotation of the rotor; second, the generator converts this mechanical energy into electrical energy, which is usually variable in voltage and frequency; third, this electrical output is passed through power electronic converters that adjust it into stable, grid-compatible AC power; fourth, a transformer increases the voltage to a higher level suitable for transmission; fifth, the power from multiple turbines is collected at a substation where further voltage regulation and protection are applied; and finally, the electricity is fed into the main power grid for distribution to homes, industries, and other users.

The importance of grid integration lies in ensuring stable, reliable, and efficient electricity supply. Without proper integration, fluctuations in wind energy can disturb the grid, leading to voltage instability or power quality issues. For example, when wind speed suddenly increases, power output also increases, which must be controlled before feeding into the grid. Similarly, when wind drops, the system should maintain supply balance using other sources.

Grid integration also enables large-scale use of renewable energy. In modern power systems, wind farms are connected to national grids so that electricity can be transmitted over long distances and shared across regions. This helps reduce dependence on fossil fuels and supports sustainable energy development. Figure 5.7 shows the step-by-step flow of energy conversion and transmission from a wind turbine to the electrical grid through generator, power electronic interface, transformer, and substation.

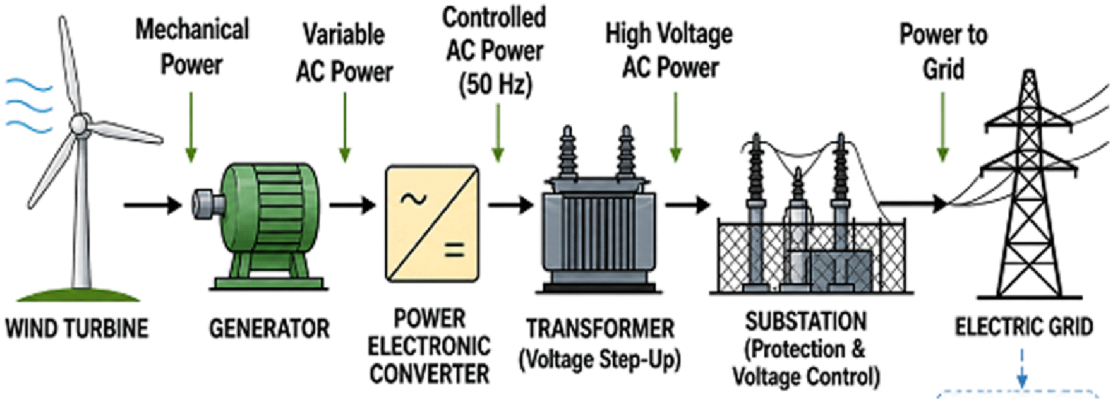


Figure 5.7 Steps of Energy Conversion

5.7.1 Power Electronic Interfaces

Power electronic interfaces are devices that convert and control electrical power produced by wind turbines so that it becomes suitable for grid connection. Since wind turbines often generate variable frequency and variable voltage power, these interfaces are essential to make the output compatible with the grid, which operates at fixed frequency (like 50 Hz in India). These interfaces mainly include converters and inverters. First, the electrical power from the generator (which may be AC with variable frequency or even DC) is converted into a controlled form. Then, using an inverter, it is converted into grid-compatible AC power with fixed frequency and voltage.
Power electronic interfaces are employed in different types of wind turbines:

- In variable-speed turbines, they allow the rotor speed to change with wind speed while still supplying constant-frequency power to the grid.
- In doubly-fed induction generators (DFIG), partial-scale converters are used.
- In full converter systems, the entire power passes through the converter.

The benefits of power electronic interfaces are very important:
They maintain constant frequency and voltage, ensuring compatibility with the grid.
They improve power quality by reducing harmonics and fluctuations.
They enable maximum power extraction from wind at different wind speeds.
They provide control features such as reactive power support and fault ride-through capability.
A simple real-life example is similar to using a mobile charger. The electricity from the wall socket is converted into a suitable form before charging the phone. Similarly, power electronic interfaces “condition” wind power before sending it to the grid. Figure 5.8 shows how power electronic interfaces are used in different types of wind turbines to regulate and deliver stable electrical power to the grid.

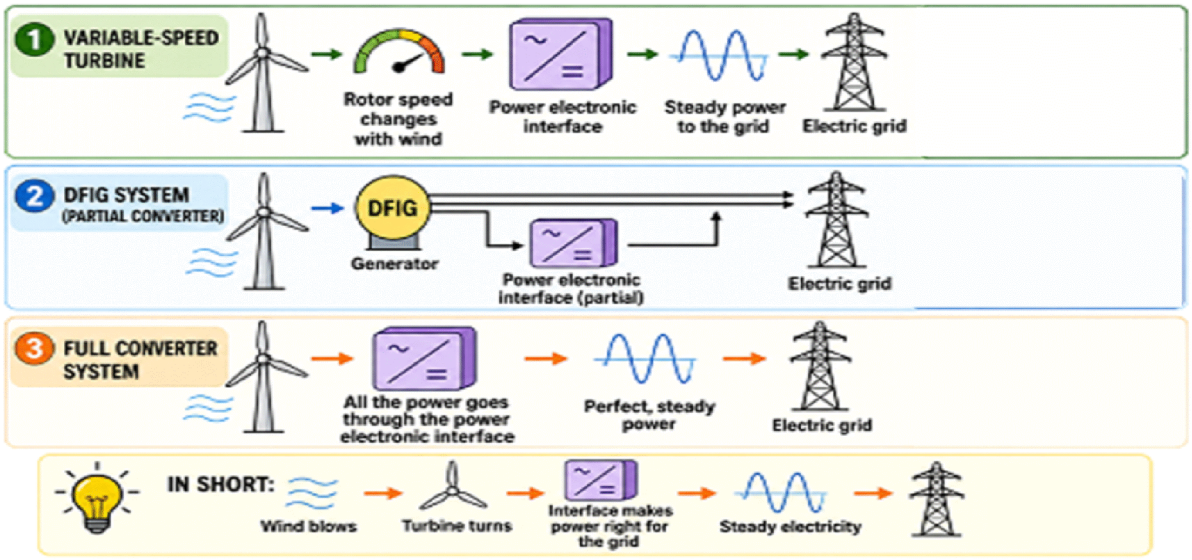


Figure 5.8: Power electronic interfaces in different types of wind turbines

5.7.2 Grid Interconnection Topologies

Grid interconnection topology refers to the way in which wind turbines or wind farms are connected to the electrical grid. It defines the structure of connections between turbines, substations, and transmission lines.
The meaning of topology here is simply the arrangement or configuration of connections used to deliver power from wind turbines to the grid.

There are several types of grid interconnection topologies:

1. Direct Grid Connection (Fixed-Speed System)
In this simple method, the wind turbine is directly connected to the grid, usually through an induction generator. This system is easy and low-cost but has limitations because it cannot control power output effectively and is sensitive to wind variations.
2. Partial Power Converter Topology (DFIG System)
In this system, only part of the generated power passes through a converter. The stator is directly connected to the grid, while the rotor is connected through power electronics. This allows variable-speed operation with better efficiency and control.
3. Full Power Converter Topology
Here, all the generated power passes through a full-scale converter before reaching the grid. This provides complete control over voltage, frequency, and power quality. It is widely used in modern wind turbines, especially offshore wind farms.
4. Wind Farm Collection System
In large wind farms, multiple turbines are connected together using cables and linked to a substation. The substation steps up the voltage and sends power to the main grid. This arrangement ensures efficient transmission over long distances.
5. Offshore Grid Connection
For offshore wind farms, power is transmitted using submarine cables. Sometimes HVDC (High Voltage Direct Current) systems are used to reduce transmission losses over long distances.

Importance of Grid Topology

The choice of topology affects:

- efficiency of power transmission
- system reliability
- cost of installation
- ability to handle large-scale wind energy

For example, modern large wind farms use full converter systems with advanced grid connections to ensure stable and efficient operation.

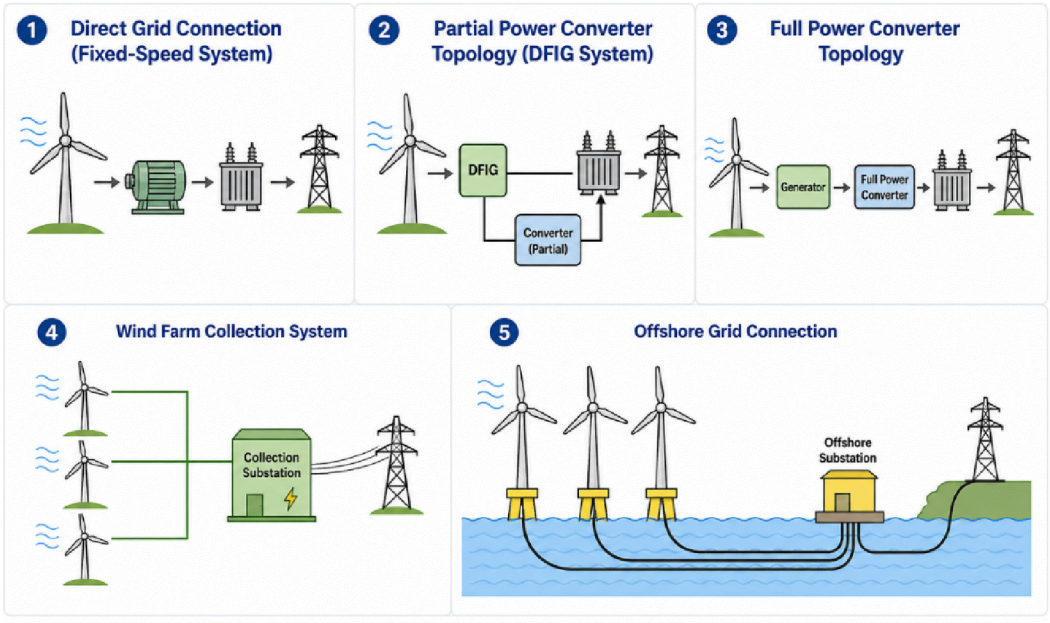


Figure 5.9: Types of grid interconnection topologies

5.8 CHALLENGES OF WIND ENERGY TECHNOLOGIES

Wind energy is a clean and renewable source of power, but it comes with several technical and practical challenges. These challenges arise due to the natural behaviour of wind and the complex design and operation of wind turbines.

- **Wind is not constant :**Wind speed keeps changing with time. Because of this, the power produced by wind turbines is not steady.
- **Low efficiency at low wind speeds :**At very low wind speeds, turbines produce very little or no electricity, which reduces overall performance.
- **Extreme wind conditions :**Very high wind speeds (storms) can damage turbines. So, turbines must be designed to handle extreme conditions safely.
- **Structural loads and fatigue :**Wind turbines face continuous forces due to wind. Over time, this can cause wear and tear (fatigue) in blades and other parts.
- **Complex aerodynamics :**The flow of air around blades is complex, especially at different wind speeds. This makes design and analysis difficult.

- **Noise generation** :Wind turbines produce noise due to blade movement and airflow, which can affect nearby residents.
- **Vibration problems** :Turbines can experience vibrations due to changing wind forces, which may reduce their lifetime if not controlled.
- **Control system requirements** :Turbines need proper control systems to regulate speed and power. Without control, efficiency and safety decrease.
- **Material and design limitations** :Blades must be strong, light, and durable. Finding suitable materials and designs is challenging.
- **Maintenance difficulties** :Wind turbines are often installed in remote or offshore locations, making maintenance difficult and costly.
- **Energy capture limitations** :There is a physical limit (like Betz limit) on how much energy can be extracted from wind, so 100% efficiency is not possible.
- **Grid integration issues** :Because wind power fluctuates, connecting it smoothly to the electrical grid requires advanced systems.

CHECK YOUR PROGRESS

Q1: What is wind energy?
Q2: What factors affect wind power generation?Why
Q3: What are the main types of wind turbines?
Q4: What are the main components of a wind turbine?
Q5: What is the function of an aerofoil in a wind turbine?
Q6: Why are power electronic interfaces used in wind turbines?
Q7: What are the major challenges of wind energy technology?

5.9 LET US SUM UP

- Wind energy is a renewable source of energy generated by converting wind motion into electrical power using wind turbines.
- The power available in wind depends on wind speed, air density, and the swept area of the turbine blades.
- Wind turbines are devices that convert the kinetic energy of wind into mechanical and electrical energy.
- Wind turbines are mainly classified into horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT).
- The main components of a wind turbine include blades, rotor, nacelle, gearbox, generator, tower, and yaw mechanism.
- The aerodynamics of wind turbines involve aerofoil design and the lift and drag forces that affect turbine performance.
- Grid integration of wind turbines requires power electronic interfaces and suitable grid interconnection topologies for stable power delivery.
- Wind energy technology faces challenges such as high installation costs, variability of wind speed, noise, land requirements, and grid stability issues.

5.10 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Wind energy is a renewable source of energy obtained by converting the kinetic energy of wind into electrical energy using wind turbines.

Ans to Q2: Wind power generation depends on wind speed, air density, and the swept area of the turbine blades.

Ans to Q3: The two main types of wind turbines are Horizontal-Axis Wind Turbines (HAWT) and Vertical-Axis Wind Turbines (VAWT).

Ans to Q4: The main components include blades, rotor, nacelle, gearbox, generator, tower, and yaw mechanism.

Ans to Q5: An aerofoil helps generate lift force, which rotates the turbine blades and improves energy conversion efficiency.

Ans to Q6: Power electronic interfaces are used to control voltage, frequency, and power quality before connecting the turbine to the grid.

Ans to Q7: Major challenges include variable wind speed, high installation cost, noise, large land requirements, and grid integration issues.

5.11 FURTHER READING

- Kothari, D. P., Singal, K. C., &Ranjan, R. (2011). Renewable energy sources and emerging technologies. Prentice Hall of India Private Limited.
- Burton, T., Jenkins, N., Sharpe, D., &Bossanyi, E. (2011). Wind energy handbook (2nd ed.). Wiley.
- Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). Wind energy explained: Theory, design and application (2nd ed.). Wiley.
- Hau, E. (2013). Wind turbines: Fundamentals, technologies, application, economics (3rd ed.). Springer.
- Ackermann, T. (Ed.). (2012). *Wind power in power systems* (2nd ed.). Wiley.

5.12 MODEL QUESTIONS

Q1: What is wind energy, and how is it converted into electrical energy?

Q2: Explain the main characteristics of wind and wind power.

Q3: What are the advantages and limitations of wind energy?

Q4: Describe the working principle of a wind turbine.

Q5: Classify the different types of wind turbines and explain each briefly.

Q6: List and explain the main components of a wind turbine.

Q7: What is an aerofoil, and how does it help in wind turbine operation?

Q8: Explain the concepts of lift and drag in wind turbine aerodynamics.

Q9: What is grid integration of wind turbines, and why is it important?

Q10: Discuss the major challenges faced in wind energy technology.

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UNIT 6: HYDRO ENERGY

UNIT STRUCTURE

6.1 Learning Objectives
6.2 Introduction
6.3 Hydropower Resources
6.4 Fundamentals of Hydro Energy Estimation
6.5 Components of a Hydropower System
6.5.1 Dams and Reservoirs
6.5.2 Intake Structures and Penstocks
6.6 Hydropower Technologies
6.6.1 Small, Medium, and Large Hydro Systems
6.6.2 Pumped Storage and Micro-Hydro
6.7 Hydro Turbines
6.7.1 Pumped Hydro Energy
6.8 Environmental Impact of Hydropower Applications
6.9 Let Us Sum Up
6.10 Answers to Check Your Progress
6.11 Further Reading
6.12 Model Questions

6.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- identify the various hydropower resources
- explain the fundamentals of hydro energy estimation
- list the components of a hydropower system
- differentiate between hydropower technologies
- describe the working and effectiveness of hydro turbines
- examine the environmental impacts of hydropower applications.

6.2 INTRODUCTION

In the previous unit, we discussed wind energy. In this unit, we will focus on another important renewable energy source, namely hydro energy. This unit introduces the various hydropower resources and explains the fundamentals of hydro energy estimation. It also covers the key components of a hydropower system including dams, reservoirs, intake structures, and penstocks. The unit also differentiates between different hydro power technologies such as small, medium, large hydro systems, pumped storage, and micro-hydro. Further, the unit describes the working and effectiveness of hydroturbines. Finally,the unit concludes with an overview of the environmental impacts associated with hydropower applications.

6.3 HYDROPOWER RESOURCES

Hydropower, also known as water power, is a form of energy obtained from flowing water, mainly rivers, and is used for the generation of electricity. It is considered a renewable source of energy because it originates from natural processes such as rainfall and river flow, which are continuously replenished in nature. In simple terms, water stored at a height, such as in a dam, possesses potential energy, and when it flows downward, this energy is converted into electrical energy.

Energy sources are broadly classified into conventional and non-conventional categories. Conventional sources include thermal power, hydropower, and nuclear power, while non-conventional or renewable sources include solar, wind, biomass, and others. Hydropower holds a unique position among these sources because it is both a traditional (conventional) and renewable source of energy, and it contributes significantly to electricity generation across the world.

Hydropower resources refer to the total potential energy available from water systems such as rivers and streams. This potential is classified into three categories they are theoretical potential, which represents the total energy available from all water resources; technically feasible potential, which is the portion that can be developed using existing technology; and economically feasible potential, which is the part that can be developed in a cost-effective manner. Although the global hydropower potential is very large, a significant portion of it, more than 60 percent, remains unused.

The distribution of hydropower resources across the world is uneven. Certain major rivers such as the Amazon, Congo, Yangtze, and Brahmaputra have very high hydropower potential due to their large water flow and basin size. As a result, some regions are rich in hydropower resources, while others depend more on different forms of energy.

In India, hydropower resources are substantial, but they have not been fully utilized. The total hydropower potential is estimated to be about 148,701 MW, of which only about 34,705 MW (approximately 24%) has been developed, indicating considerable scope for future expansion. Most of this untapped potential is concentrated in the Himalayan river systems, particularly in the Brahmaputra basin. (Source: Central Electricity Authority (CEA), Government of India.). According to the latest report of the Central Electricity Authority (CEA), India possesses significant hydropower potential, with a substantial portion remaining untapped, particularly in the Himalayan river systems. India has several important hydropower projects that contribute significantly to electricity generation. Some well-known examples include the Bhakra Nangal Hydroelectric Project in Himachal Pradesh and Punjab, the Tehri Hydroelectric Project in Uttarakhand, the Nathpal Jhakri Hydroelectric Project in Himachal Pradesh, and the Subansiri Lower Hydroelectric Project on the Assam–Arunachal Pradesh border. These projects demonstrate the important role of hydropower in meeting the country's growing energy demand.

Hydropower resources have certain key characteristics. They depend primarily on water availability and flow, are influenced by rainfall and climatic conditions, and require suitable geographical features such as sufficient height difference and river discharge. Additionally, hydropower projects are often developed as multipurpose systems that also support irrigation, flood control, and water supply along with electricity generation.

The Figure 6.1 shows how hydropower resources (water) are used to generate electricity. Water stored in the reservoir behind the dam represents the hydropower resource, as it has energy due to its height. When released, it flows through the intake and penstock, converting this stored energy into moving energy. The flowing water turns the turbine, which drives the generator to produce electricity. This electricity is then transmitted through transformer and transmission lines. After use, water flows back through the tailrace, showing that it is renewable. In short, hydropower resources are represented by the stored and flowing water used to generate electricity.

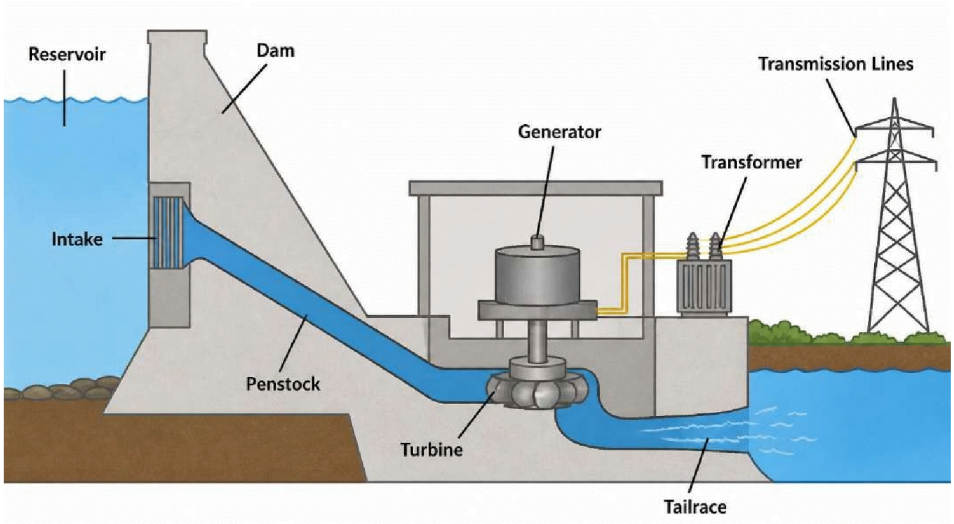


Figure 6.1: Simple schematic of a hydropower plant showing conversion of stored water energy into electricity

6.4 FUNDAMENTALS OF HYDRO ENERGY ESTIMATION

The idea of hydro energy estimation comes from the basic need to understand how much power can be produced from flowing or stored water. In water power engineering, energy is obtained when water at a higher level (height) moves to a lower level. During this movement, the water possesses energy, which can be converted into electrical energy using turbines and generators. Thus, hydro energy estimation means calculating the amount of useful energy or power available from water resources.

According to the general principles, hydropower depends mainly on two natural factors: the quantity of water available (flow) and the effective head (net head) through which the waterfalls. The net head is the actual head available at the turbine after accounting for hydraulic losses due to friction and other flow resistances. These two parameters together determine the total energy that can be extracted from water. If either the flow is small or the height is low, the power generation will also be less. Therefore, both must be considered together.

In simple terms, the fundamental equation of hydro energy estimation is based on physics. The power available from water can be expressed as:

$$P = \rho g Q H \eta$$

Here, P = power produced (in watts)
ρ = density of water (kg/m³) (about 1000 kg/m³)
g= acceleration due to gravity(m/s²)(9.81m/s²)
Q = discharge or flow rate of water (m³/s)
H = effective (net) head available at the turbine after accounting for hydraulic losses (m)
η = efficiency of the system (turbine + generator losses) (dimensionless)
This equation shows that hydro power is directly proportional to flow (Q) and head (H). That means:
More water flow → more power Greater height → more power
However, in real systems, not all the energy is converted into electricity. Some energy is lost due to friction, turbulence, and mechanical inefficiencies. That is why an efficiency factor (η) is included in the equation.
From an academic point of view, hydro energy estimation is not only about using this formula. It also involves studying natural conditions such as rainfall, river flow variation, seasonal changes, and storage capacity of reservoirs. These factors help engineers estimate how much energy can be generated throughout the year, not just at one moment.
In summary, the fundamental of hydro energy estimation is based on a simple concept. Energy from water depends on how much water is available and how far it can fall.
By combining physical laws with real-world hydrological data, engineers can estimate the potential of hydro-power projects in a reliable and scientific manner.

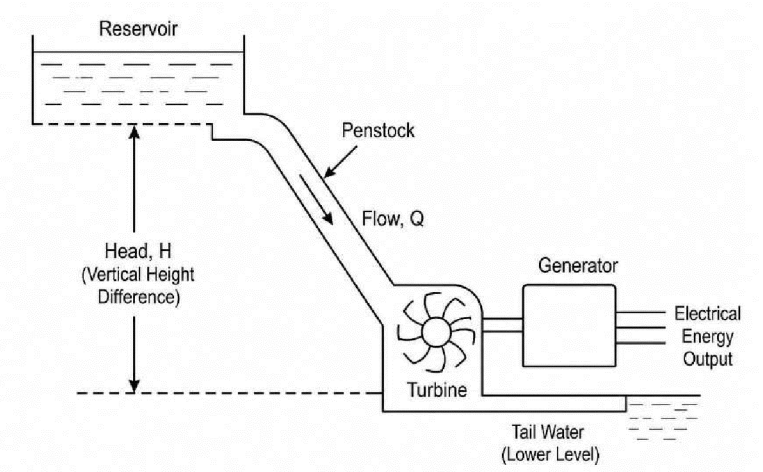


Figure 6.2: Basic hydro-power system showing effective head (H), discharge (Q), and conversion of water energy into electrical energy.

6.5 COMPONENTS OF A HYDROPOWER SYSTEM

A hydropower system is a combination of structures and equipment used to convert the energy of flowing or stored water into electrical energy. Water stored at a higher level possesses potential energy. When it is allowed to flow downward, this potential energy is converted into kinetic energy. This moving water drives turbines, which in turn generate electricity.
To ensure that this energy conversion process is efficient, controlled, and continuous, several important components are required. Among these, dams, reservoirs, intake

structures, and penstocks are the most basic and essential parts of a hydropower system.

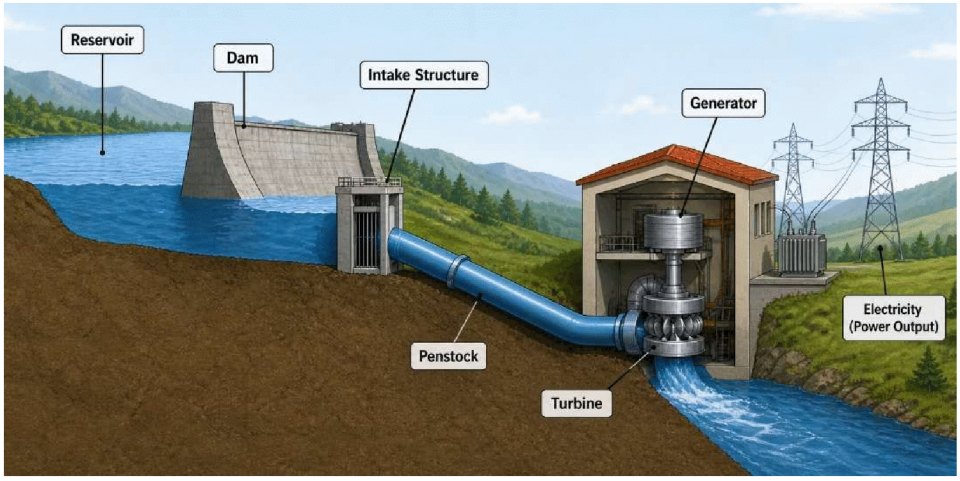


Figure 6.3:Components of a Hydropower system

6.5.1 Dams and Reservoirs

A dam is a large structure built across a river or stream to stop or regulate the flow of water. It is generally constructed using materials such as concrete, earth, or rock. The main function of a dam in a hydropower system is to store water and create a height difference, known as the head, which is necessary for generating power. In simple terms, a dam acts like a barrier that holds water at a higher level so that its stored energy can be used when required.

Dams perform several important functions in hydropower systems. They store large quantities of water and create a difference in water level, which is essential for energy generation. They also help control river flow, especially during floods, and ensure a continuous supply of water even during dry seasons. Because of these functions, dams are not only important for electricity generation but also for irrigation, flood control, and water supply.

A reservoir is the artificial lake or water body formed behind a dam. It stores water collected from rainfall, rivers, and streams. In simple terms, a reservoir can be understood as a very large water storage tank.

Reservoirs play a vital role in hydropower systems. They store energy in the form of water and allow controlled release of water, ensuring steady and reliable power generation. They also help manage seasonal variations in water availability, thereby improving the efficiency and reliability of the power plant. Without a reservoir, electricity generation would depend entirely on the natural flow of rivers, which is often irregular and unreliable.

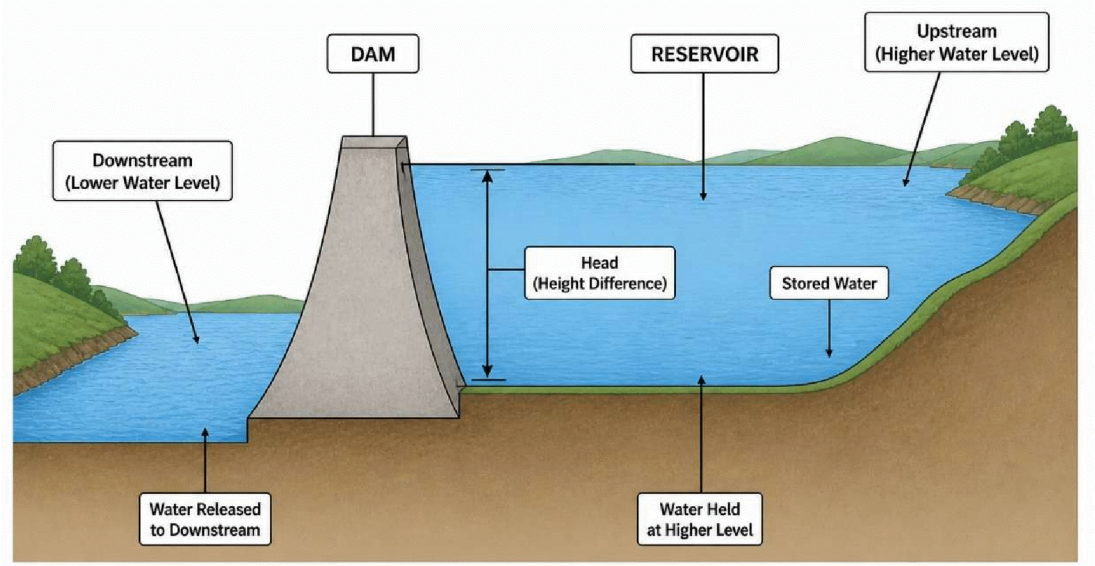


Figure 6.4:Dam and reservoir of a Hydropower system

6.5.2 Intake Structures and Penstocks

An intake structure is the point through which water from the reservoir enters the hydropower system. It is specially designed to control, regulate, and filter the flow of water before it reaches the turbine.

The intake structure performs several important functions. It controls the amount of water entering the system with the help of gates or valves. It also prevents debris, sediments, and floating materials from entering by using screens. Additionally, it ensures smooth and safe flow of water into the penstock and helps maintain proper flow conditions for efficient turbine operation. In simple terms, the intake acts like a gatekeeper that allows only clean and controlled water to enter the system.

A penstock is a large pipe or conduit that carries water from the intake structure to the turbine. It is usually made of steel or reinforced concrete and is designed to withstand high pressure.

Penstocks transport water efficiently from the reservoir to the turbine while maintaining high pressure and velocity, which are necessary to rotate the turbine. They are also designed to minimize energy losses due to friction. In simple terms, a penstock acts like a pipeline that delivers high-energy water to the turbine.

Penstocks have several important features. They are strong and leak-proof to handle high pressure. They may include valves and control systems to ensure safety, and their design ensures that energy loss during water flow is kept to a minimum.

Figure 6.5 illustrates the intake structure and penstock arrangement in a hydropower system. It shows the entry of water through the intake and its controlled flow into the penstock. The diagram also depicts the movement of water under pressure towards the turbine.

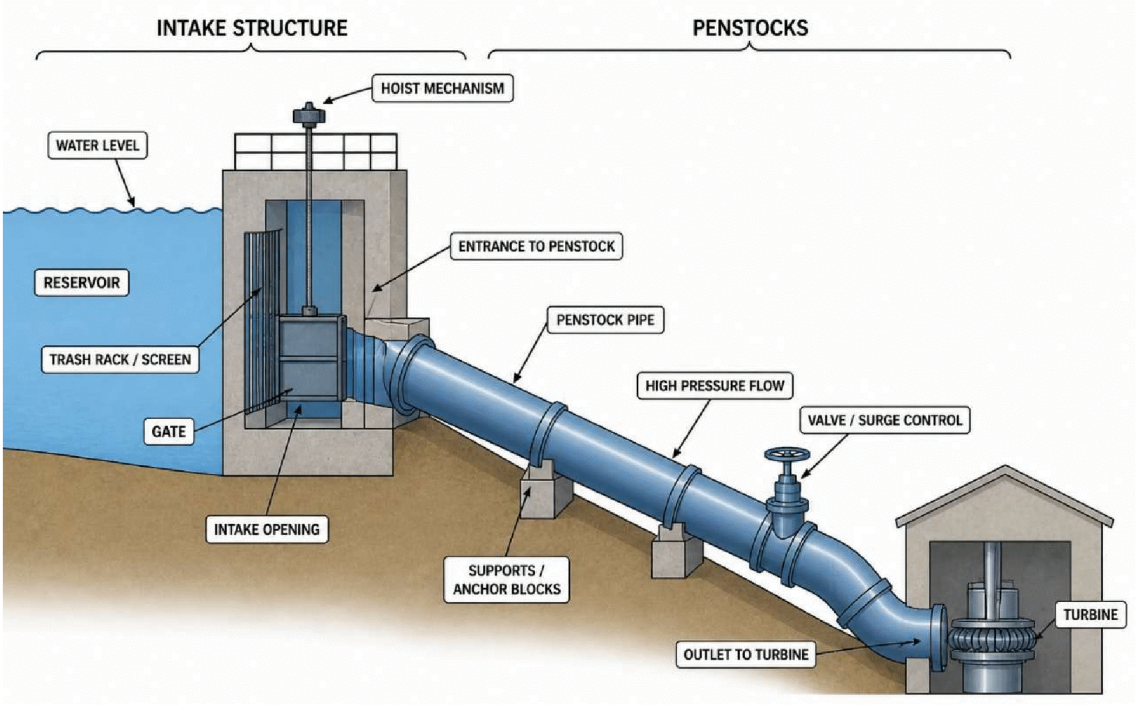


Figure 6.5: Intake structure and penstocks of a Hydropower system

6.6 HYDROPOWER TECHNOLOGIES

Hydropower technology converts the energy of flowing or falling water into electrical energy using turbines and generators. Hydropower plants are classified in different ways, such as based on the method of water utilization (run-of-river, storage, diversion, and pumped storage) or based on their installed generating capacity. In this unit, the classification based on installed generating capacity is discussed, namely small, medium, and large hydropower systems, along with pumped storage and micro-hydro technologies. These technologies differ in their design, infrastructure requirements, operational characteristics, environmental impacts, and applications.

6.6.1 Small, Medium, and Large Hydro Systems

Depending on the installed generating capacity, hydropower plants are generally classified into small, medium, and large hydro systems. These systems differ in their scale, infrastructure requirements, environmental impact, and applications.

Small Hydropower Systems

Small hydropower systems generally have an installed capacity of up to 10 MW, although the classification may vary slightly across countries and regulatory authorities. These systems are usually developed on small rivers, streams, canals, and existing water distribution structures where sufficient water flow is available for electricity generation. Most small hydro plants operate as run-of-river systems, which require little or no water storage reservoir. This reduces environmental and ecological impacts. Due to their relatively simple design and smaller infrastructure requirements, small hydropower projects involve lower capital investment and shorter construction periods compared to large hydroelectric plants. A small hydropower plant consists of an intake

structure, penstock, turbine, generator, control unit, and tailrace channel for returning water back to the river.

The operation process of small hydropower technology is continuous and automatic with minimum human intervention. The of flow of operation is illustrated in figure 6.6 (a).

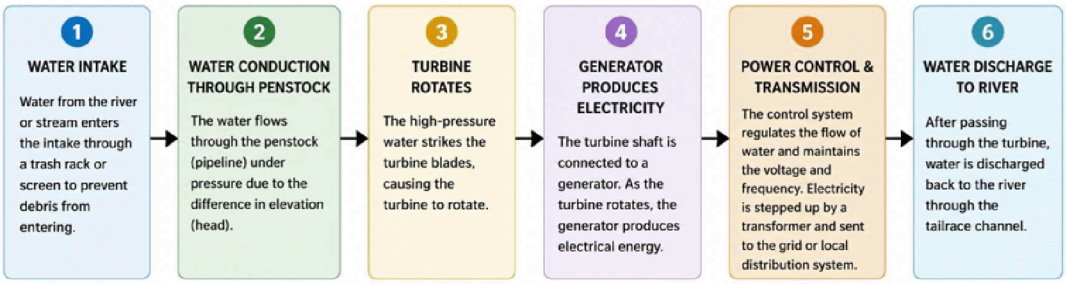


Figure 6.6 (a): Schematic Illustration of the Process Flow in a Small Hydropower Plant

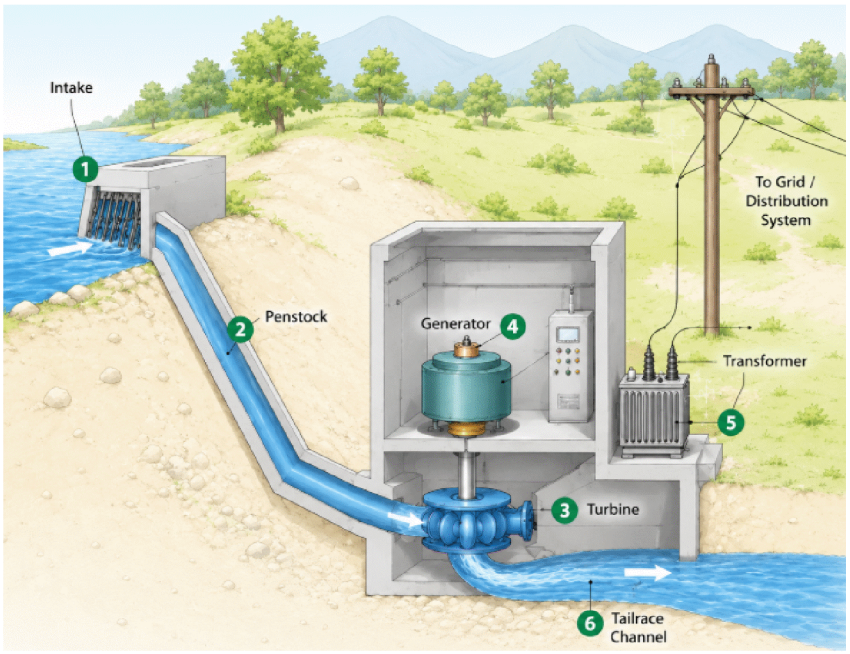


Figure 6.6 (b): Small hydropower system

Small hydro plants are widely used for rural electrification, agricultural water pumping, community-based power supply, mini-grid systems, and isolated energy networks. However, their electricity generation capacity is limited and strongly dependent on seasonal water availability and river flow conditions. Consequently, small hydropower systems may not be sufficient for supporting large industrial or urban electricity demands.

Medium Hydropower Systems

Medium hydropower systems generally have an installed capacity ranging from 10 MW to 100 MW and are mainly used for regional electricity generation. These plants are commonly developed on rivers with moderate water flow and often include medium-sized reservoirs to maintain a stable and continuous power supply. Medium hydro plants are usually connected to regional power grids and require moderate civil infrastructure such as dams, penstocks, turbines, generators, and transmission

systems. The operation process of medium hydropower technology is continuous and controlled manner. The flow of operation is illustrated in figure 6.7 (a).

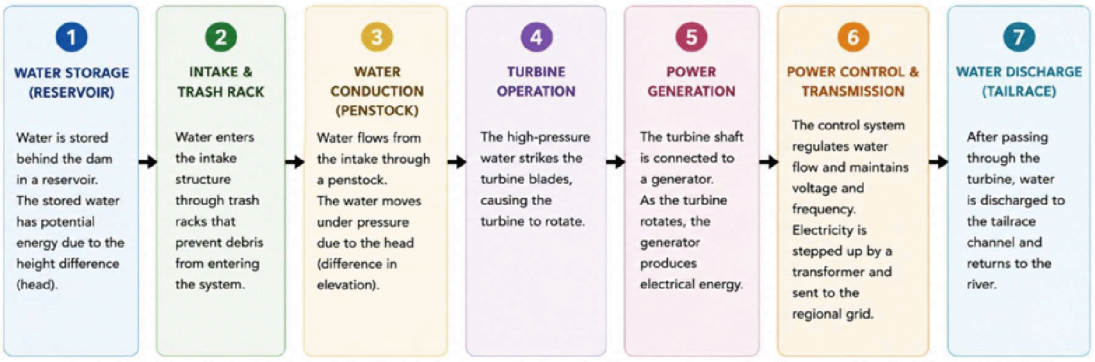


Figure 6.7 (a): Schematic Illustration of the Process Flow in a Medium Hydropower Plant

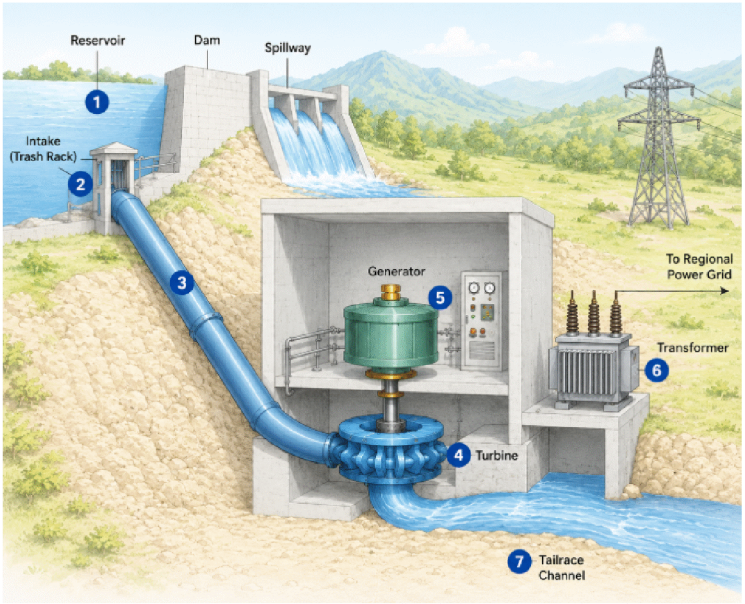


Figure 6.7 (b): Medium hydropower system

Medium hydropower plants offer higher efficiency and greater energy output than small hydro systems. It provides better grid stability and reliable electricity supply for industrial, commercial, and urban applications. They also have comparatively lower environmental impacts than large hydropower projects. However, these systems involve higher construction and maintenance costs and may cause ecological disturbances in river ecosystems. Medium hydropower technology is widely used for regional power generation and grid-connected renewable energy applications.

Large Hydropower Technology

Large hydropower systems generally have an installed capacity exceeding 100 MW and are major sources of national electricity generation. These plants use large dams, reservoirs, and extensive civil infrastructure to convert the potential and kinetic energy of stored or flowing water into electrical energy. A large hydropower plant includes a dam, reservoir, spillway, penstock, turbine-generator units, powerhouse, and transmission system. Large reservoirs help regulate water flow, ensuring reliable long-term operation and continuous power supply. The operation process of large

hydropower technology is continuous and carried out in an efficient manner. The flow of operation is illustrated in figure 6.8(a).

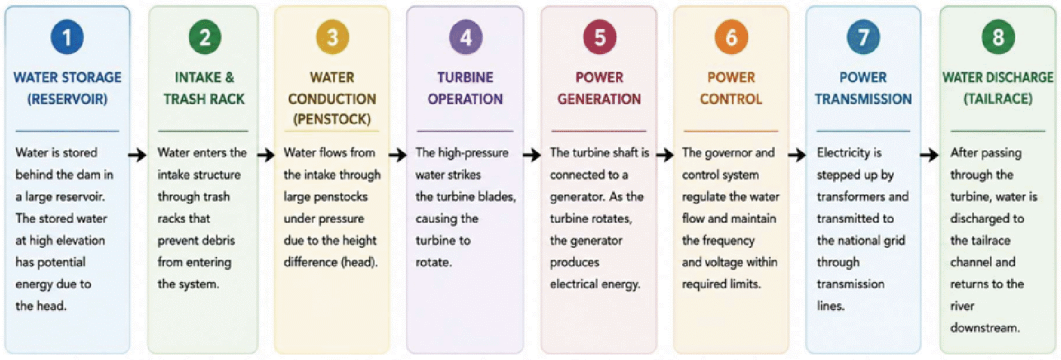


Figure 6.8 (a): Schematic Illustration of the Process Flow in a Large Hydropower Plant

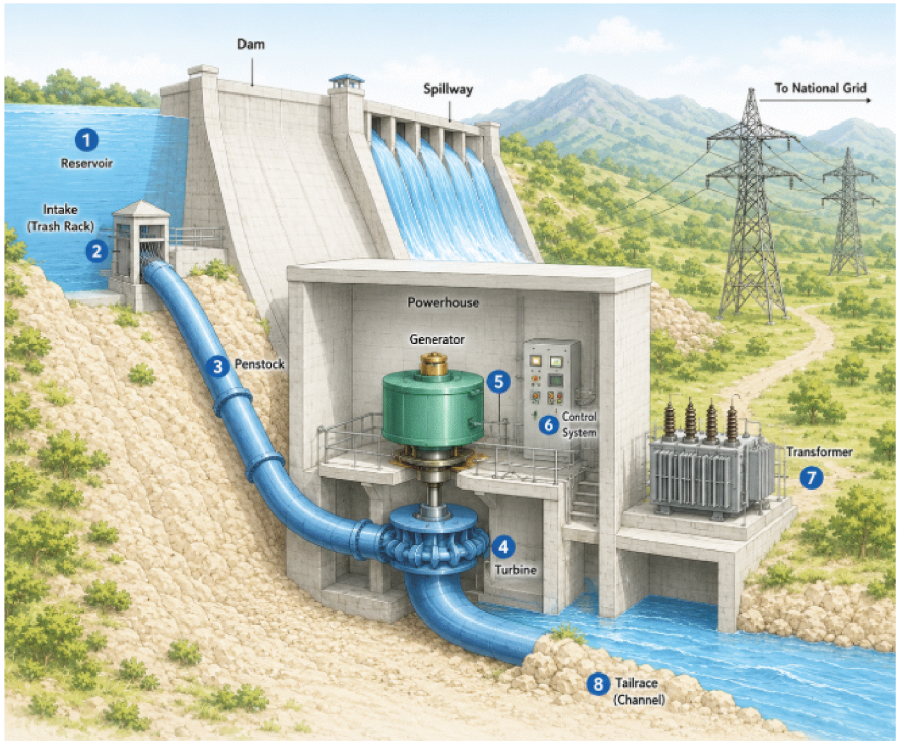


Figure 6.8 (b): Large hydropower system

Large hydropower technology offers several advantages, including very high electricity generation capacity, reliable base-load and peak-load power supply, and support for additional functions such as flood control, irrigation, water supply, and pumped hydro energy storage. However, these projects require very high capital investment and cause significant environmental and ecological impacts, such as land submergence, displacement of local communities, and alteration of river ecosystems. Large hydropower plants are widely used for national grid power generation, industrial electricity supply, and multipurpose water resource management. Examples of large hydropower plants in India include the Bhakra Nangal, Tehri, Nathpa Jhakri, and Subansiri Lower Hydroelectric Projects.

6.6.2 Pumped Storage and Micro Hydro

Pumped storage hydropower is a type of hydroelectric energy storage technology used to balance electricity demand and supply in power systems. It operates using two reservoirs located at different elevations. During periods of low electricity demand, excess electrical energy from the grid is used to pump water from the lower reservoir to the upper reservoir. During peak demand periods, the stored water is released back to the lower reservoir through turbines, which generats electricity.

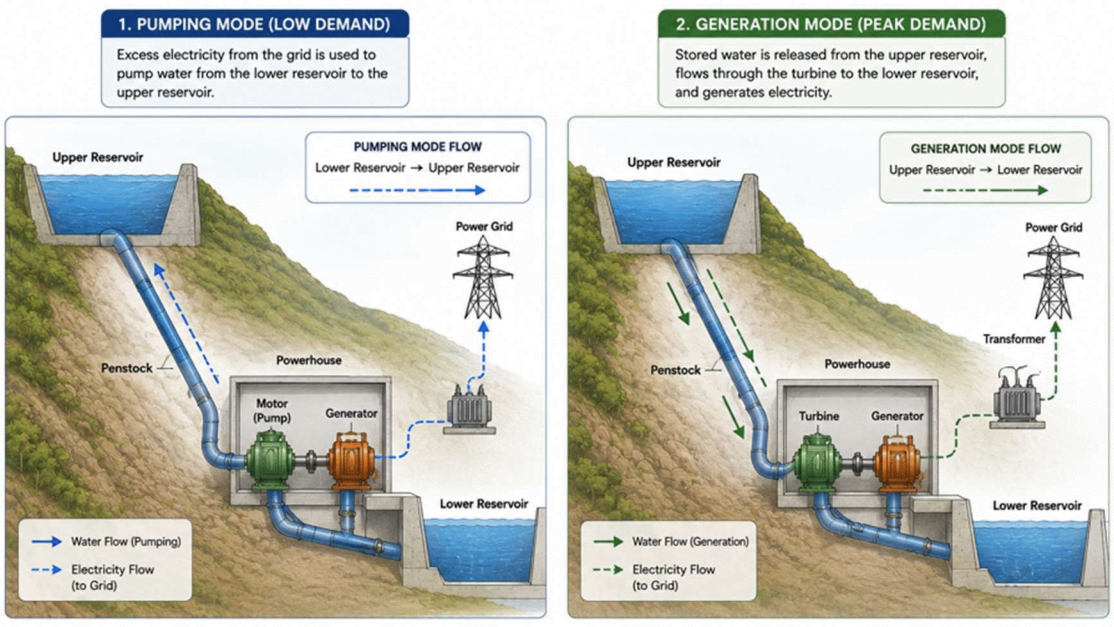


Figure 6.9: Pumped storage hydropower system with two operating modes

A pumped storage system mainly consists of upper and lower reservoirs, pumps, turbines, generators, penstocks, and control systems. These systems provide several advantages such as large-scale energy storage, improved grid stability, peak-load power supply, and support for integrating renewable energy sources such as solar and wind power. However, pumped storage projects require high initial investment, suitable geographical conditions, and large land and water resources. Pumped storage hydropower is widely used for energy storage, load balancing, frequency regulation, and emergency power support in modern electrical grids.

Micro Hydropower Systems

Micro hydropower systems are small-scale hydroelectric plants with a capacity of typically less than 100 kW. They generate electricity by harnessing the energy of flowing water from small rivers, streams, or irrigation canals. Most systems operate as run-of-river schemes with minimal or no water storage. A micro hydropower systems are simple in design, require relatively low capital investment, and have low operation and maintenance costs. This system is widely used for rural electrification, household power supply, battery charging, agricultural activities, and standalone community energy systems.

6.7 HYDRO TURBINES

A **hydro turbine** is a machine used in hydropower plants to convert the energy of flowing or falling water into mechanical energy. This mechanical energy is then converted into electrical energy with the help of a generator. Thus, the hydro turbine serves as the main energy-converting device in a hydropower plant and plays a vital role in determining the efficiency of electricity generation. The working of a hydro turbine is simple. Water stored in a reservoir flows through the penstock towards the turbine. As the water strikes or passes through the turbine runner (blades), it causes the runner to rotate. This rotating motion is transferred to the generator through a shaft, producing electricity. After passing through the turbine, the water is discharged back into the river through the tailrace.

Hydro turbines are mainly classified into impulse turbines and reaction turbines, depending on the way they convert the energy of water.

Impulse Turbines

Impulse turbines use the kinetic energy of a high-speed jet of water to rotate the turbine runner. In these turbines, water strikes the buckets of the runner at atmospheric pressure. The Pelton turbine is the most common example of an impulse turbine. It is suitable for regions where the water falls from a great height but the water flow is relatively small.

Reaction Turbines

Reaction turbines operate using both the pressure energy and kinetic energy of flowing water. In these turbines, water flows over the runner while remaining under pressure. The Francis turbine is commonly used for medium-head hydropower plants, whereas the Kaplan turbine is suitable for low-head plants with high water flow. These turbines are widely used in medium and large hydropower stations.

The choice of a hydro turbine depends mainly on the available water head, the rate of water flow, and the power required. Selecting the appropriate turbine helps improve the efficiency and performance of the hydropower plant.

Hydro turbines offer several advantages. They have high efficiency, require low operating and maintenance costs, provide reliable performance, and have a long service life. Because of these advantages, hydro turbines are widely used in small, medium, large, and pumped-storage hydropower plants.

6.7.1 Pumped Hydro Energy

Pumped hydro energy is a large-scale energy storage method that stores electrical energy in the form of the gravitational potential energy of water. Unlike conventional hydropower plants, which only generate electricity from flowing water, pumped hydro systems can both store and generate electrical energy, making them an important component of modern power systems.

The system operates using two reservoirs located at different elevations and a reversible pump-turbine. When surplus electricity is available, the pump-turbine transfers water from the lower reservoir to the upper reservoir, storing energy. When electricity demand is high, the stored water is released back to the lower reservoir through the same pump-turbine, which then operates as a turbine to drive a generator and produce electricity. Modern pumped hydro systems typically achieve a round-trip efficiency of about 70–85%, making them one of the most efficient technologies for

large-scale energy storage. They help balance electricity demand and supply, improve grid stability, provide backup power, and facilitate the integration of renewable energy sources such as solar and wind.

In summary, pumped hydro energy is an effective energy storage technology that enhances the reliability, flexibility, and stability of modern electrical power systems.

6.8 ENVIRONMENTAL IMPACT OF HYDROPOWER APPLICATIONS

Hydropower is a renewable source of energy that produces very low greenhouse gas emissions during operation, making it a cleaner alternative to fossil fuel-based power generation. However, depending on the size and design of a project, it can have both environmental and social impacts.

Small and micro-hydropower plants, especially run-of-river systems, generally have lower environmental impacts because they require little or no water storage. However, they may affect local aquatic habitats and alter natural river flow if not properly designed.

Large hydropower projects can significantly modify river ecosystems. Dams may obstruct the migration of fish, although fish ladders are often provided to help fish move upstream. Reservoirs can also trap sediments, reducing storage capacity and affecting downstream ecosystems. In some cases, the decomposition of submerged vegetation in reservoirs may release methane, a greenhouse gas.

Large reservoirs may also influence water quality by changing water temperature and dissolved oxygen levels. In addition, the construction of large dams may require the rehabilitation and resettlement of local communities. Maintaining an adequate environmental flow is therefore essential to protect aquatic life and ensure sufficient water availability downstream.

CHECK YOUR PROGRESS

Q1: What are hydropower resources?
Q2: What factors affect hydro energy estimation?
Q3: What is the function of a dam?
Q4: Define a penstock?
Q5: What is a small hydropower system?
Q6: What is pumped storage hydropower?
Q7: What is a hydro turbine?
Q8: What is one environmental impact of hydropower?

6.9 LET US SUM UP

- Hydropower resources utilize the kinetic and potential energy of flowing or falling water to generate electricity.
- The fundamental estimation of hydro energy depends mainly on water head, flow rate, gravity, and turbine efficiency.

- Hydropower systems convert water energy into mechanical energy using turbines and then into electrical energy using generators.
- Dams and reservoirs are used to store water, regulate river flow, and ensure continuous electricity generation.
- India has several major hydropower projects, including the Bhakra Nangal, Tehri, Nathpa Jhakri, and Subansiri Lower projects, which contribute significantly to renewable electricity generation.
- Intake structures control the entry of water into the system, while penstocks carry high-pressure water to the turbines.
- Small hydropower systems generally have capacities up to 10 MW and are suitable for rural and decentralized electricity supply.
- Medium hydropower systems range from 10 MW to 100 MW and are mainly used for regional power generation and grid support.
- Large hydropower systems exceed 100 MW and provide large-scale electricity generation for national power grids.
- Pumped storage hydropower stores energy by pumping water to an upper reservoir during low demand and generating electricity during peak demand.
- Hydro turbines such as Pelton, Francis, and Kaplan turbines convert the energy of flowing water into rotational mechanical energy for electricity generation.

6.10 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Hydropower resources are sources of energy obtained from flowing water.

Ans to Q2: Water head, flow rate, and efficiency affect hydro energy estimation.

Ans to Q3: A dam stores and controls water for power generation.

Ans to Q4: A penstock is a pipe that carries water to the turbine.

Ans to Q5: A small hydropower system has acapacityup to 10 MW.

Ans to Q6: It stores energy by pumping water to an upper reservoir.

Ans to Q7: A hydro turbine converts water energy into mechanical energy.

Ans to Q8: Large hydro power projects may disturb river ecosystems.

6.11 FURTHER READING

- Hydropower Engineering Handbook
  Mosonyi, E. (1991). *Hydropower engineering handbook* (Vol. 1). AkademiaiKiado.
- Hydroelectric Energy
  Paish, O. (2002). Hydroelectric power: Technology and current status. *Renewable and Sustainable Energy Reviews,* 6(6), 537–556. https://doi.org/10.1016/S1364-0321(02)00006-0
- International Hydropower Association
  International Hydropower Association. (2023). 2023 hydropower status report. https://www.hydropower.org/publicationsRenewable Energy Resources

Twidell, J., & Weir, T. (2015). *Renewable energy resources* (3rd ed.). Routledge.

- Power Generation Technologies
  Paul Breeze. (2019). *Power generation technologies* (3rd ed.). Newnes.
- United States Department of Energy
  U.S. Department of Energy. (2022). Hydropower basics. https://www.energy.gov/eere/water/hydropower-basics
- Central Electricity Authority (CEA). (Year). Hydro *Electric Potential and Development Status in India.* Ministry of Power, Government of India.
- Ministry of New and Renewable Energy (MNRE). (Latest edition). Small Hydro Power Programme. Government of India.

6.12 MODEL QUESTIONS

Q1: Explain the concept of hydropower resources and their importance in renewable energy generation.
Q2: Discuss the fundamental principles involved in hydro energy estimation.
Q3: Describe the major components of a hydropower system with their functions.
Q4: Explain the role of dams and reservoirs in hydropower generation.
Q5: Discuss the operation and importance of intake structures and penstocks in hydropower plants.
Q6: Compare small, medium, and large hydropower systems based on capacity and applications.
Q7: Explain the working principle of pumped storage and micro-hydropower systems.
Q8: Describe the construction, working, and types of hydro turbines used in hydropower plants

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UNIT 7: BIOENERGY

UNIT STRUCTURE

7.1 Learning Objectives
7.2 Introduction
7.3 Introduction to Bioenergy
7.3.1 Biomass
7.3.2 Biofuels
7.4 Potential of Bioenergy
7.5 Sources of Bioenergy
7.6 Bioenergy Fuels
7.6.1 Characteristics and Applications
7.7 Environmental and Economic Aspect of Bioenergy
7.8 Let Us Sum Up
7.9 Answers to Check Your Progress
7.10 Further Reading
7.11 Model Questions

7.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- Explain the concept of bioenergy and biomass resources
- Describe different bioenergy conversion technologies
- Apply biomass-to-energy conversion processes and estimate biogas yield from different biomass sources.
- Analyze the socio-economic and environmental impacts of bioenergy.
- Evaluate the role of bioenergy in sustainable development and recommend bioenergy based solutions for local applications.

7.2 INTRODUCTION

In the previous unit, you learned about hydro energy as a renewable source of power. In this unit, you will learn about **bioenergy**, its importance, and the concept of biofuels. he unit will also introduce the potential and various sources of bioenergy. You will also explore different bioenergy fuels along with their characteristics and applications. You will also study the environmental and economic aspects of bioenergy. By the end of this unit, you will have a clear understanding of how biomass can be converted into useful energy and its significance as a renewable energy resource.

7.3 INTRODUCTION TO BIOENERGY

Bioenergy is one of the most widely used forms of renewable energy across the world. It is usually generated from biological materials which are collectively known as

biomass, and includes plants, agricultural residues, forest products, and various types of organic waste. Since these materials are naturally replenished through biological processes, bioenergy is considered a renewable and sustainable energy source when managed properly. The use of biomass as a source of energy dates back to early human civilization, when wood and other organic materials were burned for cooking, heating, and lighting. With advancements in science and technology, biomass can now be converted into modern forms of energy such as electricity, liquid fuels, and gaseous fuels. As a result, bioenergy has become an important component of the global renewable energy system.

Bioenergy can be described as a source of energy which is obtained from natural resources which are of biological origin. It can be defined as the energy obtained from biomass or organic matter of biological origin. Biomass includes renewable organic materials derived from plants, animals, and their by-products. However, materials that have been converted into fossil fuels through long geological processes are not considered biomass.

Sources of Bioenergy: Bioenergy can be produced from a wide variety of biomass resources. Major sources include forestry residues, agricultural crops and wastes, animal manure, municipal solid waste, and specially cultivated energy crops grown for fuel production. These materials contain organic compounds such as carbohydrates, fats, and cellulose that can be converted into energy through different technological processes. The main categories of biomass feedstocks used in bioenergy production include lipids, sugars or starches, and lignocellulosic materials. Lipids such as vegetable oils are commonly used for producing biodiesel, whereas sugars and starches are typically converted into ethanol. Lignocellulosic materials obtained from plant stems, leaves, and wood can also be processed into advanced biofuels and other forms of energy.

Importance of Bioenergy: Bioenergy plays a significant role in the global energy system and contributes a considerable share of the world's renewable energy supply. It is widely used for heating, electricity generation, and transportation fuels. In many developing countries, traditional biomass such as firewood, charcoal, and agricultural residues continues to serve as an essential energy source for household cooking and heating.

In recent years, modern bioenergy technologies have gained importance as alternatives to fossil fuels. By replacing coal, oil, and natural gas with biomass-based fuels, bioenergy can help reduce greenhouse gas emissions and contribute to climate change mitigation. Furthermore, bioenergy supports rural development and energy security by creating opportunities for local energy production and by converting organic waste materials into useful energy products.

7.3.1 Biomass

Biomass refers to the renewable organic material derived from plants, animals, and their by-products. It includes resources such as wood, agricultural crops and residues, animal manure, algae, and organic components of municipal waste. Biomass sources stores energy from the sun through photosynthesis, which can later be converted into useful forms of energy. Since, biomass can be replenished naturally over time, it is considered an important renewable energy resource. Biomass used for energy

production may come from forestry residues, agricultural wastes, or specially grown energy crops.

7.3.2 Biofuels

Biofuels are described as a form of fuels produced from various sources of biomass and can be found to exist in solid, liquid, or gaseous forms. They are used to generate heat, electricity, and transportation energy. Some of the common examples of biofuels include bioethanol, biodiesel, and biogas. Biofuels are produced through various processes such as fermentation, gasification, and anaerobic digestion of organic materials. These fuels are considered more sustainable than fossil fuels because they can reduce greenhouse gas emissions and help decrease dependence on non-renewable energy sources.

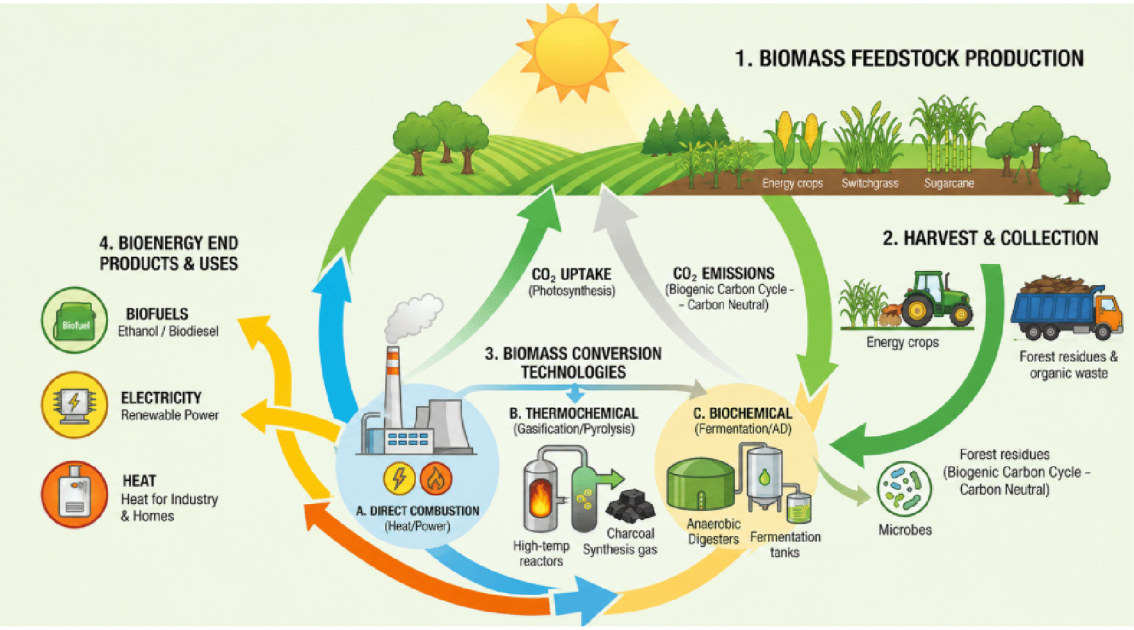


Figure 7.1: Generation of bioenergy from biomass and the bioenergy cycle

7.4 POTENTIAL OF BIOENERGY

Bioenergy refers to energy derived from biomass such as agricultural residues, forest products, organic wastes, and dedicated energy crops. It is considered one of the most important renewable energy sources and currently contributes significantly to the global energy supply. Biomass energy accounts for a considerable share of the world's renewable energy and continues to play an important role in meeting the growing demand for heat, electricity, and transportation fuels.

One of the major potentials of bioenergy lies in the abundant availability of biomass resources. Biomass can be obtained from a wide range of sources including agricultural residues (such as crop straw and husks), forestry residues, organic wastes from industries, and municipal solid waste. Dedicated energy crops such as switchgrass, poplar, and willow can also be cultivated specifically for energy

production. These diverse feedstocks provide a large and sustainable resource base for bioenergy development.

Studies indicate that the global technical potential of biomass for energy production could reach about 500 EJ (exajoule) per year by 2050, although actual deployment may range between 100 and 300 EJ per year depending on technological, economic, and policy conditions. If this potential is realized, bioenergy could make a significant contribution to global energy demand and help diversify the energy supply.

Bioenergy also has considerable potential for climate change mitigation. When biomass is produced and used sustainably, it can reduce greenhouse gas emissions by replacing fossil fuels such as coal, oil, and natural gas. Some advanced bioenergy systems can achieve 80–90% reduction in greenhouse gas emissions compared to conventional fossil fuels. In addition, biomass cultivation can increase carbon storage in soils and vegetation, particularly when grown on degraded or marginal lands.

Another important potential of bioenergy is its role in rural development and economic growth. The production, harvesting, transportation, and processing of biomass create employment opportunities in rural areas. Bioenergy supply chains are often more labour-intensive than fossil fuel systems, providing income opportunities for farmers and rural communities. Moreover, using locally available biomass resources can reduce dependence on imported fossil fuels and enhance national energy security.

Bioenergy also contributes to efficient waste management and resource utilization. Organic wastes from households, agriculture, and industries can be converted into energy through processes such as anaerobic digestion and biofuel production. This not only produces renewable energy but also reduces environmental pollution, methane emissions, and waste disposal problems. Despite its large potential, the development of bioenergy must be carefully managed. Issues such as land use competition with food production, water use, biodiversity impacts, and sustainability of biomass supply need to be addressed. Proper land management, improved agricultural productivity, and sustainable policies are necessary to ensure that bioenergy development does not negatively affect ecosystems or food security

7.5 SOURCES OF BIOENERGY

Bioenergy is the energy obtained from biomass, which includes organic materials derived from plants, animals, and biological wastes. Biomass stores solar energy through the process of photosynthesis and can be converted into useful forms of energy such as heat, electricity, biogas, bioethanol, and biodiesel. The sources of bioenergy are diverse and widely available in nature, making bioenergy an important renewable energy resource.

One of the major sources of bioenergy is forestry biomass. Forests provide materials such as fuelwood, wood chips, sawdust, bark, and logging residues like branches and tree tops. These materials can be burned directly to produce heat and electricity or converted into solid biofuels such as charcoal and wood pellets. The pulp and paper industry also generates residues such as black liquor, which can be used for energy production.

Another important source is agricultural biomass. Agriculture produces large amounts of residues after harvesting crops. Examples include rice straw, wheat straw, corn

stover, bagasse from sugarcane, and husks. These residues can be used as fuel for power generation or converted into biofuels. In addition, some crops are grown specifically for energy production and are known as energy crops. These include sugarcane, corn, switchgrass, and miscanthus for bioethanol production, as well as oilseed crops such as soybean, sunflower, and oil palm for biodiesel production.

Animal waste is also an important source of bioenergy. Manure from livestock such as cattle, pigs, and poultry can be converted into biogas through anaerobic digestion. The biogas produced contains methane and can be used for cooking, heating, and electricity generation, especially in rural areas.

Municipal and industrial organic wastes also contribute significantly to bioenergy production. Organic fractions of municipal solid waste, food waste, sewage sludge, and waste from food processing industries can be converted into energy through processes such as anaerobic digestion, gasification, and combustion. Using these wastes for energy helps reduce environmental pollution and waste disposal problems.

Another emerging source of bioenergy is algae and aquatic biomass. Algae grow rapidly and can produce large amounts of oils that can be converted into biodiesel. Due to their high productivity, algae are considered a promising future source of renewable biofuels.

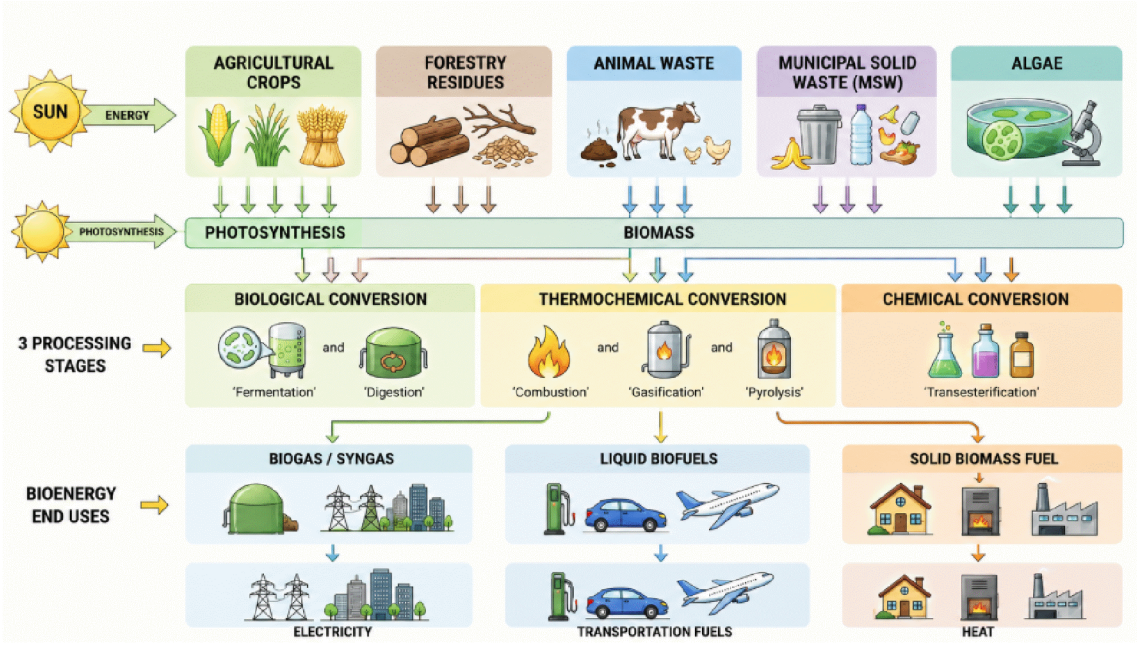


Figure 7.2: Generation of bioenergy from different sources

7.6 BIOENERGY FUELS

Bioenergy fuels, commonly known as biofuels, are fuels produced from biomass, which includes organic materials derived from plants, animals, and biological wastes. These fuels are considered renewable because the raw materials used for their production can be replenished naturally through biological processes such as photosynthesis. Bioenergy fuels are increasingly used as alternatives to fossil fuels for transportation, heating, and electricity generation because they help reduce greenhouse gas

emissions and dependence on non-renewable energy resources. One of the most widely used bioenergy fuels is bioethanol. Bioethanol is an alcohol produced through

the fermentation of sugars and starches present in crops such as sugarcane, corn, wheat, and cassava. It is commonly blended with gasoline to power vehicles and reduce harmful emissions. Countries such as Brazil and the United States widely use ethanol–gasoline blends as transportation fuel.

Another important bioenergy fuel is biodiesel, which is produced from vegetable oils, animal fats, or recycled cooking oils through a chemical process called transesterification. Common feedstocks for biodiesel production include soybean oil, sunflower oil, rapeseed oil, and palm oil. Biodiesel can be used directly in diesel engines or blended with petroleum diesel. It produces lower levels of pollutants such as sulfur oxides and particulate matter.

Biogas is another significant bioenergy fuel generated through the anaerobic digestion of organic wastes such as animal manure, agricultural residues, food waste, and sewage sludge. Biogas mainly consists of methane and carbon dioxide and can be used for cooking, heating, electricity generation, and even as vehicle fuel after purification.

Solid biofuels are also important forms of bioenergy fuels. These include firewood, charcoal, wood pellets, briquettes, and agricultural residues such as straw and husks. Solid biofuels are widely used for heating and cooking, especially in rural and developing regions. Modern technologies also allow these fuels to be used for large-scale electricity generation.

In recent years, advanced or second-generation biofuels have gained attention. These fuels are produced from non-food biomass such as lignocellulosic materials (e.g., crop residues, grasses, and wood waste) and algae. Examples include cellulosic ethanol and algal biodiesel. These advanced biofuels aim to overcome challenges related to food security and land use associated with first-generation biofuels.

7.6.1 Characteristics and Applications

One of the main characteristics of bioenergy fuels is that they are renewable, as the biomass used to produce them can be replenished naturally through processes like photosynthesis. Another important characteristic of bioenergy fuels is their environmental friendliness. Compared to fossil fuels, biofuels generally produce lower emissions of greenhouse gases, sulfur compounds, and particulate matter. Since the carbon released during combustion was previously absorbed by plants during growth, bioenergy fuels can contribute to a more balanced carbon cycle.

Bioenergy fuels are also biodegradable and less toxic, making them safer to handle and less harmful in case of spills. For example, biodiesel degrades faster in the environment compared to petroleum diesel. Many bioenergy fuels have good combustion properties, such as high oxygen content and cleaner burning characteristics. Bioethanol and biodiesel improve fuel combustion efficiency and reduce engine emissions. However, some biofuels may have slightly lower energy content than conventional fossil fuels. Another characteristic is their diversity of forms. Bioenergy fuels can exist as solid fuels (wood, charcoal, briquettes), liquid fuels (bioethanol, biodiesel), or gaseous fuels (biogas).

Applications of Bioenergy: Bioenergy fuels have a wide range of applications in different sectors. One of the most common applications is in transportation. Liquid biofuels such as bioethanol and biodiesel are blended with gasoline and diesel to power vehicles. Another important application is in electricity generation. Biomass and biogas can be used in power plants to generate electricity. Agricultural residues, wood pellets, and other biomass materials are burned or gasified to produce heat and power. Bioenergy fuels are also widely used for heating and cooking, particularly in rural and developing areas. Fuels such as firewood, charcoal, briquettes, and biogas are commonly used in households for domestic energy needs.
In addition, bioenergy fuels play a role in industrial energy supply. Industries such as the sugar and paper industries use biomass residues like bagasse and black liquor to generate heat and electricity for their operations. Another emerging application is in waste management and sustainable energy systems. Organic wastes from households, agriculture, and industries can be converted into biogas or other biofuels, helping reduce waste disposal problems while producing useful energy. Thus bioenergy fuels have important characteristics such as renewability, lower environmental impact, biodegradability, and versatility. Their applications include transportation, electricity generation, heating and cooking, industrial energy supply, and waste management. These features make bioenergy fuels a key component of sustainable and renewable energy systems.

7.7 ENVIRONMENTAL AND ECONOMIC ASPECT OF BIOENERGY

Bioenergy is a form of renewable energy derived from biomass such as agricultural residues, forest products, animal wastes, and organic municipal wastes. It plays an important role in the transition toward sustainable energy systems because it provides an alternative to fossil fuels while offering both environmental and economic benefits. However, its development must be managed carefully to ensure sustainability.

Environmental Aspects of Bioenergy
One of the most important environmental benefits of bioenergy is its potential to reduce greenhouse gas emissions. Biomass absorbs carbon dioxide from the atmosphere during plant growth through photosynthesis. When bioenergy fuels are burned, the carbon dioxide released is roughly equal to the amount previously absorbed by the plants, making the process closer to carbon-neutral compared with fossil fuels. Bioenergy also contributes to waste management and pollution reduction. Organic wastes from agriculture, households, and industries can be converted into useful energy through processes such as anaerobic digestion, gasification, and combustion. This reduces the amount of waste sent to landfills and decreases methane emissions from decomposing organic matter. Another environmental advantage is the reduction of air pollutants. Biofuels such as biodiesel and bioethanol generally produce lower emissions of sulfur dioxide, particulate matter, and other harmful pollutants compared with petroleum fuels. This can improve air quality and reduce health risks associated with air pollution.

Bioenergy production can also help in land restoration and soil improvement. Certain energy crops can be grown on degraded or marginal lands, helping to restore soil fertility and prevent soil erosion. In addition, the residues from bioenergy processes, such as digestate from biogas plants, can be used as organic fertilizers. However, there are also environmental challenges associated with bioenergy. Large-scale cultivation of energy crops may compete with food production for land and water resources. Deforestation and biodiversity loss may occur if forests are cleared to grow energy crops. Therefore, sustainable land management and careful planning are necessary to minimize these impacts.

Economic Aspects of Bioenergy

Bioenergy also has significant economic benefits. One of the main advantages is the creation of employment opportunities, especially in rural areas. The production, collection, transportation, and processing of biomass require labor, which can generate income for farmers and rural communities.

Another economic benefit is energy security. Many countries rely heavily on imported fossil fuels. By using locally available biomass resources, countries can reduce their dependence on imported energy and improve their energy independence. Bioenergy technologies such as biogas plants, biomass power plants, and biofuel production facilities can stimulate local economies by creating new industries and markets. These technologies can also promote technological innovation and investment in renewable energy sectors.

Despite these benefits, there are also economic challenges. The production of bioenergy sometimes requires significant initial investment in infrastructure and technology. In some cases, biofuels may also be more expensive than fossil fuels without government incentives or supportive policies. Therefore, bioenergy offers important environmental benefits such as reduced greenhouse gas emissions, improved waste management, and better air quality. Economically, it supports rural development, creates jobs, and enhances energy security. However, to fully realize these benefits, bioenergy must be developed in a sustainable and environmentally responsible manner.

CHECK YOUR PROGRESS

Q1: What is Bioenergy?
Q2: What is the difference between biofuels and biomass?
Q3: How bioenergy contributes to waste management?
Q4: What are bioenergy fuels?

7.8 LET US SUM UP

- Bioenergy is a renewable energy source produced from biomass.
- Biomass contain plants, agricultural residues, forest products, animal waste, and organic municipal waste.

- Biomass stores solar energy through photosynthesis which is converted into heat and electricity.
- Bioenergy fuels include bioethanol, biodiesel, biogas, and solid biofuels.
- The applications of bioenergy fuels include transportation, electricity generation, heating and cooking, industrial energy supply, and waste management.
- Bioenergy offers environmental benefits by reducing greenhouse gas emissions, improving waste management, lowering air pollution, and supporting climate change mitigation.

7.9 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Bioenergy is the energy which can be derived from any form of biomass or its metabolic by-products. Bioenergy comprises of heat, electricity, cooling, and transport fuels produced from biomass.

Ans to Q2: A biofuel is a solid, liquid, or gaseous energy carrier, based on biomass, that can provide heat, electricity, or transport services whereas biomass is renewable organic material that comes from plants and animals. Biomass as a source of energy can be obtained from wood, agricultural residues and waste materials, solid waste and animal and human manure and sewage.

Ans to Q3: Bioenergy contributes in various ways to waste management by converting organic wastes from agriculture, households and industries into useful energy. By conversion of the wastes, through various processes like anaerobic digestion and production of biofuels, it reduces waste accumulation, lowers methane emissions, controls pollution and helps in efficient utilization of resources for the benefit of humanity.

Ans to Q4: Major types bioenergy fuels include bioethanol, biodiesel, biogas, and solid biofuels.

7.10 FURTHER READING

- Thran, D. (2022), Bioenergy resource base, provision technologies and integration concepts in energy systems with net zero climate gas emissions,268,00014, 1-10, https://doi.org/10.1051/epjconf/202226800014.
- IEA Bioenergy Report (2023), How bioenergy contributes to a sustainable future, ISBN 979-12-80907-19-6.
- Williams, C.L.et al(2015), Introductio to Bioenergy, Bioenergy,1-37, http://dx.doi.org/10.1016/B978-0-12-407909-0.00001-8.

7.11 MODEL QUESTIONS

A. Very Short Answer Questions

i. Define bioenergy.
ii. What is biomass?
iii. Give two examples of biofuels.
iv. What is bioethanol?

v. What is meant by anaerobic digestion?
vi. Name two agricultural residues used for bioenergy production.
vii. What is biogas mainly composed of?
viii. Mention two sources of bioenergy.
ix. What are energy crops? Give one example.

B. Short Answer Questions

i. Explain the concept of bioenergy and its importance in the modern energy system.
ii. Write a short note on biomass as a renewable energy resource.
iii. Explain the production and uses of biogas.
iv. Write briefly about bioethanol and biodiesel.

C. Long Answer / Descriptive Questions

i. Discuss the role of bioenergy in sustainable development.
ii. Explain how bioenergy contributes to climate change mitigation and energy security.
iii. Discuss the potential of bioenergy in meeting global energy demand.
iv. Write a detailed note on bioenergy fuels such as bioethanol, biodiesel, biogas, and solid biofuels.

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UNIT 8: OCEAN ENERGY

UNIT STRUCTURE

8.1 Learning Objectives
8.2 Introduction
8.3 Ocean Energy Potential
8.4 Wave Energy Devices
8.5 Ocean Thermal Energy Conversion (OTEC) and Applications
8.6 Introduction to Osmotic Power
8.7 Let Us Sum Up
8.8 Answers to Check Your Progress
8.10 Further Reading
8.10 Model Questions

8.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- explain ocean energy and the different forms of ocean energy resources
- describe the principles and applications of wave energy conversion devices
- discuss the concept and working of Ocean Thermal Energy Conversion (OTEC) systems and applications
- illustrate the concept of osmotic power and its methods of energy generation

8.2 INTRODUCTION

In the previous unit, we discussed the bioenergy forms of renewable energy. In this unit, we will explore ocean energy potential, beginning with an introduction to various forms of ocean energy resources. The unit will then cover wave energy devices and their working principles. A discussion of Ocean Thermal Energy Conversion (OTEC) systems and their applications are also provided in this unit. Finally, the unit will conclude with the concept of osmotic power and the methods used for energy generation from salinity gradients. Finally, the unit will conclude with an assessment of the potential, applications, and challenges associated with ocean energy technologies.

8.3 OCEAN ENERGY POTENTIAL

Ocean energy is emerging as one of the most promising and sustainable renewable energy resources in the world. The oceans cover more than 70% of the Earth's surface and contain enormous reserves of energy in the form of tides, waves, ocean currents, thermal gradients, and salinity differences. With the growing demand for clean and sustainable energy, ocean energy is gaining global attention as a reliable alternative to fossil fuels. According to recent international renewable energy assessments, the theoretical global ocean energy potential is estimated to be several thousand terawatt-

hours (TWh) per year, which is sufficient to meet a significant portion of global electricity demand.

Ocean energy is a broad category that includes all forms of renewable energy obtained from the oceans and seas. It encompasses various energy sources such as tidal energy, wave energy, ocean thermal energy conversion (OTEC), ocean current energy, and salinity gradient energy. These energy sources utilize different natural processes occurring in the oceans to generate electricity. Tidal energy is a specific type of ocean energy that is produced from the periodic rise and fall of sea levels caused by the gravitational pull of the moon and the sun. We will discuss broadly the tidal energy in the next unit. Thus, ocean energy refers to all ocean-based renewable energy resources collectively.

Ocean Thermal Energy Conversion (OTEC) has significant potential in tropical and subtropical regions where the temperature difference between warm surface water and cold deep ocean water remains sufficiently high. It is estimated that OTEC could provide several thousand terawatt-hours of electricity annually. Unlike solar and wind energy, OTEC systems can operate continuously for 24 hours per day.

Ocean currents also contain large amounts of kinetic energy. Powerful and continuous currents such as the Gulf Stream have the potential to drive underwater turbines for electricity generation. In addition, salinity gradient energy, also known as blue energy, can be generated from the difference in salt concentration between seawater and freshwater at river estuaries. This source also has considerable untouched potential.

Thus, the overall potential of ocean energy is enormous because oceans are vast, renewable, and continuously replenished by natural processes. Ocean energy can contribute to global energy security, reduce carbon emissions, support coastal economies, and provide sustainable electricity to island and remote coastal communities. However, despite its huge potential, large-scale utilization is still limited by high costs, technological challenges, environmental concerns, and maintenance difficulties in harsh marine conditions.

8.4 WAVE ENERGY DEVICES

Wave energy devices are machines or systems designed to capture the kinetic and potential energy of ocean waves and convert it into electrical energy. Ocean waves are generated mainly by wind blowing over the surface of the sea, and they contain large amounts of renewable energy. Wave energy devices are considered environmentally friendly because they produce electricity without emitting greenhouse gases. These devices are generally installed near shorelines, offshore regions, or floating on the ocean surface depending on the design and operating principle.

There are several types of wave energy devices used for wave power generation. One of the most common devices is the Oscillating Water Column (OWC). In this system, ocean waves enter a partially submerged chamber and cause the water column inside the chamber to rise and fall. The movement of water compresses and decompresses the air above it, which drives an air turbine connected to a generator to produce electricity.

Another important type is the Point Absorber. This device consists of floating structures that move up and down with wave motion. The vertical movement operates hydraulic pumps or mechanical systems connected to electrical generators. Point absorbers are compact and can absorb energy from waves coming from different directions.

The Attenuator is a long floating device placed parallel to the direction of wave travel. As waves pass along the structure, different sections bend relative to each other, and this motion is converted into electrical energy through hydraulic systems. The **Pelamis wave energy converter** is a well-known example of an attenuator device.

An Overtopping Device captures wave energy by allowing waves to flow into an elevated reservoir above sea level. The stored water is then released through low-head turbines to generate electricity, similar to the operation of a small hydroelectric power plant.

Wave energy devices provide benefits such as clean and renewable power generation, minimal environmental pollution, and high energy potential. However, they also encounter challenges like high installation and maintenance costs, corrosion caused by seawater, and difficulties in operating under harsh ocean conditions.

> ***Pelamis Wave Energy Converter***: It is a floating wave energy device that converts the motion of ocean waves into electricity using connected cylindrical sections and hydraulic systems.

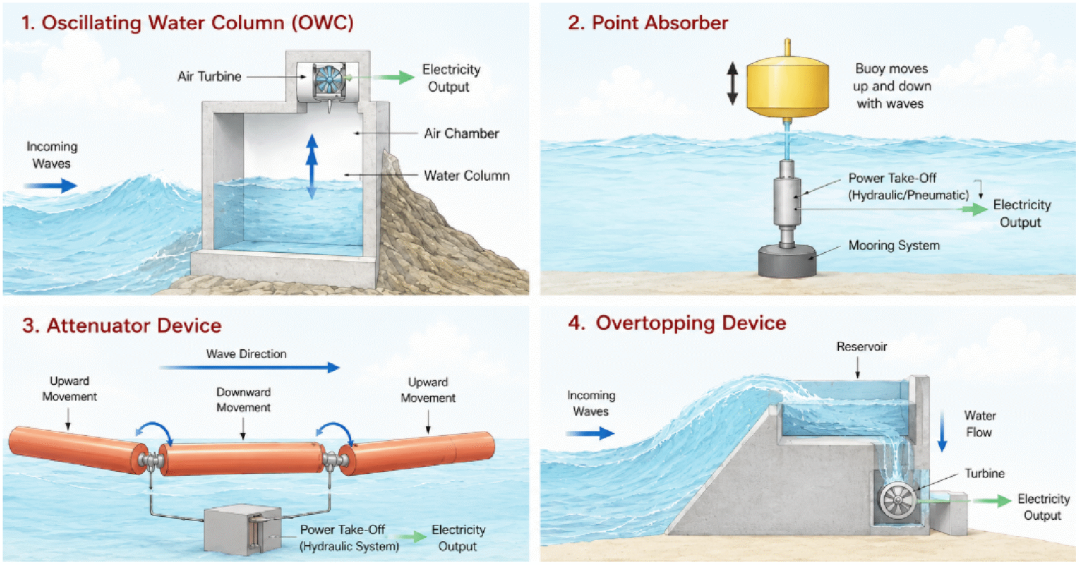


Figure 8.1: Types of wave energy devices

8.5 OCEAN THERMAL ENERGY CONVERSION (OTEC) AND APPLICATIONS

Ocean Thermal Energy Conversion (OTEC) is a technology that generates electricity by utilizing the temperature difference between the warm surface water and the cold deep seawater of the ocean. In tropical and subtropical regions, the surface seawater is heated by solar radiation to temperatures around 25-35°C, while deep ocean water at depths of about 800–1000 m remains cold at nearly 3-7°C. This temperature difference is used to operate a heat engine and produce electrical power.

The basic principle of OTEC is based on the thermodynamic cycle where heat flows from a high-temperature source to a low-temperature sink. Warm seawater acts as the heat source, whereas cold deep seawater acts as the heat sink. Since the temperature

difference is relatively small, OTEC systems require large volumes of seawater for continuous operation.

Working Principle of OTEC:

The main components of an Ocean Thermal Energy Conversion (OTEC) plant are the warm seawater intake system, heat exchanger (evaporator), working fluid (commonly ammonia), turbine and generator, condenser, cold deep seawater pipe, and pumping system. These components work together in a continuous thermodynamic cycle to generate electricity using the temperature difference between warm surface seawater and cold deep seawater.

In a closed-cycle OTEC plant, the warm seawater intake system draws warm surface water from the ocean and directs it to the evaporator or heat exchanger. Here, the thermal energy of the warm seawater is transferred to a low-boiling-point working fluid such as ammonia. Due to its low boiling temperature, the ammonia rapidly vaporizes and forms high-pressure vapour. This vapour then expands through a turbine connected to a generator, producing electricity. After passing through the turbine, the ammonia vapour enters the condenser, where cold deep seawater brought through a long cold-water pipe absorbs the heat from the vapour. As a result, the vapour condenses back into liquid form. The liquid ammonia is then recycled to the evaporator to repeat the cycle continuously. A pumping system maintains the continuous circulation of warm seawater, cold seawater, and the working fluid throughout the plant, thereby ensuring stable and efficient operation of the OTEC system.

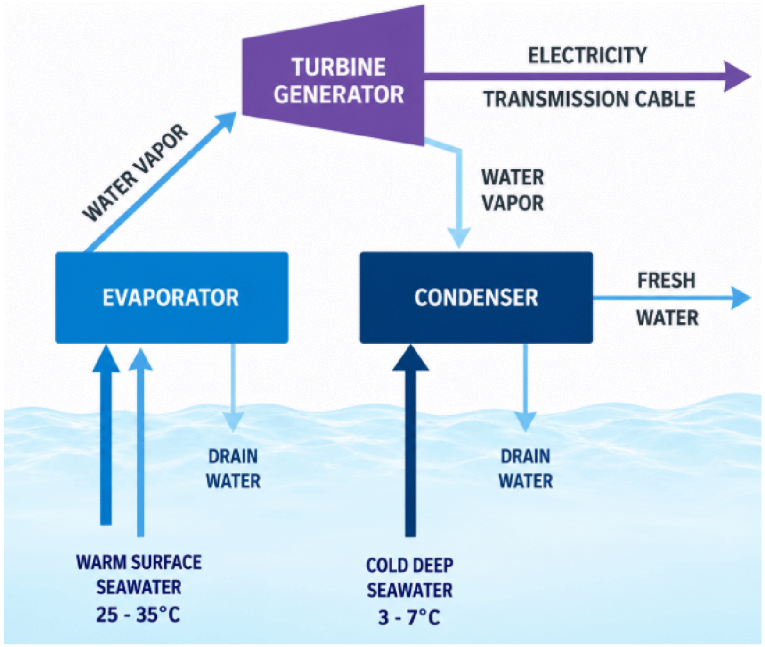


Figure 8.2: Schematic diagram of Ocean Thermal Energy Conversion technology

The OTEC can generate continuous power throughout the year because ocean temperature differences remain relatively stable. It is an environmentally friendly source of energy that produces clean electricity with very low greenhouse gas emissions. In addition to power generation, OTEC systems can also be used for useful applications such as desalination of seawater and air-conditioning, making it a versatile technology for coastal regions.

However, OTEC also has certain limitations that affect its large-scale adoption. The installation and maintenance costs are very high due to complex offshore structures and equipment. Its thermal efficiency is relatively low because the temperature difference between warm surface water and cold deep water is small. It can only be implemented in specific ocean locations where a sufficient temperature gradient exists. Moreover, OTEC plants require large and expensive underwater pipelines to bring cold water from deep ocean levels, which adds to the technical challenges and overall cost.

8.6 INTRODUCTION TO OSMOTIC POWER

Osmotic power, also known as salinity gradient energy or blue energy, is an emerging renewable energy technology that generates electricity from the difference in salt concentration between seawater and freshwater. This natural energy source is abundantly available at river mouths, estuaries, and coastal regions where freshwater mixes with seawater. Since the salinity difference exists continuously in nature, osmotic power has the potential to provide a stable and sustainable source of clean energy.

The working principle of osmotic power is based on the phenomenon of osmosis. When freshwater and seawater are separated by a semi-permeable membrane, water molecules naturally move from the low-salinity freshwater side to the high-salinity seawater side. The membrane allows only water molecules to pass while preventing salt ions from crossing. This movement of water creates osmotic pressure, which can be converted into mechanical and electrical energy.

One of the most promising methods of osmotic power generation is Pressure Retarded Osmosis (PRO). In a PRO system, freshwater is pumped into a chamber separated from seawater by a semi-permeable membrane. Due to osmotic action, freshwater permeates through the membrane into the seawater chamber, increasing its pressure. The resulting high-pressure saline water is then directed to a turbine connected to a generator, producing electricity. After passing through the turbine, the diluted seawater is discharged back into the sea.

The major components of an osmotic power plant include freshwater and seawater intake systems, semi-permeable membranes, pressure exchangers, pumps, turbines, generators, and outlet systems. Among these, the semi-permeable membrane is the most important component because the efficiency of the system largely depends on its permeability, selectivity, durability, and resistance to fouling. Recent advancements in membrane technology, nanomaterials, and energy recovery systems have significantly improved the performance and feasibility of osmotic power plants.

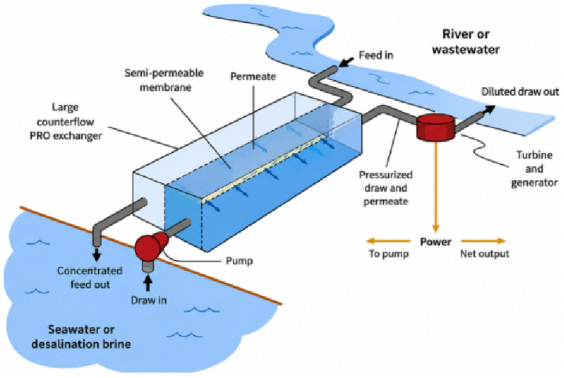


Figure 8.3: Schematic diagram of Osmotic power system

Osmotic power offers several advantages such as continuous energy production, absence of greenhouse gas emissions during operation, and minimal environmental impact compared to fossil-fuel-based power generation. In addition to electricity production, osmotic systems can also be integrated with desalination plants and wastewater treatment facilities to improve overall energy efficiency.
However, osmotic power technology still faces challenges including high membrane cost, membrane fouling, low energy conversion efficiency, and the requirement of suitable coastal locations with large freshwater discharge. Despite these limitations, ongoing research and technological developments indicate that osmotic power could become an important contributor to future renewable energy systems and sustainable coastal energy production.

CHECK YOUR PROGRESS

Q1: What is ocean energy and why is it important?
Q2: What are wave energy devices?
Q3: What is the basic principle of Ocean Thermal Energy Conversion (OTEC)?
Q4: What are the main applications of OTEC?
Q5: What is osmotic power?
Q6: What are the advantages of ocean energy resources?

8.7 LET US SUM UP

- Ocean energy is a vast renewable energy resource that includes wave energy, tidal energy, Ocean Thermal Energy Conversion (OTEC), and osmotic (salinity gradient) energy for sustainable electricity generation.
- It is highly predictable and abundant in coastal regions, making it a reliable alternative to conventional fossil fuels.
- Wave energy devices convert the kinetic and potential energy of ocean waves into electricity using systems such as oscillating water columns, point absorbers, and attenuators.
- Ocean Thermal Energy Conversion (OTEC) generates electricity by utilizing the temperature difference between warm surface seawater and cold deep seawater.
- OTEC systems can additionally support seawater desalination and cooling applications, particularly in island and coastal areas.
- Osmotic power produces electricity from the salinity difference between freshwater and seawater through semi-permeable membrane technology.
- Although ocean energy has enormous potential, its development is limited by high installation costs, technological challenges, and site-specific requirements.

8.8 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Ocean energy refers to the renewable energy obtained from the ocean in the form of waves, tides, thermal gradients, and salinity differences. It is important because it is a vast, clean, and renewable energy source that can help reduce dependence on fossil fuels and lower greenhouse gas emissions.

Ans to Q2: Wave energy devices are technologies designed to capture the kinetic and potential energy of ocean waves and convert it into electricity. Common types include point absorbers, oscillating water columns, and attenuators. These devices harness the continuous motion of waves to drive turbines or hydraulic systems for power generation.

Ans to Q3: OTEC works on the principle of using the temperature difference between warm surface seawater and cold deep seawater to operate a heat engine. The warm water acts as the heat source, while the cold water acts as the heat sink, enabling continuous electricity generation in tropical regions.

Ans to Q4: OTEC can be used for electricity generation, seawater desalination, and providing cooling for air-conditioning systems. It is especially useful for coastal and island regions where access to freshwater and conventional energy sources may be limited.

Ans to Q5: Osmotic power, also known as salinity gradient power, is a renewable energy technology that generates electricity by exploiting the difference in salt concentration between freshwater and seawater. When these two mix through a semi-permeable membrane, energy is released and can be converted into electricity.

Ans to Q6: Ocean energy resources are renewable, widely available, and environmentally friendly. They produce minimal pollution, help reduce carbon emissions, and provide a sustainable alternative energy source, especially for coastal regions with high energy demand.

8.9 FURTHER READING

- Herrera, J., Sierra, S., &Ibeas, A. (2021). Ocean Thermal Energy Conversion and Other Uses of Deep Sea Water: A Review. Journal of Marine Science and Engineering, 9(4), 356. https://doi.org/10.3390/jmse9040356
- Khan, N., Kalair, A., Abas, N., &Haider, A. (2017). Review of ocean tidal, wave and thermal energy technologies. Renewable and Sustainable Energy Reviews, 72, 590–604. https://doi.org/10.1016/j.rser.2017.01.079
- Curto, D., Franzitta, V., & Guercio, A. (2021). Sea Wave Energy: A Review of the Current Technologies and Perspectives. Energies, 14(20), 6604. https://doi.org/10.3390/en14206604
- Gallutia, D., TahmasbiFard, M., Gutierrez Soto, M., & He, J. B. (2022). Recent advances in wave energy conversion systems: From wave theory to devices and control strategies. Ocean Engineering, 252, 111105. https://doi.org/10.1016/j.oceaneng.2022.111105

- Ahmed, A., Khalid, M., & Ahmed, S. (2022). Harvesting Energy from Ocean: Technologies and Perspectives. Energies, 15(9), 3456. https://doi.org/10.3390/en15093456
- Golbaz, D., Asadi, R., Amini, E., Mehdipour, H., Nasiri, M., Nezhad, M. M., Omid Naeeni, S. T., &Neshat, M. (2021). Ocean Wave Energy Converters Optimization: A Comprehensive Review on Research Directions. Renewable and Sustainable Energy Reviews. https://arxiv.org/abs/2105.07180.

8.10 MODEL QUESTIONS

Q1: What is ocean energy potential, and why is it considered an important renewable energy source?
Q2: Explain the different forms of energy available from oceans.
Q3: What are wave energy devices? Describe any two types used for power generation.
Q4: How does an oscillating water column (OWC) wave energy device work?
Q5: Explain the working principle of Ocean Thermal Energy Conversion (OTEC).
Q6: Describe the main components and working of an OTEC plant.
Q7: Discuss the applications of OTEC in electricity generation and other fields.
Q8: What is osmotic power? Explain its basic principle.
Q9: Compare wave energy and OTEC in terms of working principle and resource utilization.
Q10: What are the major challenges in harnessing ocean energy for large-scale power production?

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UNIT 9: TIDAL ENERGY

UNIT STRUCTURE

9.1 Learning Objectives
9.2 Introduction
9.3 Energy from Wave
9.4 Wave Energy Devices
9.5 Introduction to Tidal Energy
9.6 Tide Energy Technologies
9.7 Let Us Sum Up
9.8 Answers to Check Your Progress
9.9 Further Reading
9.10 Model Questions

9.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- describe the renewable energy obtained from waves
- explain the formation of wave energy and the working of wave energy devices
- discuss different tide energy technologies used for power production
- illustrate the concept of tidal energy and the principles behind its generation
- describe the principles and applications of wave energy conversion devices

9.2 INTRODUCTION

In the previous unit, we explored various forms of ocean energy and their significance as renewable energy resources. In this unit, we will focus on wave energy and study how tides can be connected for electricity generation. The unit will further discuss different wave energy conversion devices and their operating principles used to capture wave power. In addition, it will introduce tidal energy and explain its origin. Finally, the unit will conclude with an overview of the various tidal energy technologies employed for power generation.

9.3 ENERGY FROM WAVE

Wave energy is a form of renewable ocean energy obtained from the kinetic and potential energy of surface ocean waves generated by wind blowing over the sea surface. The energy transferred from wind to water produces continuous wave motion, which can be converted into electrical energy through specialized wave energy conversion systems. Since ocean waves are more predictable and possess higher energy density than many other renewable sources, wave energy is considered a promising option for future sustainable power generation, particularly in coastal and island regions.

The power available in ocean waves depends on wave height, wavelength, water density, and wave velocity. Waves store energy both in the vertical motion of water

particles (potential energy) and in the horizontal movement of the wave (kinetic energy). The wave power per unit crest length increases significantly with increasing wave height and wave period. Regions with strong and persistent winds, such as the Atlantic and Pacific coastal zones, generally possess high wave energy potential.

Wave energy offers several advantages as a renewable and environmentally sustainable source of power. Ocean waves possess significantly higher energy density than many other renewable resources, such as solar and wind energy, enabling the generation of substantial amounts of electricity. In addition, wave patterns are comparatively predictable, which enhances the reliability and stability of power production. Since most wave energy converters are deployed offshore, they require minimal land usage and are particularly suitable for coastal and island regions where access to conventional energy resources may be limited. Furthermore, wave energy systems produce electricity with very low greenhouse gas emissions, contributing to sustainable and clean energy development.

Despite these advantages, wave energy technology faces several technical and economic challenges. The installation, operation, and maintenance costs are relatively high because offshore systems must withstand harsh marine conditions, including strong waves, storms, and continuous exposure to seawater. Wave energy installations may also influence marine ecosystems, fishing activities, and navigation routes. In addition, the technological complexity and limited large-scale commercial deployment of wave energy systems remain significant barriers to their widespread adoption.

9.4 WAVE ENERGY DEVICES

The conversion of wave energy into electricity is achieved using Wave Energy Converters (WECs). These devices capture wave motion and transform it into mechanical energy, which subsequently drives electrical generators. You have already studied these devices in Unit 8. Based on how they work and where they are installed, wave energy converters are divided into different types.

Types of Wave Energy Devices

1. Oscillating Water Column (OWC)

The Oscillating Water Column (OWC) is one of the most widely used wave energy conversion systems. It consists of a partially submerged chamber that is open to the sea below the water surface. As ocean waves enter and leave the chamber, the water column inside rises and falls continuously. This oscillating motion compresses and decompresses the air trapped above the water column.

The compressed air is forced through a turbine connected to a generator, causing the turbine to rotate and produce electricity. When the wave recedes, the airflow reverses and passes back through the turbine. To ensure continuous power generation, special bidirectional turbines such as Wells turbines are used. These turbines are designed with symmetrical blades that allow the turbine to rotate in the same direction regardless of the direction of airflow. As a result, continuous and efficient electricity generation is achieved without the need for complex mechanical systems.

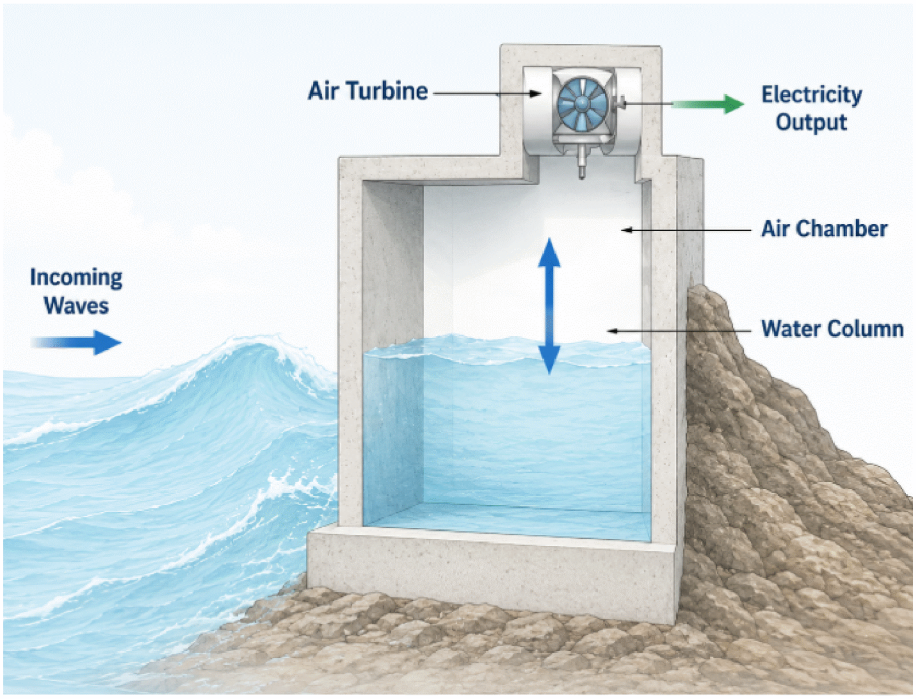


Figure 9.1: Diagrammatic representation of Oscillating Water Column system

2. Point Absorber

A Point Absorber is a floating wave energy device that extracts energy from the vertical motion of waves. It usually consists of a Buoy: It is a floating device on the ocean surface used for navigation guidance, weather data collection and hazard warnings.

As waves pass, the buoy moves upward and downward relative to the fixed structure. This relative motion drives hydraulic pumps, pistons, or linear generators that convert mechanical motion into electrical energy. Point absorbers can capture wave energy from multiple directions and are suitable for deep-water offshore applications.

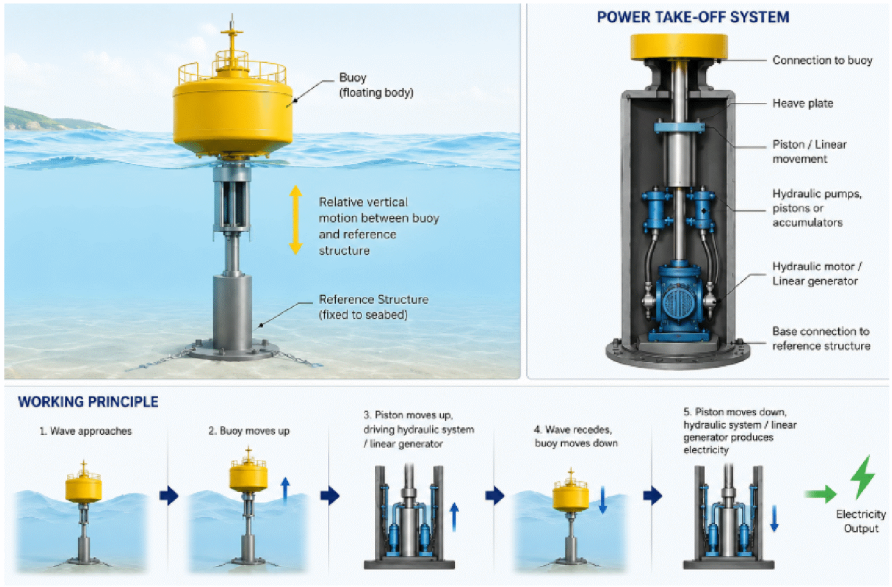


Figure 9.2: Diagrammatic representation of Point Absorber wave energy device

3. Attenuator Devices

Attenuator devices are long floating structures positioned parallel to the direction of wave propagation. These devices are made of multiple connected sections that flex and bend as waves travel along their length. The bending motion caused by wave generates electrical energy.

The relative motion between the sections operates hydraulic systems located at the joints. The hydraulic fluid under pressure drives hydraulic motors connected to electrical generators, thereby producing electricity. Attenuator systems are generally installed offshore where wave intensity is high and continuous.

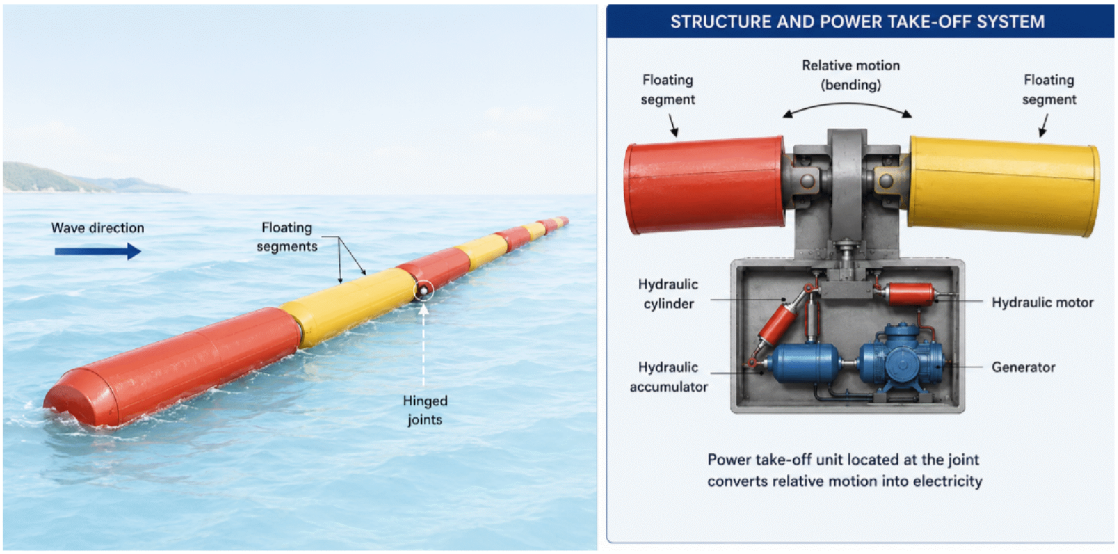


Figure 9.3 (a): Diagrammatic representation of Attenuator wave energy device

Working Principle: The working principle of attenuator device is explained below:

1. **Incoming Wave**
   Ocean waves approach and travel along the length of the attenuator device and cause continuous motion on the water surface.
2. **Device Bending**
   As the waves move beneath the structure, the connected segments bend at their joints due to the varying wave heights and forces acting on different sections.
3. **Relative Motion Between Segments**
   The wave-induced bending creates relative motion between adjacent segments. This motion is the primary source of mechanical energy in the system.
4. **Hydraulic Energy Conversion**
   Hydraulic cylinders or pumps installed at the joints are activated by the relative movement of the segments. The hydraulic system pressurizes fluid, converting mechanical wave motion into hydraulic energy.
5. **Electricity Generation**
   The pressurized hydraulic fluid drives a hydraulic motor connected to an electrical generator. The generator then converts the mechanical energy into electrical energy for power production.

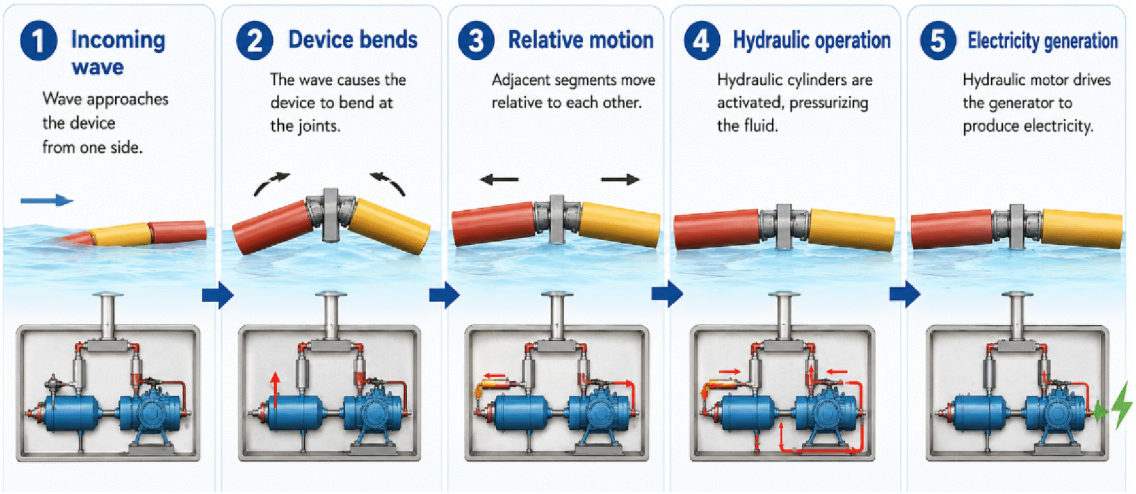


Figure 9.3 (b): Schematic illustration of the working principle of an attenuator wave energy device

4. Overtopping Devices

Overtopping systems collect seawater in an elevated reservoir using incoming waves. The stored water is then released through low-head turbines to generate electricity, operating similarly to a small hydropower plant.

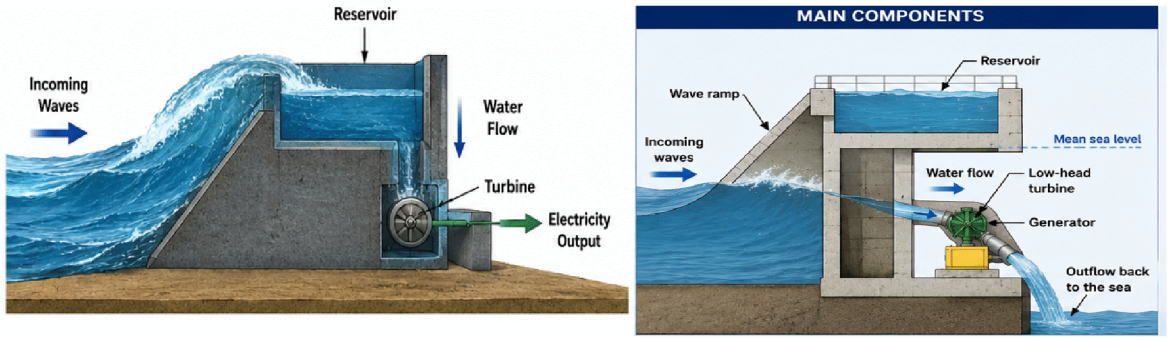


Figure 9.4 (a): Diagrammatic representation of over topping wave energy device

Working principle: The working principle of overlapping device is explained below

1. **Wave Approach:** Ocean waves travel toward the overtopping device.
2. **Overtopping Process:** Waves run up a sloping ramp and flow into an elevated reservoir above sea level.
3. **Water Storage:** The overtopped water is temporarily stored in the reservoir, increasing its potential energy.
4. **Power Generation:** Stored water is released through low-head turbines, which rotate generators to produce electricity.
5. **Water Discharge:** After passing through the turbines, the water returns to the sea, and the cycle repeats with incoming waves.

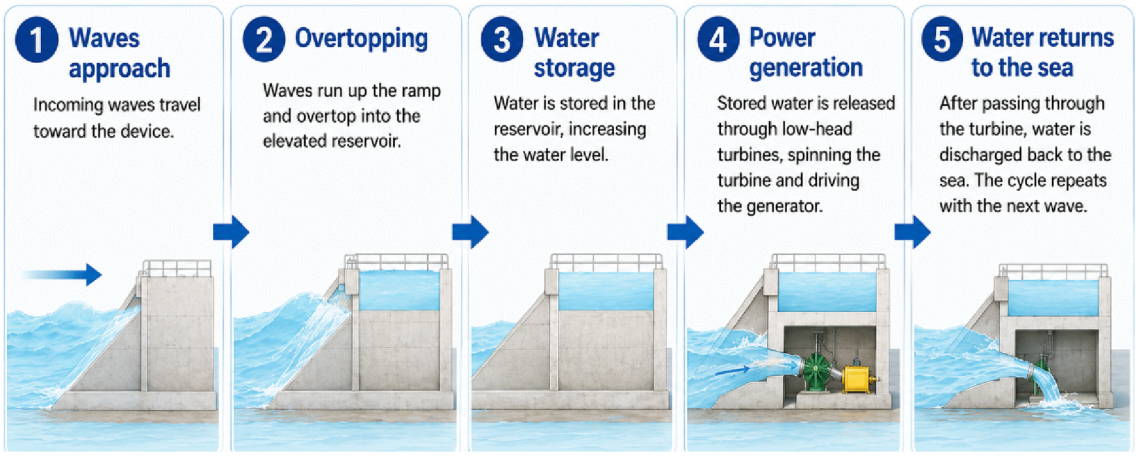


Figure 9.4 (b): Schematic illustration of the working principle of an overtopping wave energy device

9.5 INTRODUCTION TO TIDAL ENERGY

Tidal energy is a renewable form of ocean energy generated by the periodic rise and fall of sea levels caused by the gravitational forces of the Moon and the Sun acting on the Earth. It is considered one of the most reliable and predictable renewable energy sources because tidal cycles occur at regular and measurable intervals. The continuous movement of seawater during high and low tides contains significant kinetic and potential energy that can be harnessed for electricity generation.

Tidal energy is primarily captured using technologies such as tidal barrages, tidal lagoons, and tidal stream turbines. These systems convert the energy of moving or stored seawater into electrical power through turbines and generators.

With the growing demand for clean and sustainable energy, tidal energy has emerged as a promising alternative to conventional fossil fuels. It offers several advantages, including low greenhouse gas emissions, high energy predictability, and long operational life. Although challenges such as high installation costs, environmental concerns, and maintenance in harsh marine conditions still exist, ongoing technological advancements are improving the efficiency and economic viability of tidal power systems. Consequently, tidal energy is expected to play an important role in the future global renewable energy mix.

A tidal barrage is constructed across an estuary or bay to store seawater during high tide. As the water flows in and out through turbines during changing tides, electricity is generated. Tidal stream systems use underwater turbines placed in regions of strong tidal currents, where the moving seawater rotates the turbine blades in a manner similar to underwater wind turbines. Tidal lagoons operate on a principle similar to tidal barrages but use enclosed coastal reservoirs to capture tidal water.

Regions with large tidal ranges and strong tidal currents are suitable for tidal power generation. Countries such as the United Kingdom, Canada, France, South Korea, and China have significant tidal energy potential due to favorable coastal conditions.

Significance of Tidal Energy in India:

India has considerable tidal energy potential due to its extensive coastline of about 7,500 km and favourable coastal regions with high tidal ranges and strong tidal currents. The major potential sites for tidal power generation are the Gulf of Khambhat,

Gulf of Kutch in Gujarat, and the Sundarbans region in West Bengal. Among these, the Gulf of Khambhat located on the western coast of India in the state of Gujarat, along the Arabian sea, possesses the highest tidal energy potential because of its exceptionally large tidal range. It lies between the Kathiawar Peninsula (Saurashtra region) and the mainland of Gujarat. The major rivers flows into the Gulf of Khambhat are the Narmada, Tapi, Mahi, and Sabarmati drain.

Tidal energy is significant for India as it provides a clean, renewable, and highly predictable source of electricity. Unlike solar and wind energy, tidal cycles occur regularly and can be accurately forecasted. The development of tidal energy can help reduce dependence on fossil fuels, lower greenhouse gas emissions, and support India's transition toward sustainable energy systems. Although challenges such as high installation costs, environmental impacts, and technological limitations remain, continuous advancements in marine energy technologies are improving the feasibility of tidal power generation in India.

9.6 TIDAL ENERGY TECHNOLOGY

Tidal energy technology refers to the methods and systems used to convert the kinetic and potential energy of ocean tides into electrical energy. Tidal energy conversion technologies mainly utilize either the potential energy associated with tidal height differences or the kinetic energy of tidal currents. Depending on the operating principle and site conditions, tidal energy systems are broadly classified into tidal barrages, tidal stream turbines, and tidal lagoons.

Tidal Barrage Technology: A tidal barrage is a dam-like structure constructed across an estuary or bay with a high tidal range. The barrage contains sluice gates and low-head turbines. In advanced systems, reversible turbines enable power generation during both incoming and outgoing tides, thereby improving overall efficiency. Tidal barrage systems primarily utilize the potential energy created by the difference in water levels between the basin and the sea.

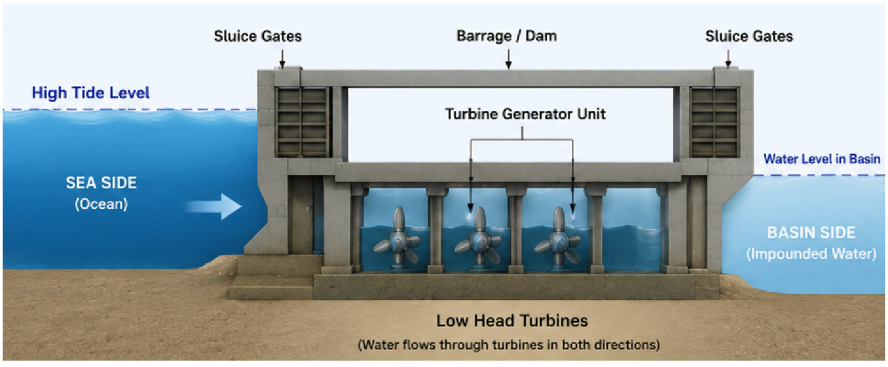


Figure 9.5 (a): Diagrammatic representation of tidal barrage technology

Working Principle:

The working principle of a tidal barrage system is based on the periodic rise and fall of sea levels during high and low tides. During high tide, the seawater level outside the barrage rises significantly, creating a difference in water level between the sea and the

basin behind the barrage. As the sluice gates open, seawater flows into the basin through turbines, causing the turbines to rotate and drive generators for electricity production. When the tide recedes and low tide occurs, the water stored in the basin is released back to the sea through the turbines. The flowing water again rotates the turbines, enabling additional power generation. Thus, the kinetic and potential energy of tidal movements are converted into electrical energy through continuous turbine operation during both incoming and outgoing tidal flows.

Tidal Stream Turbine Technology

Tidal stream technology extracts kinetic energy directly from moving tidal currents using underwater turbines. The operating principle is similar to that of wind turbines, except that water currents instead of air rotate the turbine blades. These turbines are installed in regions with strong tidal currents, such as narrow channels and coastal passages. Due to the high density of seawater, tidal stream turbines can generate significant power even at relatively low flow velocities. The key components of this technology are turbine blades, Nacelle, support structure, foundation, under water power cable and onshore substation.

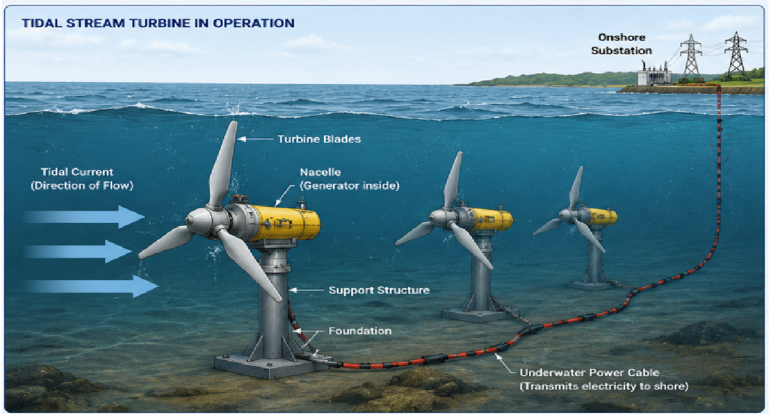


Figure 9.5 (b): Diagrammatic representation of tidal stream turbine technology

Working Principle: When tidal currents flow through the turbine blades, the flowing seawater causes the blades to rotate. The rotating blades drive a shaft connected to a generator, converting the mechanical energy of the rotating turbine into electrical energy. The generated electricity is then transmitted to the shore through underwater cables for distribution and utilization. Since tidal currents are regular and predictable, tidal stream turbines provide a reliable and sustainable source of renewable energy.

Tidal Lagoon Technology:

A tidal lagoon is an enclosed coastal reservoir constructed using breakwaters or embankments. It operates on a principle similar to tidal barrages but is generally built independently of river estuaries, reducing ecological impacts.

Water enters and exits the lagoon through turbines during tidal changes, generating electricity from the head difference between the lagoon and the sea.

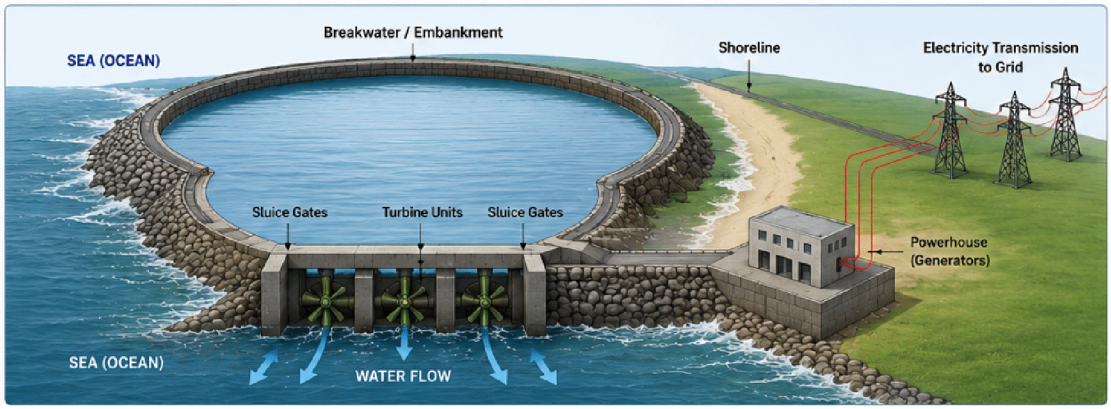


Figure 9.5 (c): Diagrammatic representation of tidal lagoon technology

Working principle:

During high tide, the sea level rises above the water level inside the lagoon. The sluice gates are opened, allowing seawater to flow into the lagoon through turbines. The flowing water rotates the turbine blades, which drive generators to produce electricity. As the water levels inside and outside the lagoon become nearly equal, the flow of water gradually decreases and the turbines stop operating temporarily.

During low tide, the sea level outside the lagoon falls below the water level inside the lagoon. The stored water in the lagoon is then released back to the sea through the turbines. This outgoing water again rotates the turbines and generates electricity. Once the water levels equalize again, the flow stops until the next tidal cycle begins. Thus, electricity is produced during both the incoming and outgoing tidal flows using the potential energy created by tidal height differences.

CHECK YOUR PROGRESS

Q1: Why is tidal energy highly predictable?
Q2: How does an attenuator device generate electricity?
Q3: Why are high tidal range regions suitable for tidal power?
Q4: What is the main function of an overtopping device?
Q5: What is a major limitation of tidal energy systems

9.7 LET US SUM UP

- Wave energy devices convert the kinetic and potential energy of waves into electrical energy.
- Common wave energy devices include attenuators, point absorbers, oscillating water columns, and overtopping devices.
- Tidal energy is produced from the periodic rise and fall of sea levels caused by gravitational forces.
- Tidal energy is highly predictable and reliable compared to other renewable energy sources.
- Major tidal energy technologies include tidal barrages, tidal lagoons, and tidal stream turbines for electricity generation.

9.8 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Because tidal cycles are governed by regular gravitational forces of the Moon and the Sun.

Ans to Q2: It converts the bending motion of floating segments caused by waves into electrical energy.

Ans to Q3: They provide greater energy potential due to larger water level differences.

Ans to Q4: It stores wave water in a reservoir and releases it through turbines to generate electricity.

Ans to Q5: High construction and maintenance costs in marine environments.

9.9 FURTHER READING

- Khare, V., Khare, C., Nema, S., & Baredar, P. (2019). *Tidal energy systems: Design, optimization and control.* Elsevier.
- Murali, K., &Sundar, V. (2017). Reassessment of tidal energy potential in India and a decision-making tool for tidal energy technology selection. International Journal of Ocean and Climate Systems, 8(2), 85–97. https://doi.org/10.1177/1759313117694629
- Rai, G. D. (2018). *Non-conventional sources of energy* (6th ed.). Khanna Publishers
- Khare, V. (2021). *Status of tidal energy system in India. Journal of Marine Engineering & Technology*, 20(5), 289–298. https://doi.org/10.1080/20464177.2019.1633224
- Greaves, D., & Iglesias, G. (2018). *Wave and tidal energy*. Wiley.
- Neill, S., &Hashemi, M. R. (2018). *Fundamentals of ocean renewable energy: Generating electricity from the sea.* Academic Press.

9.10 MODEL QUESTIONS

Q1: What is tidal energy and how is it generated?

Q2: Explain why tidal energy is considered a highly predictable renewable energy source.

Q3: Describe the working principle of tidal barrages used in tidal energy technology.

Q4: What are the main differences between tidal stream systems and tidal barrage systems?

Q5: Explain the working principle of an attenuator wave energy device.

Q6: What is an overtopping wave energy device and how does it generate electricity?

Q7: Describe the function of an oscillating water column (OWC) device in wave energy conversion.

Q8: What are the major advantages and limitations of wave energy systems?

Q9: Discuss the key tidal energy technologies used for power generation.

Q10: Explain the environmental impacts associated with tidal and wave energy systems.

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UNIT 10: GEOTHERMAL ENERGY

UNIT STRUCTURE

10.1 Learning Objectives
10.2 Introduction
10.3 Geothermal Resources
10.4 Potential of Geothermal Energy
10.5. Geothermal Technologies and Application
10.6. Let Us Sum Up
10.7. Answers to Check Your Progress
10.8. Further Reading
10.9. Model Questions

10.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- discuss the basic concept of geothermal energy and its resources
- explain the potential and types of geothermal energy
- analyze the technologies and applications of geothermal energy

10.2 INTRODUCTION

In the previous unit, you learned about tidal energy. This unit focuses on geothermal energy. The term “Geothermal” derives from two Greek words geo, meaning earth, and therme, meaning heat. It is considered as a renewable and sustainable energy source because the Earth continuously generates heat from natural geological processes. Geothermal energy has a wide range of uses. People have long utilized it for bathing and hot springs, and today it is also used for heating buildings, supporting various industrial processes, and generating electricity. In this unit, we will learn about the different types of geothermal resources, the technologies used to harness them, and their important applications.

10.3 GEOTHERMAL RESOURCES

Geothermal resources are sources of energy obtained from the natural heat stored within the Earth’s interior. This heat originates from the formation of earth and the continuous decay of radioactive elements within its core. However, geothermal resources are not evenly distributed across the globe. They are mainly found in regions with volcanic activity or tectonic plate boundaries.

Let us first get a basic idea of how geothermal energy is produced inside the Earth. You can refer to the figure 10.1 for a clearer understanding.

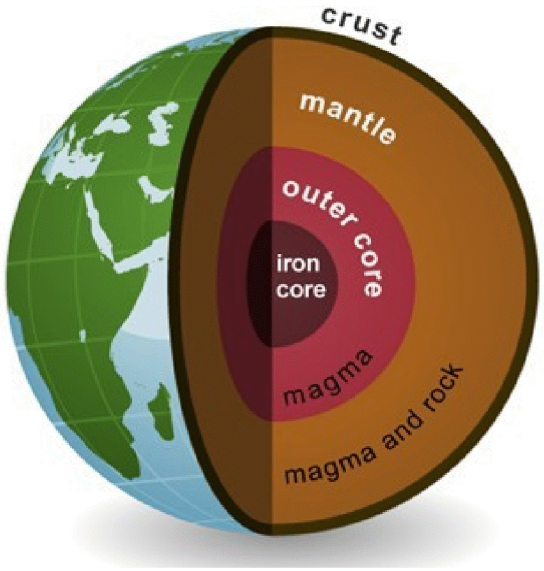


Figure 10.1: The Earth's Interior

Source: Adapted from a National Energy Education Development Project graphic (public domain Retrived from : https://www.eia.gov/energyexplained/geothermal/#:~:text=Geothermal%20energy%20comes%20from%20deep,This%20is%20where%20volcanoes%20occur.

The Earth is composed of four main layers. At the center lies the inner core which is made of solid iron and is about 1,500 miles wide. Surrounding it is the outer core, consisting of hot molten rock called magma and measuring approximately 1,500 miles in thickness. Above the outer core is the mantle, a thick layer of rock and magma of about 1,800 miles. The outermost and thinnest layer of the Earth is the crust. It forms the land surface and ocean floors. It has discovered by the scientists that the inner core is extremely hot about 10,800°Fahrenheit (F). Temperatures in the mantle range from 392°F to 7,230°F. Rocks and underground water absorb this heat, and their temperature increases with depth. As mentioned earlier, the most active geothermal resources are generally found along major tectonic plate boundaries where most of the world's volcanoes are located. Ring of Fire, a vast horseshoe-shaped region that encircles the Pacific Ocean is known as one of the most active geothermal zones. It starts from New Zealand, encompasses Philippines, Japan, West coast of North America and Mexico and then crosses the Aleutian Islands of Alaska.

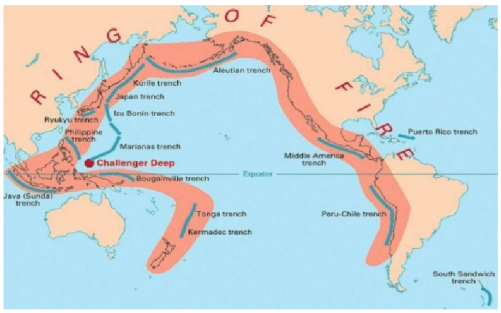


Figure 10.2: Pacific Ring of Fire

Source:https://education.nationalgeographic.org/resource/plate-tectonics-ring-fire/

Classification of Geothermal Resources: Geothermal resources are storage of hot water that subsists at different temperatures and depths below the Enthalpy: Enthalpy is the heat energy content per unit mass of the geothermal fluids, which carries heat from deep, hot rocks to the surface of the Earth. Geothermal resources are grouped into low, medium and high categories based on this enthalpy level.
Table 1: Geothermal Resources and Temperature Range

Geothermal Resources	Temperature Ranges
Enthalpy Resources(Low)	≥1250^{0}C
Enthalpy Resources (Medium)	1250^{0}C-2250^{0}C
Enthalpy Resources(High)	≥2250^{0}C

In general, geothermal resources are categorised into five types.

1. Hydrothermal: Geothermal resources are underground reservoirs of hot water or steam that can be accessed through drilling and utilized to bring heat to the surface for direct thermal applications or for generating electricity. They are again sub classified as-
   a. **Hot water:** At these locations hot water below 1000^0 C gushes out as hot spring. As for example, in Northern India, such spring exists in Tatapani on the right bank of river sutlez 54 km from Shimla.
   b. **Wet steam fields:** In these fields, the pressurized water is more than 1000^0 C and contains small quantity of steam and vapours. Examples of wet steam field generating electrical energy are: Los Azufre(Maxico), Puna (Hawaii, USA).
2. Vapour dominated resources: These produces dry saturated steam of pressure above the atmosphere and at high temperature above 3500^{0}C. Water and Steam coexist, but steam is in dominant phase and regulates pressure in the reservoir. Examples are Malsukawa (Japan), the Geyser California (USA), Kamojang (Indonesia).
3. Hot dry rock resource: These are very hot solid rocks occurring at moderate depths but to that limit water does not have asses, either because of absence of ground water or the low permeability of the rock(or both).
4. Geo-pressured resource: Geo-pressured resources contain moderate temperature brines (1600^{0}C) containing dissolved methane.
5. Magma resource : Magma is a molten rock at temperature ranging from 7000^0 C to 16000^{0}C. This hot viscous liquid comes out at active volcanic vents and solidifies. Magma chambers represent a huge energy source, but the existing technology does not allow recovery of heat from these resources.

10.4 POTENTIAL OF GEOTHERMAL ENERGY

Geothermal energy in India remains largely unexplored and underdeveloped. At the global level, geothermal power contributes about 6.5% of renewable green energy, which indicates its growing importance in the clean energy mix. India possesses significant geothermal potential and can play a meaningful role in future global

geothermal electricity generation. However, at present, power generation from geothermal resources in the country is still at a growing stage. The Geological Survey of India (GSI) has identified approximately 340 geothermal hot springs with low surface temperatures ranging from 37°C to 90°C. These geothermal manifestations are distributed across seven major geothermal provinces in India

1. **Himalayan Geothermal Province:** This province extends along the north-west to south-east Himalayan belt and represents the most promising geothermal region in India. Puga, Chhumathang, Panamik, Manikaran, Tapovan and the Beas Parvati valley are some important geothermal fields. The geothermal heat in this province is primarily generated due to active tectonics, crustal thickening and young granitic intrusions associated with the collision of the Indian and Eurasian plates.
2. **Son–Narmada–Tapti (SONATA)** Lineament Geothermal Province Located in central India, this province follows major faults and rift zones. Prominent geothermal areas include Tattapani, Salbardi, Anhoni and Unkeshwar. The geothermal activity here is mainly controlled by deep-seated fractures, fault reactivation and crustal movements, making it an important geothermal province in Peninsular India.
3. **Cambay Basin Geothermal Province:** The Cambay Basin in Gujarat forms a distinct geothermal province situated between the Narmada and Tapi rivers. Important geothermal sites include Unai, Tuwa, Dholera and Cambay. The geothermal potential of this province is linked to rift-related tectonics, thick sedimentary sequences and high heat flow, and it is considered one of the most suitable regions for geothermal power generation in India.
4. **West Coast Geothermal Province:** This province covers parts of Gujarat, Maharashtra and the Konkan coast, including geothermal manifestations at Ganeshpuri, Jalgaon and Ratnagiri. The geothermal activity is associated with coastal rifting, fault zones and the Deccan volcanic province and it results in numerous hot springs along the western coastal belt.
5. **Godavari Basin Geothermal Province:** The Godavari rift basin, extending across Telangana and Andhra Pradesh, constitutes another important geothermal province. Notable geothermal sites include Khammam, Manuguru and Bugga. The geothermal manifestations in this basin are related to rift tectonics and deep crustal faults, making it a promising area for geothermal exploration.
6. **Mahanadi Basin Geothermal Province:** The Mahanadi basin, mainly in Odisha and adjoining regions, hosts several geothermal occurrences. These are controlled by basement faults and rift-related structures within the sedimentary basin. Although still underexplored, this province adds significantly to India's geothermal resource base.
7. **Eastern and North-Eastern Geothermal Province:** This province includes geothermal fields in Bihar, Jharkhand, West Bengal, Odisha and parts of North-East India, such as Assam and Arunachal Pradesh. Important geothermal sites include Rajgir, Bakreshwar and Tantloi. The geothermal activity is mainly linked to ancient cratonic structures, fault zones and tectonic reactivation.

The geothermal provinces of India is shown in figure 10.3. The Geological Survey of India (GSI) has estimated the geothermal potential of the country to be around 10,000

MWe (megawatts electrical), based on data obtained from existing boreholes in several geothermal provinces such as Puga, Chhumathang, and Manikaran in the Himalayas, as well as Tattapani and regions along the west coast of the Indian Peninsula. Thermal discharges at Puga and Chhumathang were measured in March 2004. At Puga, a single borehole recorded a discharge of 30–40 L/s, while at Chhumathang the discharge was 15 L/s. The Puga valley, covering an area of about 10–15 sq. km, contains more than ten such discharge points. Based on these measurements and the surface temperature of approximately 95°C, the geothermal potential of Puga alone amounts to about 5000 MWt. If cumulative discharges from all points are considered, the actual potential would be significantly higher. The geothermal field at Tattapani has already been estimated to have a potential of around 1 MWe.

In addition to power generation, the Himalayan geothermal resources are highly suitable for supporting food processing industries. The lower and middle Himalayan regions have diverse agro-climatic conditions ideal for cultivating fruits such as apple, pear, peach, plum, almond, walnut, citrus fruits, mango, and raisin grapes. In Himachal Pradesh, the total fruit-cultivated area is about 2000 sq. km, with an annual production of nearly 5000 MT of assorted fruits. With an annual growth rate exceeding 15%, the food processing sector offers investment opportunities. Effective utilization of geothermal energy can help India become a global leader in value-added food products.



Figure 10.3: Geothermal Provinces in India

Source:https://www.researchgate.net/figure/Geothermal-provinces-in-India-Sharma-2017_fig1_362531589

10.5 GEOTHERMAL TECHNOLOGIES AND APPLICATION

Historical Use of Geothermal Energy: The use of geothermal energy in the form of natural heat from the Earth dates back to ancient times. Early civilizations across the world recognized the value of naturally heated water for bathing, cooking, heating and medicinal purposes. The Romans and Greeks were among the earliest to systematically use geothermal resources, constructing public baths and spas around natural hot springs. Famous examples include Bath in England and Baden-Baden in Germany which are well known as spa towns even today. Historical records show that the Romans and the inhabitants of Pompeii used geothermal water not only for bathing but also for space heating and for treating eye and skin diseases. Similarly, Vikings in Iceland and Native American communities in North America frequently used natural hot springs for bathing, cooking and healing. Archaeological evidence suggests that human beings have been using geothermal water for more than 10,000 years, making it one of the oldest forms of energy utilization. One of the earliest documented examples of organized geothermal heating is found in Chaudes-Aigues, a small village in the Cantal region of south-central France, where a geothermal district heating system was established as early as 1332. This system supplied naturally heated water to local buildings, marking a milestone in the history of geothermal energy use. In countries such as Iceland, Japan and New Zealand, geothermal bathing has remained an integral part of cultural life for centuries. In Iceland, geothermal water is widely used not only for bathing but also for heating houses, greenhouses and public buildings. The Maori people of New Zealand have traditionally used geothermal heat to cook food (hangi) for centuries. Since the 1960s, France has expanded geothermal district heating, and today geothermal water is used to heat nearly 200,000 homes, particularly in the Paris Basin.

Geothermal Energy Use in India, North-East India and Assam: India also has a long tradition of using geothermal resources, primarily in the form of hot springs, for religious, bathing and medicinal purposes. In the Himalayan region, hot springs such as Manikaran (Himachal Pradesh), Tapovan (Uttarakhand) and Puga (Ladakh) have been used for centuries by local communities. In North-East India, geothermal hot springs present in Assam, Arunachal Pradesh, Nagaland and Meghalaya, and have traditionally been used for bathing and therapeutic purposes. In Assam, hot springs such as Garampani are well known for their medicinal properties and are visited by people seeking relief from skin ailments and joint pain. Similarly, Dirang and Tawang hot springs in Arunachal Pradesh are culturally important and are widely used by local communities, monks and pilgrims for bathing, especially during winter. Although the use of geothermal energy in the North-East and Assam is still largely traditional and non-commercial, these practices demonstrate the long-standing relationship between people and geothermal resources in the region. With scientific exploration and modern technology, these resources have the potential to be developed further for space heating, eco-tourism, agro-processing and small-scale energy applications, especially in remote and hilly areas.

Application of Geothermal technologies in Modern Time:
To utilize geothermal reservoirs, deep wells are drilled to bring hot water and steam from beneath the Earth's surface. Geologists, geochemists, engineers, and drilling experts work together to identify, locate, and test underground areas that contain geothermal water. Once a suitable reservoir is confirmed, production units are established to efficiently harness geothermal energy for practical use.

1. Power Generation:
   Deep wells allow geothermal fluids to rise to the surface under high pressure, usually at temperatures around 400°F or higher. As the fluid ascends, the pressure drops and about 40–45 percent of the water instantly "flashes" into steam. This steam is used to rotate turbines connected to generators for electricity production. After energy extraction, the remaining water is reinjected into the reservoir to maintain pressure and ensure long-term productivity of the system.
   Indian government has set a target of generating 10 GW electric powers through Geothermal by 2030.

2. Industrial and Domestic Uses:
   Geothermal energy is widely applied in industries and households for space heating and cooling. It is also used for drying fruits and vegetables, dyeing clothes, paper manufacturing, and milk pasteurization. These applications help reduce dependence on non-renewable energy sources while promoting cleaner and more sustainable production practices.
   Geothermal hot water in the Puga Valley is utilized for refining locally available borax and sulphur and for processing salt from Tsokar Lake. The extraction plant has the capacity to handle about 2 tonnes per day of borax ore, while the refining unit canprocess nearly 500 kg per day of borax. In addition, a pilot plant for sulphur refining is capable of processing around 100 kg of sulphur per day, demonstrating the practical industrial application of geothermal energy in the region.

3. Greenhouse Heating:
   Geothermal water is used at Chumangthang (J&K) for greenhouse crop cultivation. During winter, when outside temperatures fall to around –25°C, geothermal heating maintains a suitable internal greenhouse temperature of about 20–25°C for agricultural production. This controlled environment enables the cultivation of various varieties of vegetables and flowers throughout the year.

4. Refrigeration: A geothermal energy based absorption refrigeration system operates a 7.5 tonne capacity cold storage plant at Manikaran (HP). Ammonia is used in the plant as refrigerant .

Potential application of Geo-thermal Energy: Geothermal energy can be applied for generation of power, cooking, heating of space, Greenhouse operation etc. Geothermal energy is a source of heat which is clean and sustainable and comes from inside the Earth. It can be used directly for many purposes such as space heating, water heating, crop drying, greenhouse cultivation, poultry and dairy activities, and central heating for schools, hospitals, and government buildings. Heat can be collected using shallow geothermal systems like Ground Source Heat Pumps (GSHP), and this can be

designed to suit the needs of individual villages. One major advantage of geothermal energy is that, unlike solar and wind energy, it is not dependent on weather conditions.

CHECK YOUR PROGRESS

Q1: What does the term geothermal mean?
Q2: Why geothermal energy is considered renewable?
Q3: Name the four main layers of the Earth.
Q4: Where geothermal resources are commonly found?
Q5: How are geothermal resources classified?
Q6: Which organization has identified geothermal potential in India?
Q7: Name one major geothermal province in India.
Q8: Mention one traditional use of geothermal energy.
Q9: What technology is used for shallow geothermal energy use?
Q10: State one advantage of geothermal energy over solar and wind energy.

10.6 LET US SUM UP

- Geothermal energy comes from the natural heat stored inside the Earth and is a clean, renewable, and sustainable energy source.
- The term geothermal is derived from Greek words meaning “earth” and “heat.”
- The Earth’s inner layers, especially the core and mantle, generate extremely high temperatures that heat rocks and underground water.
- Geothermal resources are mainly found in tectonically active regions along plate boundaries such as the Ring of Fire.
- Based on temperature (enthalpy), geothermal resources are classified into low-medium, and high-enthalpy resources.
- India has large but underutilized geothermal potential, with about 340 identified hot springs across seven major geothermal provinces.
- The Geological Survey of India estimates the country’s geothermal potential at around 10,000 MWe.
- Important geothermal provinces in India include the Himalayan, Cambay Basin, SONATA Lineament, Godavari Basin, and North-Eastern regions.
- Traditionally, geothermal energy has been used for bathing, cooking, heating, and medicinal purposes in many parts of the world, including India and North-East India.
- Modern geothermal technologies involve drilling wells to access hot water and steam for direct use or electricity generation.
- Geothermal energy is widely used for space heating, water heating, greenhouse cultivation, crop drying, food processing, and industrial applications.
- Shallow geothermal systems such as Ground Source Heat Pumps (GSHP) are suitable for village-level and community applications.
- Unlike solar and wind energy, geothermal energy is reliable and not dependent on weather conditions.

- With technological advancement and proper exploration, geothermal energy can play a significant role in sustainable development, especially in remote and hilly areas.

10.7 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: Geothermal means heat derived from the Earth.

Ans to Q2: Because the Earth continuously produces heat through natural geological processes.

Ans to Q3: Inner core, outer core, mantle, and crust.

Ans to Q4: They are classified into low-, medium-, and high-enthalpy resources based on temperature.

Ans to Q5: They are classified into low, medium, and high-enthalpy resources based on temperature.

Ans to Q6: The Geological Survey of India (GSI).

Ans to Q7: The Himalayan Geothermal Province.

Ans to Q8: Bathing in hot springs.

Ans to Q9: Ground Source Heat Pump (GSHP).

Ans to Q10: It is not dependent on weather condition

10.8 FURTHER READING

- Bhat, G. M. (2025). *Geothermal resource: World scenario and India's outlook. Journal of the Geological Society of India,* 101(4), 431–436. https://doi.org/10.17491/jgsi/2025/174112
- Sheorey, A. (2025). *Geothermal Resources*. Discovery Publishing House (India). ISBN 9789362244185
- Kumar, S., Gupta, S. K., &Rawat, M. (2020). *Resources and utilization of geothermal energy in India: An eco-friendly approach towards sustainability. Materials Today: Proceedings,* 26(Part 2), 1660–1665. https://doi.org/10.1016/j.matpr.2020.02.
- U.S. Energy Information Administration page: U.S. Energy Information Administration. (2025,) *Geothermal energy explained*. U.S. Department of Energy. Retrieved December 22, 2025, from https://www.eia.gov/energyexplained/geothermal/
- Energetica India. (2025). *Empowering rural India with clean heat: The role of geothermal energy.*Energetica India. Retrieved December 22, 2025, from https://energetica-india.net/articles/empowering-rural-india-with-clean-heat- the-role-of-geothermal-energy)

- 6.Geothermal Basics, U.S. Department of Energy – Energy Efficiency & Renewable Energy (EERE) retrieved from https://www.energy.gov/eere/geothermal/geothermal-basics
- Dhanya, M. S. M. S., & Singh, Y. (n.d.). *Geothermal energy.* In Energy and environment. INFLIBNET e-Book. Retrieved January 3, 2026, from https://ebooks.inflibnet.ac.in/esp07/chapter/geothermal-energy/
- Sircar, A., Yadav, K., &Sahajpal, S. (2016). *Overview on direct applications of geothermal energy.* International Advanced Research Journal in Science, Engineering and Technology, 3(9), 128–132.
- Yadav, K., &Sircar, A. (2021). *Geothermal energy provinces in India: A renewable heritage.* International Journal of Geoheritage and Parks, 9(1), 93–107. https://doi.org/10.1016/j.ijgeop.2020.12.002
- Kothari, D. P., Singal, K. C., & Ranjan, R. (2011*). Renewable energy sources and emerging technologies* (2nd ed.). PHI Learning Private Limited.

10.9 MODEL QUESTIONS

Q1: Explain the origin of geothermal energy and describe the structure of the Earth responsible for its generation.

Q2: Classify geothermal resources based on enthalpy and discuss their major applications.

Q3: Discuss the geothermal energy potential in India, highlighting the major geothermal provinces.

Q4: Describe the traditional and modern uses of geothermal energy with suitable examples from India.

Q4: Evaluate the role of geothermal energy in sustainable development and its advantages over other renewable energy sources.

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UNIT 11: ENERGY STORAGE DEVICES AND HYBRID RENEWABLE ENERGY SOURCES

UNIT STRUCTURE

11.1 Learning Objectives
11.2 Introduction
11.3 Battery
  11.3.1 Types of Battery
  11.3.2 Battery Specifications, Charging and Discharging Characteristics
11.4 Definition and Classifications of Hybrid Systems
  11.4.1 Standalone System
  11.4.2 Grid-Tied System
  11.4.3 Microgrid-Based Hybrid System
11.5 Role of Storage in Hybridization
11.6 Hybrid Systems for EV Charging
11.7 Let Us Sum Up
11.8 Answers to Check Your Progress
11.9 Further Reading
11.10 Model Questions

11.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- explain the concept of energy storage devices and their role in renewable energy systems.
- discuss different types of batteries and their specifications for renewable energy applications.
- describe battery charging and discharging characteristics for system design and safety.
- familiarize themselves with the essential aspects of hybrid renewable energy systems, their classifications, and functionalities.
- acquire an overview of standalone, grid-tied, and microgrid-based hybrid systems.
- analyze the role of energy storage in hybrid systems and its importance in grid stability.
- discuss the application of hybrid systems in electric vehicle (EV) charging infrastructure.

11.2 INTRODUCTION

In the previous unit, you have learned about geothermal energy. In this unit, you will study about batteries and their importance in energy storage. The unit will provide you different types of batteries, their specifications, and charging and discharging characteristics. You will also study the definition and classification of hybrid energy systems including standalone, grid-tied, and microgrid-based systems. Further, the unit

explains the role of energy storage in hybridization. At the end of the unit you will explore the application of hybrid systems for electric vehicle (EV) charging, their significance in improving energy reliability, efficiency, and sustainability.

11.3 BATTERY

Batteries are electrochemical devices that convert chemical energy into electrical energy through redox reactions. These reactions involve the transfer of electrons between reactants, leading to changes in their oxidation states. In renewable energy applications, batteries serve as critical energy storage components, enabling the reliable supply of electricity from intermittent sources, such as solar and wind. Battery performance is determined by several parameters including voltage, capacity, energy density, charge/discharge rates, cycle life, and efficiency.

Voltage: Voltage is the electrical potential difference (measured in volts) that a battery can provide. For example, lithium-ion batteries typically have a nominal voltage range of 3.6-3.7V per cell, while lead-acid batteries provide 2V per cell.

Capacity: Capacity of a Battery is measured in ampere-hours (Ah). Battery capacity represents the total amount of charge a fully charged battery can deliver. A 100 Ah battery can deliver 100 amperes for 1 hour or 10 amperes for 10 hours.

Energy Density: Energy Density is the amount of energy stored per unit mass (Wh/kg) or volume (Wh/L) in a battery. Lithium-ion batteries have energy density of 150-250 Wh/kg, while lead-acid batteries have only 30-40 Wh/kg, making lithium-ion superior for weight-sensitive applications.

Cycle Life: Cycle life is the number of complete charge-discharge cycles a battery can undergo before its capacity degrades to 80% of nominal capacity. Lithium-ion batteries typically have 3,000-5,000 cycles, while lead-acid batteries have 1,000-2,000 cycles.

Self-Discharge Rate: It is the rate at which a battery loses charge, when not connected to a load. Lead-acid batteries have the lowest self-discharge rate, while lithium-ion batteries have approximately 1.5-2% per month.



Figure 11.1: Battery Parameters

11.3.1 Types of Battery

Lead-acid batteries

Lead-acid batteries are the most economical and widely used battery type, despite the evolving types of newer technologies available in the market. They consist of lead dioxide (positive plate), sponge lead (negative plate), and sulfuric acid electrolyte. The charging rate is typically set at C/10 (where C is the battery capacity), meaning a 100 Ah battery charges at 10 Amps.

Lead-acid batteries are low-cost, easy to manufacture, highly recyclable (about 98%), and capable of delivering high discharge rates with low self-discharge and minimal maintenance. However, they have low energy density, a relatively short lifespan, cannot be stored in a discharged state, require careful temperature control, and contain lead, which poses environmental concerns. They are widely used in backup power systems, off-grid household systems, and small standalone energy installations.

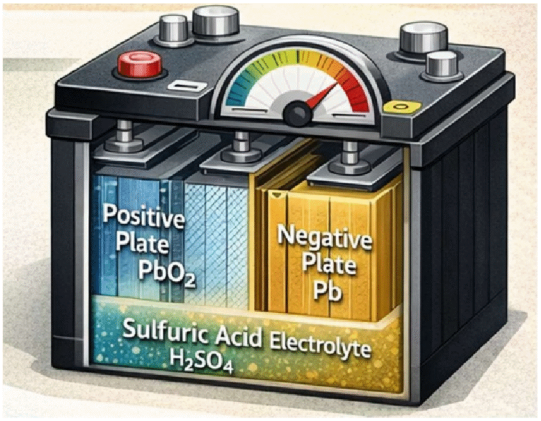


Figure 11.2: Lead-Acid Battery

Lithium-Ion Batteries (Li-ion)

Lithium-ion batteries use lithium ions as charge carriers moving between anode and cathode. The charging rate for Li-ion is typically C/5 (20% of capacity per hour). However, overcharging protection is crucial for these batteries, to avoid permanent damage. They have 3-5 times higher energy density than lead-acid batteries and offer 45% more discharge capacity for the same weight.

Lithium-ion batteries have high energy density, long cycle life, fast charging capability, low self-discharge, and require little maintenance. They also support deeper discharge and perform well over a wide temperature range. However, they have a high initial cost, require advanced battery management systems, are sensitive to high temperatures, and may experience thermal runaway if overcharged. These batteries are widely used in electric vehicles, grid-scale energy storage, and solar power systems.

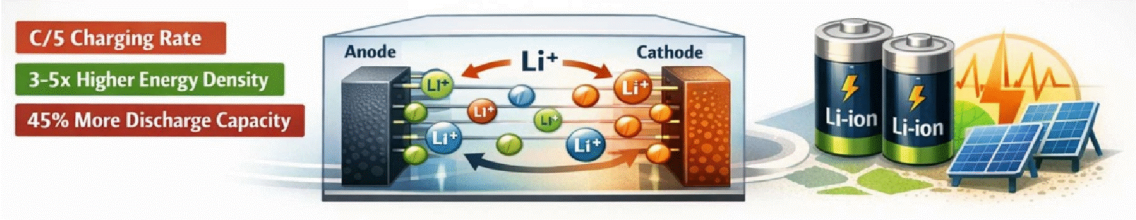


Figure 11.3: Lithium-Ion Battery

Other Battery Types

Nickel-Metal Hydride (NiMH): These batteries have moderate energy density, excellent temperature tolerance (-40°C to +60°C), longer calendar life, but exhibit memory effect, i.e., they require complete discharge before recharging.

Nickel-Cadmium (NiCd): These batteries can withstand mechanical and electrical abuse, extreme temperature range capability, but memory effect is more pronounced than NiMH.

Sodium-Ion and Solid-State Batteries: These are emerging technologies, promising higher energy density and safer operation, currently under development for commercial applications.

11.3.2 Battery Specifications, Charging and Discharging Characteristics

Charging Characteristics

Battery charging involves the movement of lithium ions (in Li-ion) or chemical reactions (in lead-acid) that store electrical energy. Charging is characterized by constant current and constant voltage (CC-CV) phases.

Constant Current Phase:

The battery charges at a fixed current rate until it reaches a predetermined voltage limit. This phase of current flow is called as constant current phase. For example, a lead-acid battery charges with constant current (C/10 rate) until reaching the rated voltage level.

Constant Voltage Phase:

Once the voltage limit is reached, the charger maintains constant voltage while current gradually decreases. This phase is called the Constant Voltage Phase. This topping charge phase completes the charging process and maintains the full charge level.

End-of-Charge Voltage:

It is the maximum safe voltage at which the battery should be disconnected from the supply. Exceeding this voltage causes overcharging, leading to heat generation, plate corrosion, chemical property deterioration and reduced battery life. Lithium-ion cells have end-of-charge voltage of 4.2V per cell; lead-acid batteries have 2.4V per cell.

Charging Rate Effect on Lifespan: Higher charging rates (e.g., C/2) can reduce battery cycle life compared to standard rates (C/5 to C/10). Temperature also affects charging efficiency; optimal charging occurs at 20-25°C for most battery types. Therefore, charging rate is an important parameter for the health and life of a battery.

Discharging Characteristics

During discharge, the chemical reactions in a battery reverse and ions flow from positive to negative electrode, generating electrical current. Battery voltage decreases gradually during discharge. During discharging the following parameters are noticed.

Discharge Profile:

For lithium-ion batteries, voltage remains relatively constant at the rated value (3.6-3.7V per cell) for most of the discharge cycle, then drops sharply near complete discharge. Lead-acid batteries show a more gradual voltage decline from maximum charge voltage. This voltage versus time graph plotted during the discharge state is called as the discharge profile for a battery.

End-of-Discharge Voltage:

It is the minimum voltage at which the battery should be disconnected to prevent over-discharge. Over-discharge causes capacity loss, internal short circuits, and potential battery damage. Lithium-ion cells typically have end-of-discharge voltage of 2.5-3.0V per cell; lead-acid batteries have 1.75V per cell. Hence, the battery must be charged before it reaches the end-of-discharge-voltage level.

Discharge Rate and Temperature Dependence:

At lower temperatures, battery capacity decreases significantly. For example, at 0°F, lithium-ion batteries discharge at 70% of rated capacity while lead-acid batteries discharge at only 45% capacity. Higher discharge rates increase voltage drop and heat generation, affecting overall efficiency.

Self-Discharge During Storage:

Lead-acid batteries have minimal self-discharge and can be stored in charged state. Lithium-ion batteries lose 1.5-2% charge monthly and should be stored at 50-60% state of charge for optimal longevity.

Battery Performance Parameters

Efficiency: It is the ratio between the output and input energy for a battery. In other words, it is the ratio of energy discharged to energy charged, typically 85-95% for lithium-ion and 80-90% for lead-acid batteries. The remaining energy dissipates as heat.

Round-Trip Efficiency: It is the overall efficiency, considering both charging and discharging losses, important for calculating system costs and performance. The total energy lost in the process of charging and discharging for the battery is calculated from this efficiency.

State of Charge (SOC): It is the current charge level expressed as a percentage of maximum capacity (0% = fully discharged, 100% = fully charged).

Depth of Discharge (DOD): It is the percentage of battery capacity that has been discharged. Limiting DOD (typically to 80-90% for lithium-ion) extends cycle life and overall lifespan.

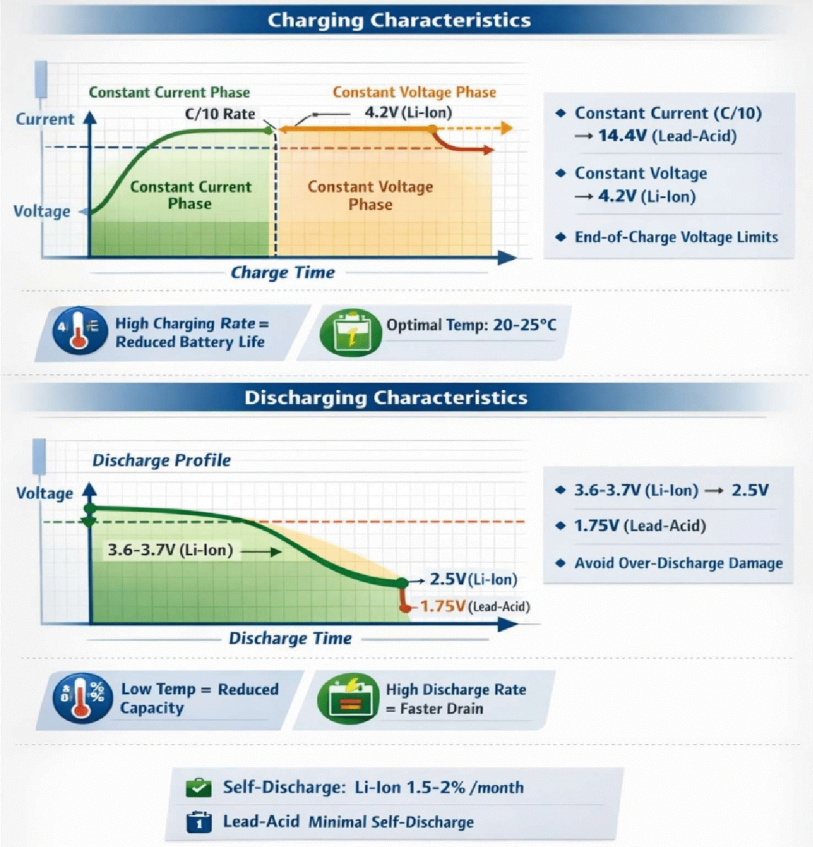


Figure 11.4: Battery Charging and Discharging Characteristics

11.4 DEFINITION AND CLASSIFICATIONS OF HYBRID SYSTEMS

A Hybrid Renewable Energy System (HRES) is an integrated power generation and storage system that combines two or more renewable energy sources (such as solar PV, wind turbines, micro-hydro) with energy storage devices (batteries, supercapacitors) and control systems to provide reliable electricity supply while optimizing efficiency and minimizing environmental impact. The coordination among multiple sources addresses the intermittency problem inherent in individual renewable sources.

Key Advantages of Hybrid Systems:

- Improved reliability and reduced power interruptions
- Better utilization of available renewable resources
- Reduced energy storage size compared to single-source systems
- Enhanced grid stability and power quality
- Economic viability through diversified resource utilization
- Reduced dependence on fossil fuels and battery backup alone

Classification Based on Grid Connection:

Hybrid renewable energy systems are primarily classified into three categories based on their connection to the utility grid: standalone (off-grid), grid-tied (on-grid), and

microgrid-based systems. This classification determines system design, control strategies, regulatory compliance, and economic operation.

11.4.1 Standalone System

A standalone (off-grid) hybrid renewable energy system operates completely independent of the utility grid, generating and consuming electricity locally without any connection to centralized power distribution infrastructure. These systems are self-sufficient and must satisfy all energy demands from local renewable sources and storage.

System Components:

- Renewable Energy Sources: Multiple generators (solar PV arrays, wind turbines, micro-hydro turbines).
- Energy Storage: Battery banks (typically lead-acid or lithium-ion) for storing excess energy.
- Power Electronics: DC-DC converters, inverters converting DC to AC power.
- Load Management Controller: Regulates power distribution and prevents over/under-voltage conditions.
- Backup Generator: Optional diesel/petrol generator for critical situations.



Figure 11.5: Standalone Systems

Operating Principles:
In standalone systems renewable sources generate variable power, based on weather conditions. Excess generation charges the battery bank, while during periods of low generation or high demand, the battery discharges to supply the load.
Design Considerations:

- Autonomy Period: It is the number of days the battery can supply full load without renewable generation, typically 3-5 days.
- System Reliability: It is the minimum power availability, typically targeted at 95-99%.
- Component Sizing: It is composed of the solar capacity, wind turbine rating, battery size calculated based on average load and autonomy period.
- Voltage Regulation: Maintaining stable voltage output despite variable input and load is the process called voltage regulation.

Standalone systems do not require grid connection which makes them suitable for remote areas, islands, and off-grid communities. They provide complete energy independence, resilience, and allow gradual system expansion. However, they involve high initial investment due to large battery requirements, depend on local renewable resource availability, and require complex control systems with higher maintenance and battery replacement costs. They also have lower overall efficiency due to energy conversion losses. These systems are commonly used for remote village electrification, island communities, mountain lodges, research stations, rural agricultural applications, and emergency backup power for critical facilities.

11.4.2 Grid-Tied System

A grid-tied (on-grid) hybrid renewable energy system is directly connected to the utility grid, allowing two-way power exchange. Surplus electricity generated from renewable sources can be fed back to the grid, often with financial incentives, while the grid serves as a backup during low generation periods.
System Components:

- Renewable Energy Sources: Solar PV, wind turbines, other renewable generators.
- Power Electronics: Inverters with grid-synchronization capability (converts DC to grid-compatible AC).
- Net Metering System: Bidirectional meter measuring power flow in both directions.
- Grid Connection Equipment: Transformers, circuit breakers, safety disconnects, anti-islanding protection.
- Optional Small Storage: Battery systems (10-20% of peak load) for short-term fluctuations.

Operating Principles:
Grid-tied systems generate power that first supplies local loads. When generation exceeds local demand, surplus power flows to the grid, reversing the meter. During periods of low generation or high demand, electricity flows from the grid to the load.

The grid effectively serves as an infinite source of power, providing complete energy backup.

Key Technical Features:

- Synchronization: Inverters must synchronize with grid frequency (50 Hz) and voltage.
- Anti-Islanding Protection: They must automatically disconnection when grid fails, preventing backfeeding to de-energized grid.
- Power Quality: Total Harmonic Distortion (THD) must be less (< 5%). Voltage regulation must be within a limit (±10%).
- Response Time: These systems must have a rapid response to grid voltage and frequency changes.

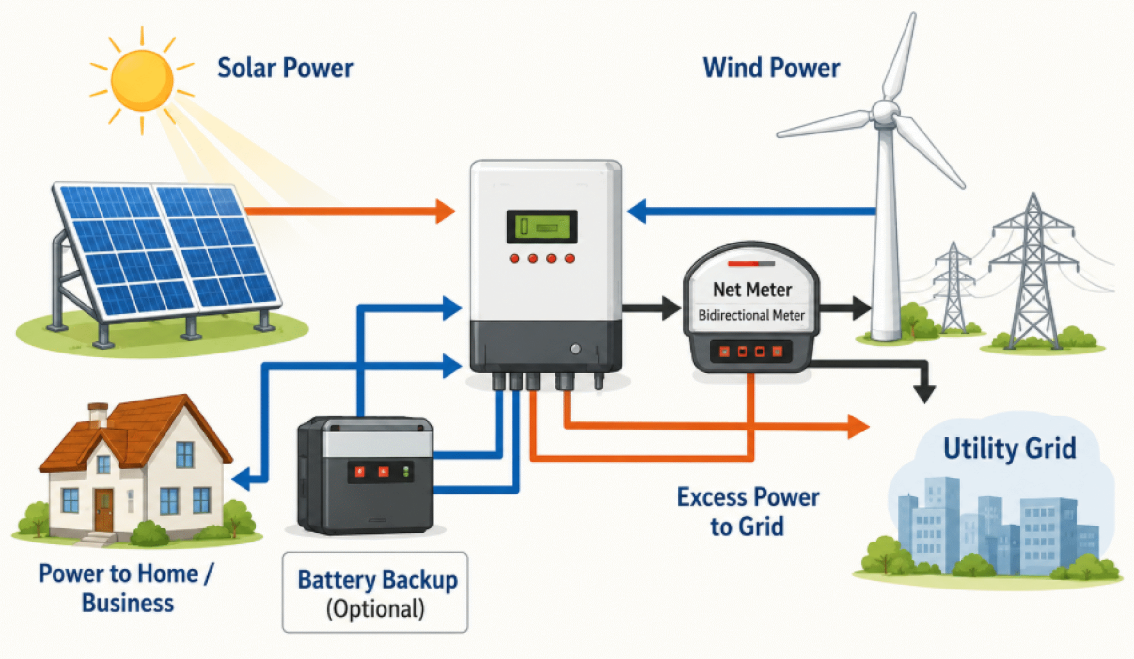


Figure 11.6: Grid-Tied System

11.4.3 Microgrid-Based Hybrid System

A microgrid is an engineered, localized energy ecosystem that integrates diverse renewable energy sources, energy storage, intelligent control systems and loads within defined geographic boundaries. Microgrids can operate connected to the main grid or in islanded (autonomous) mode, providing resilience and supporting broader sustainability objectives.

System Architecture:

Microgrids comprise multiple interconnected components managed by sophisticatedcontrol systems:

- Multiple RenewableGenerators:Distributed solar,wind, andother renewable sources.
- Energy Storage Systems: Battery banks, supercapacitors, thermal storage.

- Smart Controllers: Microgrid management systems (MGMS) optimizing power flow.
- AdvancedMetering: Real-time monitoringofgeneration,storage,and consumption.
- CommunicationNetworks:IoTsensorsandcontrolnetworksfor coordination.
- Multiple Loads: Residential, commercial, industrial, EV charging stations.

Two Primary Operational Modes:

Grid-Connected Mode: The microgrid operates in parallel with the main utility grid, exchanging power seamlessly. It can provide ancillary services, such as- voltage support, frequency regulation etc. to the grid. Advanced controls manage power flow, minimize losses and optimize economic operation. Surplus power is sold to the grid, while grid power backs up local generation.

Islanded Mode: During grid disturbances or planned islanding, the microgrid disconnects and operates independently. Local generation and storage supply all local loads. Sophisticated frequency and voltage regulation controls maintain stability. Demand-side management may be activated to balance supply and demand.

11.5 ROLE OF STORAGE IN HYBRIDIZATION

Energy storage is the fundamental enabler of hybrid renewable energy systems, addressing the core challenge of renewable source intermittency. Without storage, renewable energy systems cannot guarantee reliable power supply, making storage technology essential for system viability and grid integration.

The Intermittency Problem

Renewable energy sources exhibit inherent variability:

- Solar Generation: Zero output at night, reduced output during cloudy days, follows seasonal patterns
- Wind Generation: Variable output based on wind speed, typically lower during calm periods, seasonal variations
- Hydroelectric: Dependent on seasonal precipitation and water availability
- Biomass: Limited by feedstock availability

This intermittency creates misalignment between generation and consumption patterns, causing grid frequency and voltage instability if not properly managed. Traditional grids rely on dispatchable fossil fuel generation to match load, while renewable-dominant grids require storage to fulfill this function.

Storage Functions in Hybrid Systems

1. Energy Arbitrage (Time-Shifting)

Storage enables temporal separation of generation and consumption. Solar energy generated during peak daytime generation can be stored and discharged during evening peak demand, shifting energy from high-supply to high-demand periods. This function increases the economic value of renewable generation and reduces reliance on costly grid power during peak hours.

Example: A 100 kWh battery in a solar-rich location can shift 50 kWh of daytime solar energy to evening peak demand (5 PM - 9 PM), potentially multiplying energy value by 3-5 times due to time-of-use tariff differences.

2. Peak Shaving and Load Leveling

Batteries discharge during peak demand periods, reducing overall system peak power requirement. This reduces:

- Peak demand charges (typically 30-50% of commercial electricity bills)
- Grid capacity expansion requirements
- System losses from lower average load
- Stress on aging grid infrastructure

Load leveling smooths the demand curve, enabling smaller and more efficient generation and distribution infrastructure.

3. Renewable Firming and Variability Smoothing

Storage systems rapidly absorb and release power, smoothing generation fluctuations. When cloud cover causes sudden solar output drops, battery discharge maintains relatively constant power output. Similarly, wind power fluctuations are absorbed by battery charge/discharge cycling. This requires fast-response storage (typically batteries rather than long-duration storage).

4. Frequency and Voltage Regulation

Storage systems provide real-time frequency and voltage support, critical for grid stability. When system frequency drops (due to sudden load increase or generation loss), battery discharge immediately increases, restoring frequency. Modern fast-response batteries can provide this service faster than traditional generators.

Fast-frequency response time (< 100 milliseconds) prevents cascade failures and blackouts. This service is increasingly critical as inertia from synchronous generators (fossil fuel plants) decreases in renewable-heavy grids.

5. Black Start and System Restoration

During large-scale blackouts, storage systems with capacity to energize transformers and restart generators enable grid recovery. Without storage, renewable systems cannot restore the grid from a blackout. Energy storage provides the critical "seed power" to restart conventional generators.

6. Grid Defection and Off-Grid Operation

In hybrid systems with multiple sources, storage enables seamless transition to islanded mode when grid fails or during planned islanding. Combined with adequate renewable capacity, storage maintains continuous supply to critical loads independent of grid availability.

7. Demand Flexibility and Demand Response

Smart storage systems respond to price signals and grid needs, charging when electricity is cheap (high renewable generation or low demand) and discharging when electricity is expensive (low generation or high demand). This demand flexibility reduces overall system costs and enhances grid stability.

Impact on System Sizing

The presence of storage dramatically changes hybrid system design:

- Without Storage: A hybrid system requires 2-3 times the renewable capacity to directly supply peak loads
- With Storage: The same loads can be supplied with optimized renewable capacity plus appropriately sized battery storage

Example: A 10 MW peak demand load in a solar-dominant area without storage would require ~20-30 MW solar capacity. With 5 hours of energy storage (50 MWh battery), only 12-15 MW solar capacity is needed, reducing capital costs despite battery expense.

Storage Duration and System Reliability

Different storage durations provide different functions:

- Minutes (Supercapacitors): Frequency response and short transient smoothing
- Hours (Batteries): Daily load leveling and peak shaving
- Days (Long-duration storage): Seasonal variations and multi-day low-generation periods

Most hybrid systems use batteries (hours-duration storage) combined with either:

- Seasonal storage (pumped hydro, compressed air) for multi-day gaps
- Oversized renewable capacity to minimize storage requirement
- Grid connection for backup.

Cost-Benefit Analysis of Storage

The economic value of storage comes from:

1. Avoided grid peak demand charges
2. Time-of-use tariff arbitrage (buying cheap, selling expensive)
3. Feed-in tariffs for excess generation
4. Reduced need for system overprovisioning
5. Avoided fuel costs for backup generators
6. Grid service payments (in advanced markets)

In cost-benefit analyses, storage becomes economically attractive when:

- Retail-wholesale electricity price ratio > 2:1
- Peak demand charges > 30% of total electricity cost
- Battery capital cost < $500/kWh for behind-the-meter systems
- Grid connection and extension costs > battery storage costs

Storage Technology Selection for Hybrid Systems

Lead-Acid Batteries:

- Best for: Small standalone systems, emergency backup
- Suitable autonomy: 1-3 days
- Cycle life limitation requires deeper sizing

Lithium-Ion Batteries:

- Best for: Most modern hybrid systems, grid-scale deployment
- Suitable autonomy: 1-7 days depending on capacity
- Superior cycle life and efficiency justify higher cost

Long-Duration Storage:

- Pumped Hydro: Best for days-weeks duration (only in suitable geography)
- Compressed Air: Medium-duration storage with site-specific requirements
- Thermal Storage: Useful for heating/cooling loads, molten salt for CSP systems
- Hydrogen/Synthetic Fuels: Emerging for seasonal storage

11.6 HYBRID SYSTEMS FOR EV CHARGING

Electric vehicles represent the largest emerging load in modern power systems, potentially consuming 30-50% of total electricity by 2050. Hybrid renewable energy systems specifically designed for EV charging integrate renewable generation, energy storage, and intelligent charging management to maximize sustainability while maintaining grid stability.

EV Charging Demand Characteristics

Load Pattern:

- Fast charging (200-350 kW): 20-30 minutes, high power demand
- Level 2 charging (7-19 kW): 4-8 hours, moderate continuous power
- Level 1 charging (1.4-1.9 kW): Overnight charging, lowest power demand
- Fleet charging: Highly concentrated demand peaks (e.g., buses returning to depot at shift end)

Charging Variability:

- Time of use: Predominantly evening peak hours for personal vehicles
- Seasonal: Higher demand in winter (colder temperature reduces range)
- Weather dependent: Rainy days increase charging needs due to reduced alternative mobility
- Grid impact: Uncontrolled charging at peak hours exacerbates peak demand stress

Grid Challenges:

Without coordinated management, EV charging creates several grid challenges:

- Peak demand increase of 50-100% during evening hours
- Voltage violations in distribution networks due to uncontrolled high-power charging
- Transformer overloading in local neighborhoods
- Increased emissions from fossil fuel plants running to meet peak EV demand
- Reduced battery cycle life from suboptimal charging patterns

Hybrid EV Charging System Architecture

1. Solar-PV Based EV Charging Stations

Solar generation directly aligns with EV usage patterns in many applications (workplace, fleet depots, shopping centers). A solar-battery EV charging system integrates:

- Rooftop or canopy solar PV arrays (typically 50-200 kW for medium station)
- Battery energy storage (typically 100-500 kWh)
- Bidirectional chargers supporting vehicle-to-grid (V2G) capability
- Intelligent energy management systems (EMS)
- Grid connection with net metering

Operational Principle:

During sunny periods, solar energy charges EV batteries and charges the storage system. During peak EV demand (evening), stored energy supplies charging stations, reducing grid power import. The grid provides backup when both solar and battery are depleted.

Economic Performance:

- 40-60% reduction in grid electricity import
- 60-80% reduction in peak demand charges
- Payback period: 6-10 years in high-solar-resource locations
- Combined with V2G technology, vehicles can export power during critical periods

2. Wind-Battery EV Charging Systems

In windy regions or island locations, wind turbines combined with battery storage provide renewable EV charging. Wind generation is often stronger during winter and evening hours, complementing EV charging demand.

Advantages of Wind-Based Systems:

- Year-round generation independent of season (unlike solar)
- Synergy with evening EV charging demand
- Excellent for remote locations with strong wind resources
- Scalable from standalone stations to regional charging networks

3. Hybrid Solar-Wind-Battery Systems

The most robust hybrid EV charging systems combine solar and wind generation with storage:

- Solar provides peak daytime generation
- Wind provides complementary generation, especially evening/winter
- Battery storage buffers both sources' variability
- Grid connection provides final reliability backup

Resource complementarity improves system capacity factor and reduces overall battery sizing requirement.

4. Grid-Connected Hybrid Systems with V2G Technology

Vehicle-to-Grid (V2G) transforms EV batteries from pure loads to distributed energy resources:

V2G Functionality:

- During off-peak hours, EVs charge from renewable energy, grid, or storage
- During peak hours or grid stress events, EVs export stored energy back to grid
- Provides frequency regulation and voltage support services
- Reduces need for centralized energy storage

System Architecture:

- Bidirectional chargers: Communicate with vehicle and grid, managing power flow direction
- Aggregationplatforms:Coordinatemultiplevehiclechargingand discharging
- Time-varying tariffs: Incentivize charging during low-demand/high-renewable periods
- Grid services market participation: EVs generate revenue by providing frequency regulation

Grid Integration Scenarios:

Scenario 1 - Isolated Renewable Station (Off-Grid):

A rural EV charging station powered by solar PV and battery, serving occasional travelers. No grid connection requires oversized battery capacity (20-30 hours autonomy).

Scenario 2 - Semi-Autonomous Workplace Charging:

Corporate charging station with rooftop solar and 4-hour battery storage. Supplies 70-80% of daily EV charging energy, with grid providing backup during peak demand.

Scenario 3 - Urban Fast-Charging Hub with V2G:

High-power fast-charging station with 100-200 vehicle daily throughput. Limited local renewable capacity but coordinated V2G enables vehicles themselves to store and export energy. Real-time EMS optimizes vehicle charging timing based on wholesale electricity prices and renewable availability.

Scenario 4 - Fleet Depot Integration:

Urban bus or delivery vehicle depot with predictable overnight charging pattern. Oversized solar arrays and 8-12 hour battery storage system supply entire fleet charging energy. Peak solar generation (midday) misaligned with charging (evening) requires substantial storage.

Advanced Energy Management for EV Charging

1. Predictive Energy Management

Machine learning models predict:

- EV arrival/departure patterns and energy requirements
- Solar and wind generation based on weather forecasts
- Wholesale electricity price variations
- Grid demand forecasts

Optimization algorithms use these predictions to:

- Precharge batteries during cheap/high-renewable periods
- Schedule EV charging for optimal economic and grid impact
- Reserve battery capacity for high-price periods
- Coordinate V2G discharge during grid peak stress

2. Smart Charging Algorithms

- Availability-based charging: Charges only when solar/wind generation available
- Time-of-use scheduling: Shifts charging to low-tariff periods
- Grid-aware charging: Adjusts charging power based on real-time grid frequency
- Vehicle-integratedoptimization:Communicateswithdriverappfor destination/arrival time
- Demand response participation: Reduces charging during grid peak emergencies

3. Microgrid Operating Modes for EV Charging

EV charging stations integrated into microgrids benefit from coordinated control: Grid-connected mode: Maximize renewable utilization while minimizing peak import through time-shifting and V2G.

Islanded mode: During grid outages, EV charging provides grid services while maintaining charging for essential vehicles. Sophisticated load management prioritizes critical EV charging (emergency vehicles, public transport) over non-essential private vehicles.

Environmental and Economic Benefits

Emissions Reduction:

- Direct reduction in tailpipe emissions (zero at charging point)
- Indirect reduction through renewable-powered charging (60-90% lower emissions vs. diesel-powered vehicles)
- Additional grid emission reduction through V2G frequency regulation services

Economic Benefits:

- 40-70% reduction in EV charging costs vs. grid-only charging
- Revenue generation through V2G services (V2G-capable vehicles)
- Reduced grid infrastructure investment through distributed storage
- Job creation in installation, operation, and management
- Corporate sustainability goals achievement

Challenges and Solutions

Challenge	Solution
Chargingdemandpeakalignment withpeakelectricity price	Smart charging algorithms and V2G technology
Vehiclebatterydegradationfrom rapidcharging	Intelligent thermal management and optimizedchargingprofiles
Gridsynchronizationandstability withhighchargerdensity	Advancedgrid-forminginvertersandreal-timecontrol
Consumer acceptanceand charging anxiety	Mobileapps,predictivescheduling,V2G revenueincentives
Regulatory uncertainty in some markets	Pilotprograms,gridcodesdevelopment, tariffincentives
Highupfrontcapitalcost	Governmentsubsidies,decliningbattery costs,revenuefromgridservices

Future Developments

- Wireless charging: Eliminates connector use, enables dynamic charging on roadways
- Autonomous vehicle charging: Self-driving vehicles optimize charging timing independently
- Integrated Energy Storage: Dual-purpose vehicle batteries for both transport and stationary grid support
- High-power charging networks: 350+ kW charging reducing charge time to
- < 15 minutes
- Renewable charging corridors: High-density solar/wind charging networks along major EV corridors
- Sector coupling: Hybrid EV charging with heating/cooling loads and hydrogen production for transportation diversity



Figure: 11.7 Hybrid System for EV Charging

CHECK YOUR PROGRESS

Q1: Fill in the blanks:

i. The_____ of a battery, measured in Ampere-hours (Ah), represents the total amount of electrical charge that a fully charged battery can deliver.

ii. _____ is the maximum safe voltage at which a battery should be disconnected from the supply to prevent overcharging and extend battery life.

iii. A_____ is connected to the utility grid, allowing two-way power exchange, and uses the grid as virtual storage.

iv. _____ enables time-shifting of renewable generation, allowing solar/wind power generated during favorable conditions to be used during peak demand periods.

v. _____ transforms electric vehicles from pure loads into distributed energy resources capable of providing grid support services.

Q2: What is a microgrid system?

Q3: Name two types of batteries.

Q4: State one role of energy storage in hybrid systems.

11.7 LET US SUM UP

- Batteries are key storage devices in hybrid systems and lithium-ion is more efficient than lead-acid.
- Battery life depends on proper charging/discharging and factors like temperature, depth of discharge, and discharge rate.
- Hybrid systems include standalone, grid-tied, and microgrid types.
- Energy storage enables load balancing, peak shaving, and smooth renewable integration.

- Storage supports grid stability through frequency control, voltage regulation, and black-start capability.
- Hybrid EV charging reduces grid stress and enables smart charging and V2G systems.

11.8 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: i. capacity, ii. End-of-charge voltage, iii. grid-tied hybrid system, iv. Energy storage, v. V2G (Vehicle-to-Grid) technology]

Ans to Q2: A small grid that can operate independently or with the main grid.

Ans to Q3: Lead-acid and lithium-ion.

Ans to Q4:Energy storage helps in balancing supply and demand by storing excess energy and supplying it when needed.

11.9 FURTHER READING

- ErsanKabalci (2021). Hybrid Renewable Energy Systems and Microgrids. Academic Press.
- Apel Mahmud, Jahangir Hossain (2014). Renewable Energy Integration: Challenges and Solutions. Springer Nature Singapore.
- Gilbert M. Masters, Kevin F. Hsu (2023). Renewable and Efficient Electric Power Systems. John Wiley & Sons, Incorporated.
- Masters, G. M. (2013). Renewable and Efficient Electric Power Systems. Wiley.

11.10 MODEL QUESTIONS

Q1: Classify the different types of batteries and briefly explain each type.
Q2: What are the key specifications of a battery, and how do charging and discharging characteristics affect its performance?
Q3: Define hybrid systems and explain their classification.
Q4: Differentiate between standalone, grid-tied, and microgrid-based hybrid systems.
Q5: Explain the role of energy storage in hybrid systems and its importance in EV charging applications.

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UNIT 12: ENERGY ECONOMICS AND AUDITING

UNIT STRUCTURE

12.1 Learning Objectives
12.2 Introduction
12.3 Economics of Energy Savings Schemes
  12.3.1 Costs and Interest Components
  12.3.2 Depreciation Methods and Calculations
12.4 Investment in Energy Saving Projects
  12.4.1 Rate of Return Analysis
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12.5 Case Studies: Energy Audit Applications
  12.5.1 Energy Audit of Electrical, Mechanical, and Thermal Equipment
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12.6 Lifecycle Assessment of Energy Systems
12.7 Socio-Economic Aspects of Energy Transition
12.8 Let Us Sum Up
12.9 Answers to Check Your Progress
12.10 Further Reading
12.11 Model Questions

12.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- analyze costs, interest, and depreciation components in energy savings schemes
- calculate depreciation using various accounting methods applicable to energy systems
- explain the time value of money and its role in energy project economics
- apply rate of return, payback period, and discounted cash flow methods to evaluate energy investments
- evaluate financial viability of energy saving projects using multiple financial metrics
- conduct comprehensive energy audits across electrical, mechanical, and thermal equipment

12.2 INTRODUCTION

This unit focuses on the principles of energy economics and their role in sustainable energy planning and decision-making. It introduces the concepts of energy cost analysis, interest calculations, and depreciation methods, followed by investment evaluation techniques such as rate of return, payback period, and discounted cash flow analysis. The unit also explores energy auditing through practical case studies across residential, commercial, and industrial sectors to identify energy-saving opportunities. In addition, it examines lifecycle assessment (LCA) for evaluating the environmental and economic impacts of energy systems. Finally, the unit discusses the socio-economic aspects of energy transition, including employment generation, public health, energy access, and equitable development. Practical examples and case studies are integrated throughout the unit to demonstrate the application of these concepts in achieving sustainable energy solutions in line with NEP-2020 principles.

12.3 ECONOMICS OF ENERGY SAVINGS SCHEMES

The economics of energy savings schemes require comprehensive accounting of all direct and indirect costs associated with efficiency improvements and their financial benefits. Understanding cost structures and time-value-of-money principles is essential for comparing alternative efficient investments and making optimal capital allocation decisions.

Energy savings projects involve calculations of multiple cost types, that must be included in financial analysis. Capital costs include equipment purchase price, installation charges, engineering design and permitting fees etc. These are the up-front investments required to implement energy efficiency measures.

Operating costs include maintenance, spare parts replacement, operator training and monitoring system expenses that occur throughout the project lifetime. Disposal costs address end-of-life removal and recycling expenses for replaced equipment. Financing costs arise when capital is borrowed through loans or credit arrangements and include both principal repayment and interest payments. Understanding these cost components enables accurate project budgeting and realistic financial forecasting.

Interest calculations account for the cost of borrowed capital and the time value of money. Simple interest, calculated as-

$$S = (1 + ni) \quad (1)$$

Here, S represents the cost of the object including non-compounding interest, where n is the number of periods and i is the periodic interest rate.

For example, Rs.1,00,000 borrowed for 3 years at 10% simple annual interest yields:

$$S = 1{,}00{,}000(1 + 3 \times 0.10) = Rs.\ 1{,}30{,}000$$

Here, Rs. 30,000 is the total interest cost.

However, most financial arrangements use compound interest, calculated as-

$$S = (1 + i)n \quad (2)$$

Here the interest accumulates on previous interest.

The same Rs.1,00,000 at 10% compound interest for 3 years yields:

$$S = 1,00,000(1.10)3 = Rs.\ 1,33,100$$

In this case Rs. 33,100 is the total interest cost.

Compound interest effects become substantial over longer periods. It is particularly important for energy systems with 10-25 years of lifetimes. Effective annual interest rates account for compounding frequency, with more frequent compounding resulting in higher effective rates despite identical nominal rates.

Energy saving projects frequently employ debt financing, making interest calculation critical to determining true project costs. Monthly or quarterly compounding is standard for commercial loans and understanding the relationship between nominal and effective interest rates prevents underestimating actual financing costs. Many energy efficiency programmes offer below-market financing rates to accelerate adoption, making financial analysis crucial for evaluating program benefits against standard market financing.

12.3.1 Costs and Interest Components

Energy savings schemes must consider purchase costs for efficient equipment, which may exceed conventional alternatives by 20-40%, though this premium is recovered through reduced operating costs. A premium-efficiency motor costing Rs.2,00,000 versus Rs.1,50,000 for standard efficiency represents a Rs.50,000 capital cost increment. However, if annual electricity savings is total Rs.25,000, the payback occurs within 2 years. After that the project generates pure savings. Installation costs for efficiency improvements vary widely. For example, LED retrofits require basic labour while insulation upgrades need specialized contractors and may cost Rs.150-200 per square meter.

Interest charges on borrowed capital significantly impact project economics, particularly for large investments. A Rs.5,00,000 energy efficiency loan at 8% annual interest repaid over 5 years incurs approximately Rs.1,16,000 total interest cost, or 23% of the principal. Shorter repayment periods reduce total interest but increase annual payments, while longer terms reduce annual obligations, but increase total interest paid. Energy project financing often uses 5-10 year terms, requiring careful analysis of cash flow adequacy for loan servicing alongside operational expenses.

12.3.2 Depreciation Methods and Calculations

Depreciation allocates an asset's capital cost systematically across its useful life for accounting and tax purposes. The straight-line depreciation method divides total depreciable cost equally across useful life years:

$$\text{Annual Depreciation} = \frac{\text{Capital Cost} - \text{Salvage Value}}{\text{Useful Life Years}}$$

For example, a Rs.10,00,000 solar thermal system with Rs.2,00,000 salvage value and 20-year useful life depreciates Rs.40,000 annually:

$$(10,00,000 - 2,00,000)/20 = Rs.\ 40,000/year.$$

This method is most common for energy equipment and creates tax deductions that reduce overall project costs.

Accelerated depreciation methods front-load deductions, providing faster tax benefits. The double-declining-balance method applies double the straight-line rate to the declining book value, creating larger early-year deductions. For the Rs.10,00,000 system with 5% straight-line rate, year 1 depreciation is calculated as-

$$10\% \times 10,00,000 = Rs.\ 1,00,000$$

The year 2 depreciation will be-

$$10\% \times 9,00,000 = Rs.\ 90,000$$

Accelerated methods improve early cash flow, but total depreciation across asset life remains identical.

Units-of-production depreciation ties cost allocation to actual usage rather than calendar years, appropriate for equipment whose wear correlates with operational intensity. A Rs.5,00,000 pump system operating 8,000 hours annually with 40,000-hour useful life depreciates at Rs.62.50/hour. This amount to an annual depreciation of Rs.5,00,000 × (8,000 hours). This method aligns cost recognition with actual value consumption and is increasingly used for energy equipment subject to variable utilization.

12.4 INVESTMENT IN ENERGY SAVING PROJECTS

Evaluating energy-saving projects requires financial methods that consider project cost, duration, profitability, and risk. Common evaluation techniques include the payback period, rate of return (ROR), and discounted cash flow (DCF) methods, each providing different insights into project performance.Since energy efficiency projects compete with other investment opportunities, organizations use these financial metrics to compare alternatives, prioritize projects, and allocate resources effectively. Final investment decisions also consider factors such as risk, strategic objectives, and technical feasibility.

12.4.1 Rate of Return Analysis

Rate of Return (ROR) or Return on Investment (ROI) expresses project profitability as a percentage of capital invested:

$$\text{Rate of Return } (\%) = \frac{\text{Annual Net Savings}}{\text{Total Investment}} \times 100$$

A Rs.5,00,000 LED retrofit generating Rs.1,00,000 annual electricity savings yields 20% ROR:

$$(1,00,000/5,00,000) \times 100 = 20\%$$

This metric directly indicates annual return percentage and is easily communicated to non-financial audiences. ROR comparison, for example, 20% for the LED project versus 12% for alternative insulation upgrades, clearly indicates LED investment preference on profitability grounds.

However, simple ROI ignores project duration effects, treating one-year and twenty-year projects identically if annual savings percentages match. A 20% ROR project generating savings for only 5 years has fundamentally different total returns than a 20% ROI project with 20-year life. Therefore, ROR should accompany project duration information for complete evaluation context.

Cumulative Return calculates total savings across the project lifetime: Cumulative Return = Annual Savings × Useful Life Years.

The LED retrofit with Rs.1,00,000 annual savings over 20 years generates Rs.20,00,000 cumulative savings. This is four times the initial investment. Subtracting cumulative costs (maintenance, replacement parts) from cumulative savings yields net project benefit, enabling evaluation of absolute financial magnitude alongside percentage metrics.

12.4.2 Payback Period Method

Payback Period measures the time required to recover the initial investment through accumulated project savings:

$$\text{Simple Payback Period (years)} = \frac{\text{Initial Investment}}{\text{Annual Savings}}$$

A Rs.2,50,000 building automation system saving Rs.50,000 annually via HVAC optimization has a 5-year payback:

2,50,000/50,000 = 5 years

This metric directly answers "How long until I recover my money?" and appeals to risk-averse decision-makers preferring faster capital recovery.

Payback period's primary limitation is ignoring benefits beyond payback completion and disregarding time-value-of-money. A project with 4-year payback generating savings for 15 years delivers substantially more total benefit than a 4-year payback project with 5-year useful life, yet simple payback treats them equivalently. Additionally, Rs.1 in year-4 savings is worth less than Rs.1 in year-1 savings due to inflation and investment opportunity costs, but simple payback ignores this distinction.

Discounted Payback Period addresses the time-value limitation by using present-value cash flows:

Discounted Payback = First year when cumulative PV cash flows equal initial investment

Using 10% annual discount rate, Rs. 50,000 annual savings from the automation system has present values:

Year 1: Rs.45,454;

Year 2: Rs.41,322;

Year 3: Rs.37,567;
Year 4: Rs.34,155;
Year 5: Rs.31,050.
Cumulative PV: Year 4 total Rs.1,58,498, Year 5 total Rs.1,89,548.
The discounted payback occurs between years 5 and 6, which is substantially longer than the simple 5-year payback. This reflects that inflation reduces real value of future savings.
Payback analysis is particularly useful for organizations with limited capital availability, high uncertainty regarding equipment life, rapid technological change, or short planning horizons. Many utilities and energy service companies use payback periods to pre-screen projects, setting maximum acceptable payback targets of 4-7 years before proceeding to more detailed financial analysis.

12.4.3 Discounted Cash Flow Methods

Discounted Cash Flow (DCF) methods account for time-value-of-money by discounting all future cash flows to present value, using methods including Net Present Value (NPV) and Internal Rate of Return (IRR). These methods are superior for long-duration projects, volatile savings streams, or when accurate discount rate determination is possible.

$$\text{Net Present Value (NPV)} = \sum \frac{\text{Cash Flow}_t}{(1+r)^t} - \text{Initial Investment}$$

Where Cash Flow$_t$ is savings in year *t, r* is the discount rate, and *t* is the year number. NPV represents the additional net benefit of the project compared to alternative investments earning the discount rate of return. Positive NPV indicates the project exceeds minimum return requirements. An energy project with Rs.5,00,000 initial investment, Rs.1,00,000 annual savings for 10 years, and 10% discount rate has:

$$\text{NPV} = \left[\frac{1{,}00{,}000}{1.10^1} + \frac{1{,}00{,}000}{1.10^2} + \cdots + \frac{1{,}00{,}000}{1.10^{10}}\right] - 5{,}00{,}000$$

NPV = 6,14,456 − 5,00,000 = Rs.1,14,456

The positive NPV of Rs.*1,14,456* indicates the project provides returns exceeding the 10% hurdle rate, justifying investment from a financial perspective.
Internal Rate of Return (IRR) is the discount rate at which NPV equals zero, the breakeven return rate. Projects with IRR exceeding the organization's cost of capital are financially acceptable. For the above project, IRR can be calculated as approximately 15.1%, indicating the project returns 15.1% annually—substantially exceeding the 10% hurdle rate.
DCF methods are particularly suitable for energy efficiency projects where careful economic analysis is warranted. However, they require reliable future cash flow estimates and selection of appropriate discount rates, which may be controversial for long-duration projects or novel technologies with uncertain performance.

12.5 CASE STUDIES: ENERGY AUDIT APPLICATIONS

Energy audits systematically identify efficiency improvement opportunities by measuring current energy consumption, comparing against benchmarks, and prioritizing recommendations by financial return and technical feasibility. Different facility types, such as- industrial plants, commercial buildings, residential homes require audit approaches matched to their specific energy use patterns and operational constraints. Case studies demonstrate audit methodology application and quantifiable results achieved across diverse sectors.

12.5.1 Energy Audit of Electrical, Mechanical, and Thermal Equipment

Comprehensive equipment audits assess power consumption, efficiency, and operating conditions using instruments such as power quality analyzers, thermal cameras, and motor testers. Electrical audits identify overloaded circuits, poor power factor, and inefficient motors. For example, replacing oversized motors in a cement plant reduced energy consumption by 8%.

Mechanical equipment audits focus on pumps, compressors, and conveyor systems. In a dairy plant, improving refrigerant pipe insulation reduced compressor runtime by 25%, while timely bearing replacement lowered energy use by 15% and prevented equipment failure.

Thermal equipment audits evaluate boilers, furnaces, and heat exchangers. In a textile plant, repairing steam pipe insulation reduced boiler fuel consumption by 12% with a 10-month payback. These examples show that systematic energy audits effectively identify energy-saving opportunities with rapid financial returns.

12.5.2 Energy Audit of Residential Sector

Residential energy audits evaluate major energy uses, including heating, cooling, water heating, lighting, and appliances. Techniques such as blower door tests detect air leakage, while thermal imaging identifies insulation gaps and heat losses for targeted improvements.

A residential audit in the Delhi NCR region recommended window replacement, insulation improvement, LED lighting, and solar water heating. These measures significantly reduced energy consumption and lowered annual electricity bills, though the payback period depended on the level of investment.

The effectiveness of residential energy audits varies with home age, design, and climate. Older homes generally achieve 25–40% energy savings through retrofitting, whereas newer energy-efficient homes typically achieve 15–25% savings.

12.5.3 Energy Audit of Industrial Sector

Industrial energy audits can reduce energy consumption by 20–30%, with many measures achieving payback within 3 years. Audits identify opportunities such as installing variable frequency drives (VFDs), improving process efficiency, and optimizing equipment performance.
A sugar processing plant reduced cooling tower power consumption through water treatment and cleaning, achieving significant energy savings with a 0.5-year payback. Similarly, a textile mill reduced energy losses by repairing steam leaks, recovering the investment within 3 months.

These case studies show that industrial energy audits effectively identify cost-effective measures that improve energy efficiency, reduce operating costs, and enhance process reliability.

12.5.4 Energy Audit of Commercial Sectors

Commercial buildings, including offices, hospitals, hotels, and shopping malls, consume most of their energy in HVAC systems (40–50%) and lighting (20–30%). Energy audits identify opportunities to improve efficiency through equipment optimization and better energy management.
In office buildings, measures such as variable frequency drives (VFDs) significantly reduce HVAC energy use. Hospital audits recommend upgrading outdated equipment and improving maintenance while ensuring uninterrupted operations. Shopping mall audits commonly promote LED lighting, occupancy sensors, and escalator/elevator optimization, resulting in substantial energy savings, lower maintenance costs, and short payback periods.
These examples demonstrate that commercial energy audits effectively reduce energy consumption, operating costs, and improve overall building performance.

12.6 LIFECYCLE ASSESSMENT OF ENERGY SYSTEMS

Lifecycle Assessment (LCA) is a standardized methodology evaluating environmental and economic impacts of products and systems across their complete lifespan from raw material extraction through manufacturing, transportation, operation, and end-of-life disposal/recycling. For energy systems, LCA quantifies total greenhouse gas emissions, resource depletion, water consumption, and other environmental burdens across all life stages, enabling objective comparison between competing technologies and informing policy decisions regarding technology support.
LCA methodology standardized by ISO 14040/14044 comprises:

(1) Goal and Scope Definition establishing system boundaries, functional units (e.g., 1 MWh electricity generation), and assumptions;
(2) Inventory Analysis quantifying material and energy flows for each lifecycle stage;
(3) Impact Assessment converting inventory data into environmental impacts;

(4) Interpretation synthesizing results and comparing alternatives.

For renewable energy systems, lifecycle assessment reveals dramatic differences compared to fossil fuel plants. Coal-fired electricity generation produces 900-1100 grams

CO_2-equivalent per kilowatt-hour when including fuel extraction, transportation, plant construction, operation, and decommissioning, dominated by fuel combustion emissions. Wind turbine electricity generates 10-15 grams CO_2-equivalent per kilowatt-hour, with most emissions from steel/concrete manufacturing and transportation; operation produces essentially zero emissions except manufacturing maintenance and replacement part transportation. Solar photovoltaic systems generate 40-50 grams CO_2-equivalent per kilowatt-hour, primarily from silicon processing and panel manufacturing; operation again produces near-zero emissions.

Cumulative lifecycle GHG emissions comparison reveals that renewable energy systems typically achieve carbon payback, recovering their manufacturing emissions through clean operation, within 1-3 years. A solar system operating 25-30 years will offset 15-25 times its manufacturing emissions, and wind systems offset 20-50 times manufacturing emissions through clean operation. This advantage compounds with grid decarbonization: as electricity grids add more renewables, manufacturing of new renewable equipment consumes cleaner electricity, further reducing lifecycle emissions.

Water consumption lifecycle assessment reveals less intuitive findings: coal and nuclear plants consume substantial water for cooling (10-15 liters per kWh), while solar and wind consume minimal water for operation (0.1 liters per kWh), though solar manufacturing consumes 0.5-1.5 liters per kWh. In water-stressed regions (India, Middle East, North Africa), this operational water advantage provides additional justification for renewable technology preference.

Material resource depletion analysis shows renewable energy systems use common materials, such as steel, copper, aluminum, silicon, available in abundant quantities, while fossil fuel systems permanently consume non-renewable resources. Wind turbines employ approximately 10-15 tons of steel and copper per megawatt capacity, with recycling potential for 90%+ of materials. This contrasts with coal plants consuming millions of tons of non-renewable fossil fuel that permanently leaves the resource base.

12.7 SOCIO-ECONOMIC ASPECTS OF ENERGY TRANSITION

Employment and Economic Development:

Renewable energy creates more jobs than fossil fuels in manufacturing, installation, and maintenance. India's renewable energy sector employed about 350,000 people in 2020 and is expected to exceed 1 million jobs by 2030. However, coal industry employment has declined, making worker retraining, income support, and alternative livelihoods essential.

Health and Air Quality Improvements:

Replacing fossil fuels with renewable energy reduces air pollution and prevents millions of premature deaths. In India, cleaner energy can significantly lower pollution-related illnesses and healthcare costs, with health benefits often exceeding transition costs.

Energy Access and Poverty Alleviation:

Distributed renewable systems, such as solar microgrids and mini-hydro projects, provide electricity to remote areas. Reliable energy improves income, supports agriculture and small businesses, reduces poverty, and saves time, especially for women, by reducing firewood collection.

Educational and Social Benefits:

Electricity access improves education by enabling better lighting, digital learning, and laboratory facilities. It increases school attendance and academic performance, particularly among girls, while improving overall quality of life.

Just Transition:

A successful energy transition requires fair policies to support affected workers and communities. Key measures include worker retraining, income protection, economic diversification, protection of indigenous rights, and safeguards against energy price increases to ensure an equitable transition.

CHECK YOUR PROGRESS

Q1: What is meant by the economics of energy savings schemes?
Q2: Why is depreciation important in energy projects?
Q3: What is the payback period?
Q4: What is the main purpose of an energy audit?
Q5: What is Lifecycle Assessment (LCA)?
Q6: Name two sectors where energy audits are commonly conducted.
Q7: Mention one socio-economic benefit of the energy transition.

12.8 LET US SUM UP

- The unit introduced the fundamentals of energy economics and financial analysis of energy-saving projects.
- It explained key investment evaluation methods such as ROR, Payback Period, NPV, and IRR.
- It discussed energy auditing as a tool for improving energy efficiency in different sectors.
- The unit described Lifecycle Assessment (LCA) for evaluating the environmental impacts of energy systems.
- It highlighted the socio-economic benefits of energy transition and the importance of a just transition.

12.9 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: It is the evaluation of the costs and financial benefits of implementing energy efficiency measures.

Ans to Q2: Depreciation distributes the cost of an asset over its useful life and helps determine its financial value.

Ans to Q3: The payback period is the time required to recover the initial investment from the savings generated by a project.

Ans to Q4: An energy audit identifies energy losses and recommends measures to improve energy efficiency and reduce costs.

Ans to Q5: LCA is a method used to evaluate the environmental impacts of a product or energy system throughout its entire life cycle.

Ans to Q6: Residential and industrial sectors.

Ans to Q7: It creates employment opportunities while reducing environmental pollution and improving energy access.

12.10 FURTHER READING

- Mukerji, S., Chelleri, L., & Wirth, M. (2017). Cost-Benefit Analysis of Energy Efficiency Measures. *Journal of Sustainable Development*, 10(2), 15-32. — An accessible overview of financial analysis methods applicable to diverse energy projects across sectors.
- International Organization for Standardization. (2016). *ISO 14040:2016 Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO. — The international standard defining LCA methodology for consistent environmental impact evaluation.
- National Renewable Energy Laboratory. (2023). *Life Cycle Assessment Harmonization Results and Recommendations*. NREL Technical Report. https://www.nrel.gov/analysis/life-cycle-assessment— Comprehensive harmonization of lifecycle assessment data showing renewable energy significantly outperforms fossil fuels across environmental metrics.
- Bureauof EnergyEfficiency.(2020).*EnergyAuditingGuidelinesfor Buildingsand IndustrialFacilities*.GovernmentofIndiaMinistryof Power.—Officialguidelines for conducting energy audits in India with sector-specific recommendations and case studies.
- WorldHealthOrganization.(2019).*HealthandAirPollution:QuantifyingImpacts on Health*. WHO Publications. — Systematic analysis of air pollution health impacts relevant to energy transition decision-making.
- Cole, W., et al. (2018). Cost Projections for Utility-Scale Battery Storage. *NREL Technical Report*. — Analysis of energy storage costs, important for evaluating hybrid renewable systems discussed in Unit 11.

12.11 MODEL QUESTIONS

Q1: Examine the key cost components involved in energy savings schemes and explain how each component influences overall project feasibility.

Q2: Discuss the concept of the time value of money and analyse its significance in evaluating long-term energy projects.

Q3: Compare straight-line and accelerated methods of depreciation, highlighting their implications for energy project financial planning.

Q4: Evaluate the advantages and limitations of the payback period method in assessing energy efficiency investments.

Q5: Explain the concept of Rate of Return (ROI) and assess its suitability as a decision-making tool for energy projects of varying lifespans.

Q6: Analyse the role of Discounted Cash Flow (DCF) techniques, particularly Net Present Value (NPV) and Internal Rate of Return (IRR), in energy investment decisions.

Q7: Describe the methodology of conducting an energy audit and discuss its importance in improving energy efficiency across different sectors.

Q8: Assess the significance of lifecycle assessment (LCA) in comparing renewable and conventional energy systems.

Q9: Discuss the socio-economic impacts of energy transition, with particular reference to employment, health, and energy access.

Q10: Using suitable examples, explain how energy audits can identify cost-effective opportunities for efficiency improvement in industrial or commercial sectors.

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UNIT 13: RENEWABLE ENERGY POLICIES

UNIT STRUCTURE

13.1 Learning Objectives
13.2 Introduction
13.3 National Renewable Energy Policies in India
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13.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- explain the meaning and importance of renewable energy policies
- apply major national renewable energy policies and regulatory mechanisms in India
- analyze important international renewable energy policy frameworks and partnerships
- coordinate policy implementation for rural electrification and smart city development
- justify the objectives and significance of PM-KUSUM, PM Surya Ghar, MuftBijliYojana and Green Energy Corridors.

13.2 INTRODUCTION

The previous unit discussed energy economics and auditing. In this unit, we will explore renewable energy policies. Renewable energy policies are legal, regulatory, financial, and institutional measures adopted by governments and international agencies to promote the generation, transmission, distribution, and use of energy from sustainable sources. This unit covers national and international renewable energy policies, with special emphasis on their role in rural electrification and smart cities. It also discusses three important Indian initiatives namely PM-KUSUM, PM Surya Ghar: MuftBijliYojana, and Green Energy Corridors. Finally, the unit focuses on how these policies are implemented through schemes, incentives, and infrastructure support.

13.3 NATIONAL RENEWABLE ENERGY POLICIES IN INDIA

India's renewable energy policy framework is guided by the twin goals of energy transition and inclusive development. Over time, the country has adopted a mix of legislative measures, national missions, market mechanisms and subsidy-based schemes to accelerate renewable energy deployment. The Ministry of New and Renewable Energy (MNRE), Central Electricity Authority (CEA), Central Electricity Regulatory Commission (CERC) and state agencies all play important roles in shaping and implementing these policies.

The policy direction in India reflects several priorities: reducing dependence on imported fossil fuels, improving electricity access, supporting climate commitments, promoting domestic manufacturing and strengthening energy infrastructure. Since renewable energy technologies differ in cost, scale and location requirements, policies are designed for both grid-connected and decentralized applications. This dual approach is particularly useful for a country with large urban loads as well as geographically dispersed rural settlements. Figure 13.1 shows the Renewable Energy policy framework in India.

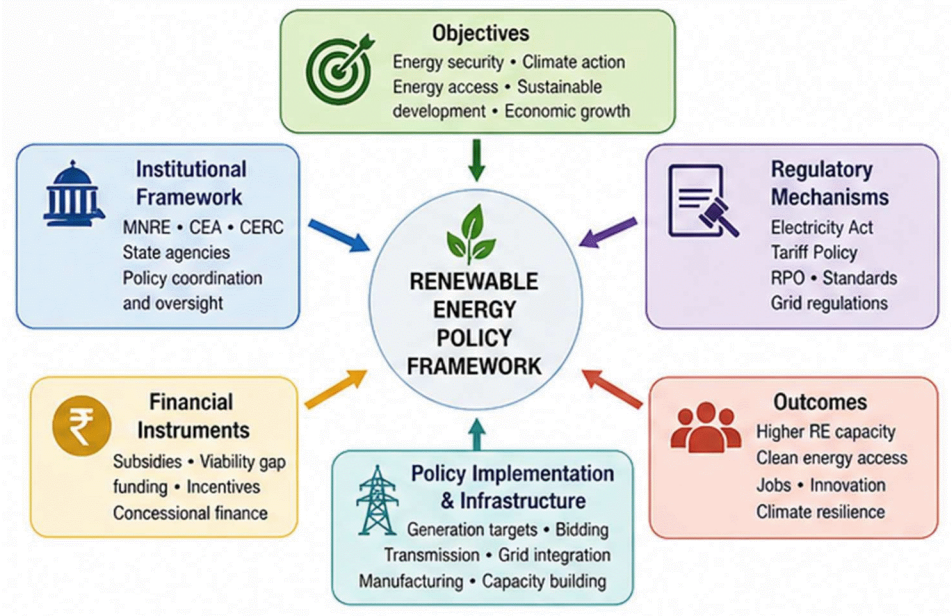


Figure 13.1: Renewable Energy Policy Framework

National Action Plan on Climate Change and Renewable Energy Missions A major policy milestone in India was the National Action Plan on Climate Change (NAPCC), which created a broad framework for climate-responsive development. One of its important components was the National Solar Mission, which aimed to promote solar power generation, technological development and cost reduction. The mission helped create a long-term policy environment for utility-scale solar parks, rooftop systems and off-grid solar applications. The renewable energy sector in India has subsequently benefited from national targets, competitive bidding, concessional financing and production-linked support. These efforts improved investor confidence and accelerated capacity addition in solar and wind power. The policy emphasis also expanded from generation alone to include transmission connectivity, storage readiness, domestic manufacturing and energy access.

National policy has gradually moved toward integrated energy planning. This means renewable energy is now viewed not only in terms of installed megawatts but also in terms of grid stability, local livelihoods, agricultural productivity, clean cooking, electric mobility and climate resilience. Such an integrated approach is essential for balancing technical feasibility with social and economic outcomes.

Electricity Act, Tariff Policy and Renewable Purchase Obligation

The Electricity Act, 2003 provided a crucial legal basis for the promotion of renewable energy in India. It enabled state electricity regulatory commissions to encourage generation from renewable sources and opened the door for grid connectivity, tariff regulation and market participation. Over time, this legal framework helped mainstream renewable electricity within the broader power sector.

The Tariff Policy and related regulatory instruments further supported renewable energy by encouraging preferential tariffs, competitive procurement and long-term planning. A particularly important mechanism is the Renewable Purchase Obligation (RPO), under which specified entities such as distribution companies and certain large consumers are

required to procure a fixed share of electricity from renewable sources. RPO has been an important demand-side instrument for building a market for renewable electricity.

Another related mechanism is the Renewable Energy Certificate (REC) framework, which allows renewable attributes to be traded separately from physical electricity in certain cases. This mechanism supports flexibility in compliance and encourages renewable generation even in regions where direct purchase is difficult. Together, the Electricity Act, tariff reforms, RPO and REC mechanisms form the regulatory backbone of renewable energy promotion in India.

13.4 INTERNATIONAL RENEWABLE ENERGY POLICY FRAMEWORKS

Renewable energy policy is not shaped only at the national level. International agreements, institutions and cooperative platforms strongly influence national targets, financing options, technology transfer, and monitoring systems. These frameworks are especially significant for developing countries, where the energy transition must proceed alongside poverty reduction and infrastructure expansion.

International policy frameworks generally promote renewable energy for three interrelated reasons: climate mitigation, sustainable development and universal energy access. They also recognize that energy transition requires differentiated responsibilities, as developed and developing countries have different historical emissions, capacities and developmental needs. Therefore, international policy often combines broad goals with flexible national pathways.

Paris Agreement and Global Climate Commitments

The Paris Agreement under the United Nations Framework Convention on Climate Change represents a major global framework influencing renewable energy policy. Countries submit nationally determined contributions, which outline how they plan to reduce emissions and enhance climate action. Although the agreement does not

prescribe a single renewable energy pathway, it has significantly strengthened policy momentum for solar, wind, storage, electrification and energy efficiency worldwide.

For India and many other nations, renewable energy expansion is a key strategy for achieving climate goals while also addressing development needs. The Paris framework encourages long-term planning, regular progress reporting and alignment between domestic policy and global climate commitments. It also increases the relevance of green finance, carbon-conscious investment and low-emission infrastructure planning.

International climate negotiations have therefore made renewable energy policy more measurable and accountable. Countries are now expected not only to announce goals but also to show progress through implementation, reporting and institutional coordination. This has improved the policy visibility of renewable energy in national planning processes.

International Solar Alliance and Sustainable Development Goals

The International Solar Alliance (ISA), launched with strong support from India, is an important intergovernmental initiative focused on expanding solar energy deployment, especially in countries with high solar potential. It promotes collaboration in areas such as finance, technology, capacity building and project development. For developing countries, the ISA helps create an enabling ecosystem for solar adoption beyond national boundaries.

Renewable energy policy is also closely linked to the United Nations Sustainable Development Goals (SDGs), especially SDG 7, which seeks affordable, reliable, sustainable and modern energy for all. However, renewable energy also contributes to other SDGs by supporting health, livelihoods, clean water, industry, climate action and reduced inequality. This broader development perspective has increased the importance of renewable policy in public planning.

Thus, international renewable energy policy frameworks operate through both formal agreements and collaborative initiatives. They do not replace national policy, but they strengthen it by offering common goals, technical cooperation and global legitimacy. In this way, national and international policy systems are mutually reinforcing. Figure 13.2 consolidates the global renewable energy policy ecosystem.

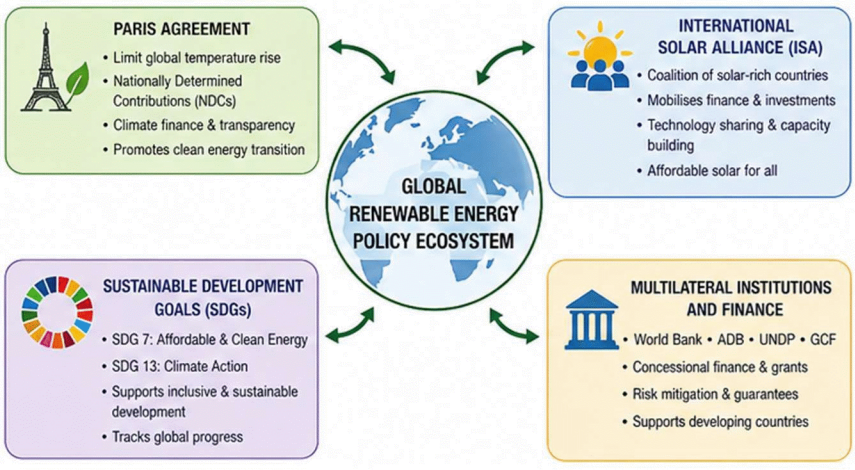


Fig. 13.2: Global Renewable Energy Ecosystems

13.5 POLICY IMPLEMENTATION FOR RURAL ELECTRIFICATION AND SMART CITIES

The success of renewable energy policy depends not only on policy design but also on implementation. In practical terms, implementation means translating goals into projects, finance, institutions, infrastructure and measurable outcomes. Rural electrification and smart city development are two important application areas where renewable energy policy can produce broad social and economic benefits. Figure 13.3 illustrates the policy implementation for sustainable development through rural electrification and smart cities.

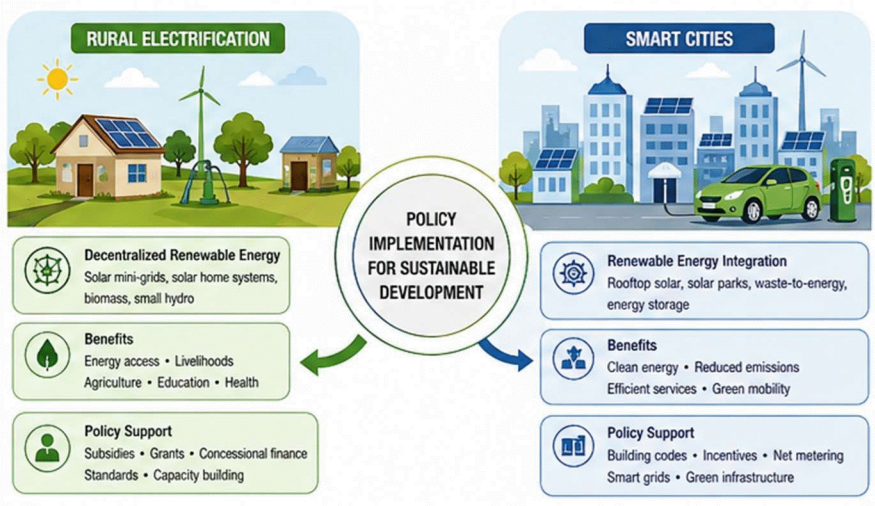


Fig. 13.3: Policy Implementation of Rural Electrification and Smart Cities

Decentralized Renewable Energy for Rural Electrification

In many rural and remote areas, extension of the conventional electricity grid may be technically difficult or economically expensive. For such locations, decentralized renewable energy systems such as solar home systems, mini-grids, solar pumps, biomass gasifiers and hybrid systems provide an effective solution. Renewable energy policy supports these systems through subsidies, soft loans, technical standards, livelihood integration and institutional support.

Policy implementation for rural electrification must address more than simple electrical connectivity. It must ensure reliable supply, affordability, maintenance support, productive end-use and local participation. When renewable systems are linked with irrigation, drinking water supply, agro-processing, rural enterprises, health centres and schools, they contribute directly to rural development rather than merely lighting households.

A strong rural implementation strategy usually includes community involvement, training of local technicians and convergence with agriculture and livelihood programmes. Such policy integration improves sustainability and reduces the risk of system failure after installation. Therefore, rural electrification through renewable energy should be seen as a development intervention rather than a standalone engineering exercise.

Renewable Energy in Smart Cities

Smart cities aim to improve urban life through efficient infrastructure, digital governance, sustainable transport, intelligent energy systems and better resource management. Renewable energy plays an important role in this framework by reducing the carbon footprint of cities and supporting resilient urban power systems. Rooftop solar, solar street lighting, battery storage, EV charging, waste-to-energy plants and smart grids are common examples.

Policy implementation in smart cities requires coordination across urban local bodies, distribution utilities, transport agencies and the government departments. Financial incentives, net metering arrangements, green building codes, energy-efficient public infrastructure and data-driven monitoring mechanisms all contribute to successful implementation. In many cases, renewable energy projects in cities work best when combined with demand-side management and digital control systems.

Smart city renewable energy policy is not limited to technology deployment. It also involves planning for equity, consumer participation, public-private partnerships and long-term maintenance. As cities grow, renewable integration becomes essential for improving sustainability, energy security and environmental quality.

13.6 MAJOR GOVERNMENT SCHEMES

India's renewable energy transition is supported by several flagship schemes that target different sectors and user groups. Some schemes focus on agriculture, some on households, and others on transmission infrastructure. Three especially important initiatives are PM-KUSUM, PM Surya Ghar: MuftBijliYojana, and Green Energy Corridors. The broad vision behind the implementation of all such schemes is illustrated in Figure 13.4.

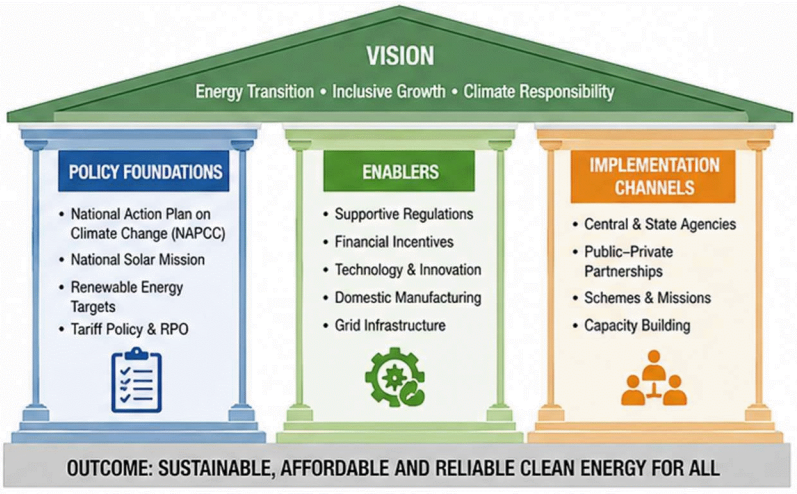


Figure 13.4: Renewable Energy Implementation in India

13.6.1 PM-KUSUM

PM-KUSUM stands for Pradhan MantriKisanUrja Suraksha evamUtthaanMahabhiyan. It is a major scheme intended to support farmers through solar energy while reducing dependence on conventional grid electricity and diesel-based irrigation. The scheme

promotes installation of decentralized grid-connected renewable power plants, standalone solar pumps and solarization of existing grid-connected agricultural pumps. The scheme is important from both the energy and agricultural perspectives. It helps reduce the subsidy burden on agricultural electricity, encourages daytime reliable power for irrigation and can create an additional source of income for farmers where surplus power is exported to the grid. By linking energy generation with agriculture, the scheme represents a productive-use model of renewable energy policy.

PM-KUSUM also contributes to environmental sustainability by reducing diesel consumption and emissions associated with conventional pumping. However, effective implementation requires attention to feeder segregation, pump sizing, groundwater management, maintenance systems and farmer awareness. Thus, the success of the scheme depends on both policy support and local institutional capacity.

13.6.2 PM Surya Ghar: MuftBijliYojana

PM Surya Ghar: MuftBijliYojana is a rooftop solar initiative designed to promote solar power adoption in households. The scheme aims to reduce electricity expenses for consumers, expand distributed generation and encourage mass participation in the clean energy transition. It supports residential rooftop solar systems through central financial assistance and a simplified consumer-oriented implementation framework.

This scheme is significant because distributed rooftop solar can reduce pressure on the distribution network during daytime demand, increase consumer awareness of clean energy and improve household energy resilience. It also creates opportunities for local employment in installation, servicing, inspection and related supply chains. In policy terms, the scheme represents a shift toward citizen-centered energy transition.

The long-term benefits of the scheme depend on effective net metering, consumer outreach, quality assurance, timely subsidy disbursement and proper system maintenance. If implemented well, it can expand consumer participation, where they also become small-scale generators of electricity. This is an important development in the modernization of the power sector.

13.6.3 Green Energy Corridors

Green Energy Corridors (GEC) refer to a dedicated transmission infrastructure initiative designed to evacuate renewable power from resource-rich regions to demand centres and to strengthen grid integration. Since many renewable energy plants are located far from major load centres, transmission planning is essential for reducing curtailment and ensuring reliable power transfer. The GEC concept therefore addresses one of the most important infrastructure bottlenecks in renewable energy expansion.

The initiative includes intra-state and inter-state transmission systems, substations, reactive power compensation and grid management measures required for integrating variable renewable energy. It supports the creation of a stronger and more flexible grid

capable of handling large shares of solar and wind power. Without such infrastructure, renewable generation targets may not translate into actual delivered electricity.
Green Energy Corridors also have strategic importance for future energy systems involving storage, green hydrogen, regional balancing and cross-sector electrification. In this sense, they are not merely transmission lines but enabling infrastructure for a broader clean energy economy. Their role demonstrates that renewable policy must include not only generation incentives but also system-level planning.

LET US KHOW

- Renewable energy policy is most effective when it integrates generation support, consumer participation, and infrastructure development.
- The success of renewable energy systems depends not only on installation but also on strong transmission networks, market mechanisms, and institutional support.
- Renewable energy systems are broadly classified into centralized systems (large-scale plants like solar parks and wind farms) and decentralized systems (rooftop solar, mini-grids, and solar pumps).
- Both centralized and decentralized approaches are essential and work best when implemented in a complementary manner.
- Renewable energy policy extends beyond the power sector and influences areas such as agriculture, housing, urban development, mobility, and industry.
- Effective policy analysis requires a multidisciplinary approach that includes technical, social, financial, and institutional perspectives.

CHECK YOUR PROGRESS

Q1: What is meant by a renewable energy policy?
Q2: Name two important regulatory mechanisms used in India to promote renewable electricity.
Q3: What is the significance of the Paris Agreement for renewable energy policy?
Q4: Why are decentralized renewable energy systems important for rural electrification?
Q5: How does renewable energy support smart city development?
Q6: Expand PM-KUSUM.
Q7: What is the main objective of PM Surya Ghar: MuftBijliYojana?
Q8: Why are Green Energy Corridors necessary in a renewable-rich power system?
Q9: Distinguish between centralized and decentralized renewable energy implementation.
Q10: Fill in the blanks:

i) The Renewable Purchase Obligation creates demand for_____ electricity.
(ii) The International Solar Alliance mainly promotes the adoption of_____ energy.
(iii) PM-KUSUM is strongly linked with the_____ sector.
(iv) Green Energy Corridors are associated with_____ infrastructure.

13.7 LET US SUM UP

- Renewable energy policies include laws, regulations, incentives, and institutional measures that promote clean energy generation and use.
- In India, renewable energy policy is shaped by national missions, electricity sector regulation, market mechanisms, and flagship government schemes.
- International frameworks such as the Paris Agreement, SDGs, and International Solar Alliance influence renewable energy planning and cooperation.
- Rural electrification and smart city programmes show how renewable energy policy can support inclusive and sustainable development.
- PM-KUSUM, PM Surya Ghar: MuftBijliYojana, and Green Energy Corridors are important examples of policy implementation in agriculture, households, and transmission infrastructure.

13.8 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: A renewable energy policy is a set of legal, regulatory, financial, and institutional measures that promote the generation, distribution, and use of energy from renewable sources.

Ans to Q2: Two important regulatory mechanisms are Renewable Purchase Obligation (RPO) and the Renewable Energy Certificate (REC) mechanism.

Ans to Q3: The Paris Agreement encourages countries to adopt cleaner energy pathways and align domestic energy planning with climate commitments.

Ans to Q4: Decentralized renewable systems are important because they can provide electricity to remote areas where grid extension is difficult or uneconomical.

Ans to Q5: Renewable energy supports smart cities through rooftop solar, smart grids, EV charging, efficient public lighting, storage systems, and sustainable urban infrastructure.

Ans to Q6: PM-KUSUM stands for Pradhan MantriKisanUrja Suraksha evamUtthaanMahabhiyan.

Ans to Q7: The main objective of PM Surya Ghar: MuftBijliYojana is to promote residential rooftop solar adoption and reduce household electricity expenses.

Ans to Q8: Green Energy Corridors are necessary to transmit renewable electricity from generation-rich regions to demand centres and to support grid stability.

Ans to Q9: Centralized implementation refers to large grid-connected renewable projects, while decentralized implementation refers to local systems such as rooftop solar, solar pumps, and mini-grids.

Ans to Q10:

(i) renewable
(ii) solar
(iii) agriculture
(iv) transmission

13.9 FURTHER READING

- Ministry of New and Renewable Energy, Government of India. Annual Reports and Scheme Guidelines.
- Central Electricity Authority. Reports on Power Sector and Renewable Integration.
- International Energy Agency. Renewables.
- International Renewable Energy Agency. Renewable Energy Policies and Market Analysis.
- United Nations Framework Convention on Climate Change. Paris Agreement and NDC documents.
- International Solar Alliance. Programmes and policy documents.

13.10 MODEL QUESTIONS

Q1: Discuss the major national renewable energy policies in India and explain their relevance for sustainable development.

Q2: Explain the role of international renewable energy policy frameworks with reference to the Paris Agreement and the International Solar Alliance.

Q3: Discuss the implementation of renewable energy policy for rural electrification and smart city development.

Q4: Write a detailed note on PM-KUSUM and PM Surya Ghar: MuftBijliYojana.

Q5: Explain the concept and significance of Green Energy Corridors in renewable energy integration.

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UNIT 14: RENEWABLE ENERGY AND ENVIRONMENT

UNIT STRUCTURE

14.1 Learning Objectives
14.2 Introduction
14.3 Environmental effect of Energy Production and Utilization
14.4 Energy and Climate Change
14.5. Green House Gas emission and Global Warming
14.6. Climate Change Mitigation and Adaptation
14.7. International Agreement, Protocols and Policies on Climate Change
14.8 Carbon Pricing and Emission Trading Systems
14.9 Let Us Sum Up
14.10 Answers to Check Your Progress
14.11 Further Reading
14.12 Model Questions

14.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- describe the environmental effects of energy production and utilization.
- explain the relationship between energy and climate change.
- identify major greenhouse gases and understand concepts such as Global warming Potential (GWP) and Carbon Dioxide Equivalent (CO_2e) in measuring and comparing emissions.
- differentiate between climate change mitigation and adaptation strategies, and describe technological solutions.
- discuss major international agreements and policy instruments change

14.2 INTRODUCTION

In the previous unit, we studied national and international renewable energy policies and major initiatives such as KUSUM, PM Surya Ghar: MuftBijliYojana, Green Energy Corridors (GEC), rural electrification, and smart cities. Building on this foundation, this unit examines the environmental impacts of energy production and utilization, the link between energy and climate change, greenhouse gas emissions and global warming, climate change mitigation and adaptation, international climate agreements and protocols, and policy instruments such as carbon pricing and emission trading systems.

14.3 ENVIRONMENTAL EFFECT OF ENERGY PRODUCTION AND UTILIZATION

Energy is utilized for almost every purpose. However, there is a question whether this utilization always safe to environment? Obviously there are environmental impacts of energy utilization. This begins with the process of extraction of the resources followed by processing, purifications and manufacture.

Environmental effects related to energy resources are connected with all stages of their life cycle, starting from extraction and processing to transportation and waste management. Each stage has consequences on human beings and the planet.
These effects are particularly well-illustrated by fossil fuels. Extraction by mining and drilling can damage fragile ecosystems, especially deep, offshore, or pristine areas. Because fossil fuels are often far from where they are used, transportation by pipelines, ships, rail, or trucks creates risks of leaks, spills, and pollution, while also consuming energy. Processing coal, oil, and gas produces emissions, wastes, and uses large amounts of water. Finally, power generation releases air and water pollutants and solid waste, requiring strict regulation to protect the environment.
These are some energy production and utilization impacts on environment. Now, let us see the scenario of energy production and utilization of energy in the context of India. Total energy supply is the all energy produced in or imported from a country except those which are stored or exported. Some of these energy sources are used directly while most are transformed into fuels or electricity for final consumption.

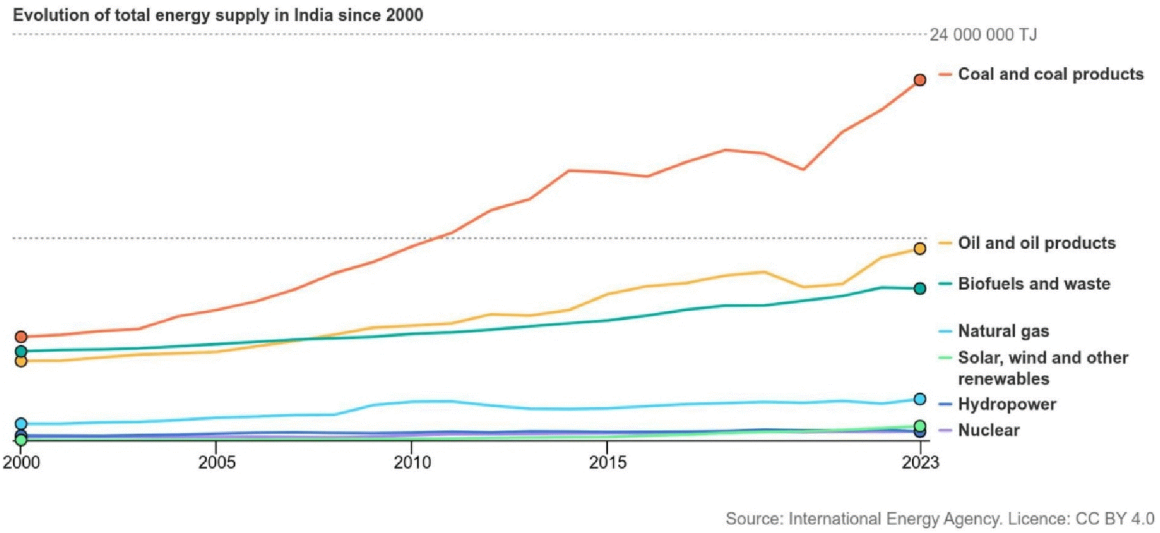


Figure14.1: Energy supply India since 2000

In the figure14.1, you can see that the largest source of energy supply in India is Coal and coal products.
Domestic Energy Production: Energy production includes production of energy by drilling and mining of fossil fuels to generate electricity or fuels, or energy produced from renewable sources like hydro, wind and solar.

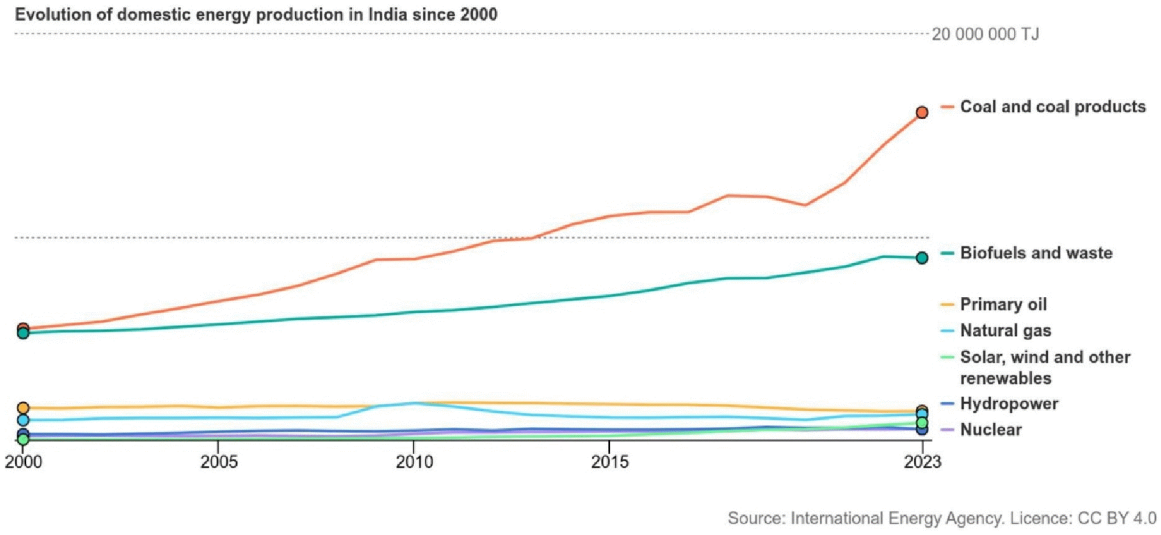


Figure 14.2: Domestic energy consumption in India

If we see the energy production in India, the largest source of domestic energy production in India is coal and coal products.

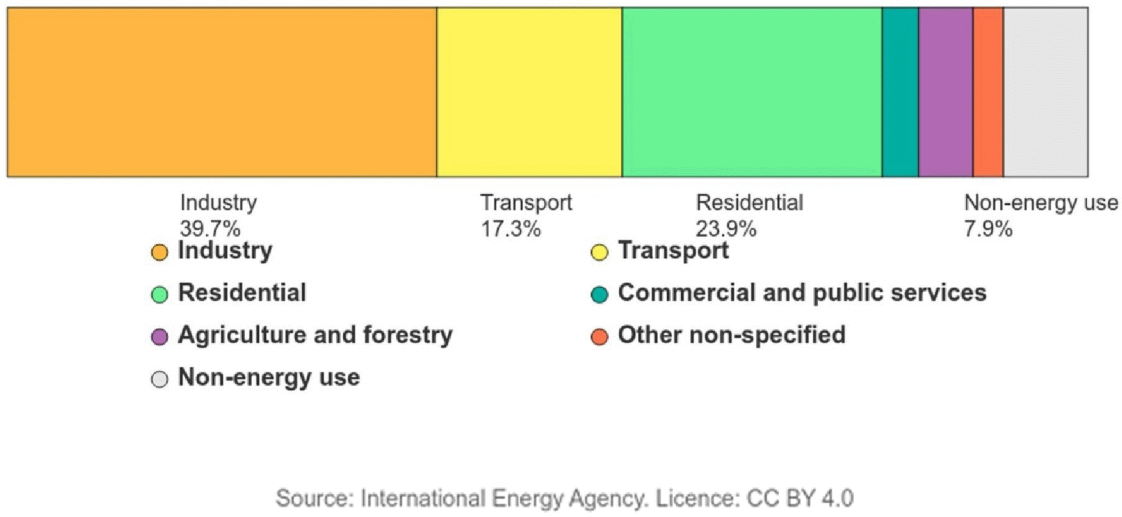


Figure 14.3: Sector wise final energy consumption in India

The industrial and power sectors account for the largest share of energy consumption, followed by transport, residential, and agriculture. Electricity demand is increasing rapidly with the spread of air conditioners, electric vehicles, irrigation pumps, and digital infrastructure. At the household level, energy is mainly used for lighting, cooking, cooling, and heating, while industries consume energy for manufacturing, processing, and machinery operations.

Energy production, especially from fossil fuels such as coal, oil, and natural gas, is a major source of environmental pollution and has serious impacts on both ecosystems and human health. When fossil fuels are burned to generate electricity, heat, or power

industry, they release large amounts of harmful pollutants into the atmosphere, including carbon dioxide (a key greenhouse gas), carbon monoxide, sulphur oxides, nitrogen oxides, particulate matter, heavy metals, and volatile organic compounds. These emissions deteriorate the air quality, contribute to smog and acid rain, and accelerate global warming. Apart from fossil fuels, other energy sources also have environmental impacts: nuclear energy produces long-lived radioactive waste, and renewable technologies like solar panels and hydroelectric dams have lifecycle effects related to manufacturing, waste, and ecosystem disruption. The pollution from energy production leads to ecosystem degradation, water and soil contamination, and serious public health outcomes, such as respiratory and cardiovascular diseases, which contribute to millions of premature deaths worldwide.

Environmental Damage Caused by Energy Production and Use

The way we produce and use energy has a major impact on the Environment. It is already mentioned that most of the world's energy still comes from burning fossil fuels like coal, oil, and gas and this is a leading cause of environmental damage.

- **Greenhouse Gas Emissions**

Energy production is responsible for most of the world's greenhouse gas emissions, especially carbon dioxide (CO_2), which are the main drivers of changing climate. Fossil fuels make up around 80 % of global energy use, with coal and oil being the biggest contributors.

- **Air and Water Pollution**

Besides CO_2, burning fossil fuels releases other harmful gases like sulphur dioxide and nitrogen oxides as well. These can lead to problems such as acid rain, smog, and damage to the ozone layer. Waste from coal and oil industries also contaminates land and water if not managed properly.

- **Waste and Resource Challenges**

Energy industries generate large amounts of solid and liquid waste. For example, coal ash and oil spills can pollute ecosystems. Even nuclear power produces radioactive waste that needs careful long-term storage.

- **Water Usage**

To produce energy huge amounts of water is required from cooling thermal power plants to extracting oil and gas.

- **Land Use**

Renewable energy systems like wind farms, solar parks, and hydropower need significant land areas. While cleaner than fossil fuels, they can still disrupt local habitats and must be planned with environmental sensitivity.

14.4 ENERGY AND CLIMATE CHANGE

Use of energy is one of the most important causes of climate change which account for about 75% of anthropogenic Green House Gases emission. Rising GHGs level due to

various human induced factors like burning of fossil fuels, land use and agricultural activities since preindustrial period have resulted earth surface temperature increase leading to global warming. One of the most important characteristics of GHGs is that, they can stay in the atmosphere for tens and hundreds of years, leading to long lasting climate change that affects current and future generations. Since the Kyoto Protocol was signed in 1997, carbon emissions from energy use have increased from about 22 billion tonnes (BT) to over 35 BT in 2023, with significant but short-lived reductions recorded only during the financial crisis of 2007-08 and the COVID-19 pandemic in 2020-22.7 (Powell and Sati, 2025)

As most of a time the term "Global warming" and "Climate Change" is used interchangeably, however climate change is not only about global warming. Climate change includes global warming and other changes like melting of glaciers, extreme weather events etc.

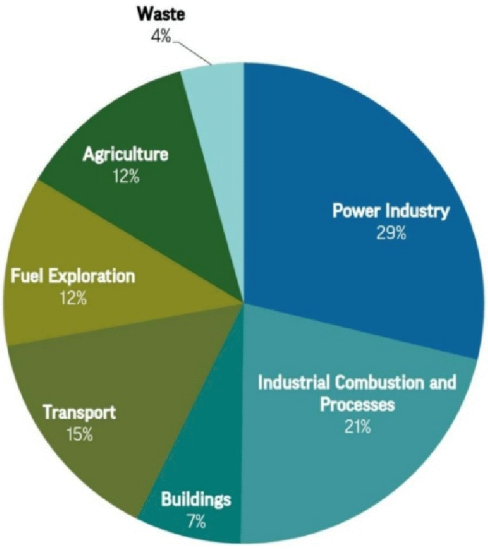


Figure 14.4: GHG Emissions of All World Countries (European Commission, 2024)

Globally, the three largest sectors of greenhouse gas emissions are the power industry (29%), industrial combustion and processes (21%), and transportation (15%).

The energy sector is a major contributor to the climate change due to combustion of fossils fuels. Growing population, industrialization, and increasing energy demand further accelerate emissions and thus energy sector became the largest source of global greenhouse gases. On the other hand, climate change also significantly affects the energy sector itself. Rising temperatures increase the demand for electricity for cooling, while changing rainfall patterns and water shortages reduce hydropower generation and affect cooling systems in thermal power plants. Extreme weather events such as floods, storms, and cyclones damage energy infrastructure, disrupt electricity supply, and affect fossil fuel extraction and transportation.

Climate change also influences renewable energy production by altering solar radiation, wind patterns, and biomass production. Thus, the report highlights that energy production contributes to climate change, while climate change simultaneously affects energy supply, demand, and infrastructure, showing and thus we can see that there is a two way relationship between the two.

14.5 GREEN HOUSE GAS EMISSION AND GLOBAL WARMING

We have mentioned above about emission of GHGs, but how they act. Naturally, GHGs are present in the atmosphere, and they act similarly as glass in greenhouse. They absorb the sun's heat that radiates from the Earth's surface, trap it in the atmosphere and prevent it from escaping into the space. This is called "Greenhouse effect". The greenhouse effect keeps the Earth's temperature warmer than it would otherwise be, supporting life on Earth. However, anthropogenic GHGs are increasing in the atmosphere leading to more trapping of heat and results in global warming.

Greenhouse gases differ in their ability to trap heat in the atmosphere, and therefore their global warming potential varies. Some greenhouse gases occur naturally but are also produced through human activities as already mentioned above and they are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Fluorinated greenhouse gases (F-gases) are entirely anthropogenic and are widely used in industrial applications. These gases have extremely high global warming potential, often thousands of times greater than CO_2. They include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). F-gases are commonly used as substitutes for ozone-depleting substances because, although they do not harm the ozone layer, they significantly contribute to global warming.

Seven types of greenhouse gases are covered by the Kyoto Protocol and the Paris Agreement, which aim to coordinate the global response to climate change. These are

1. Carbon dioxide: It is naturally released through respiration and the decomposition of organic matter, but human activities such as burning fossil fuels and industrial processes greatly increase its concentration.
2. Methane: The main component of natural gas is released from fossil fuel production and transportation, livestock farming, agricultural activities, land use changes, and the decomposition of organic waste in landfills.
3. Nitrous oxide: It is mainly generated through soil microbial processes, the use of nitrogen-based fertilizers, fossil fuel combustion, industrial activities, and wastewater treatment.
4. Hydrofluorocarbons are widely used in refrigeration, air conditioning, aerosol sprays, foams, and fire extinguishers.
5. Perfluorocarbons are primarily used in industrial manufacturing processes
6. Sulphur hexafluoride is commonly used as an insulating material in power transmission systems.
7. Nitrogen trifluoride is used in manufacturing industries, especially for cleaning microprocessors and electronic components.

Although F-gases contribute a smaller share of emissions, they are highly effective at trapping heat.

To compare their effects, greenhouse gas emissions are often expressed in carbon dioxide equivalents. Data from the European Union show that carbon dioxide accounts for the largest share of total emissions, followed by methane. While methane remains in the atmosphere for a shorter period than CO_2, it absorbs more heat and is also a hazardous air pollutant. Overall, even small amounts of certain greenhouse gases, particularly fluorinated gases, can have a significant impact on global warming due to their high heat-trapping capacity.

Now, what is Carbon dioxide equivalent (CO_2e)? It is a way to measure how different greenhouse gases affect climate change. Since different gases warm the Earth at different levels, scientists convert their impact into the equivalent amount of carbon dioxide (CO_2). This helps us compare their effects easily.
Let us discuss about Carbon dioxide (CO_2) vs Carbon dioxide Equivalent (CO_2e). When people talk about reducing emissions, they often focus on carbon dioxide (CO_2). This is because CO_2 is the most common greenhouse gas produced by human activities. It is released mainly from burning fossil fuels, industrial activities, and agricultural land use. CO_2 is responsible for about 80% of global warming caused by current emissions. However, CO_2 is not the only greenhouse gas as we have already discussed. Therefore, scientists use **CO_2e**, which includes the effects of all greenhouse gases, not just CO_2.

Global Warming Potential (GWP) and CO2e Calculation:
It is a measure used to compare how different greenhouse gases contribute to global warming. It shows how much heat a gas can trap in the atmosphere compared to carbon dioxide (CO_2) over a specific period, usually 100 years. The concept was developed by the Intergovernmental Panel on Climate Change to help scientists and policymakers understand and compare the impacts of different gases. Greenhouse gases warm the Earth by acting like a blanket that traps heat, and their warming effect depends on how strongly they absorb heat and how long they remain in the atmosphere. Carbon dioxide has a GWP of 1 because it is the reference gas and stays in the atmosphere for thousands of years. Methane has a higher GWP (about 27–30 times that of CO_2) because it traps more heat, although it remains in the atmosphere for a shorter time. Nitrous oxide is even more powerful, with a GWP about 273 times greater than CO_2 and a long atmospheric lifetime. Some industrial gases, such as CFCs, HFCs, PFCs, sulfur hexafluoride, and nitrogen trifluoride, have extremely high GWPs and can remain in the atmosphere for hundreds or thousands of years. Therefore, GWP helps in measuring total greenhouse gas emissions and supports decision-making for reducing climate change.

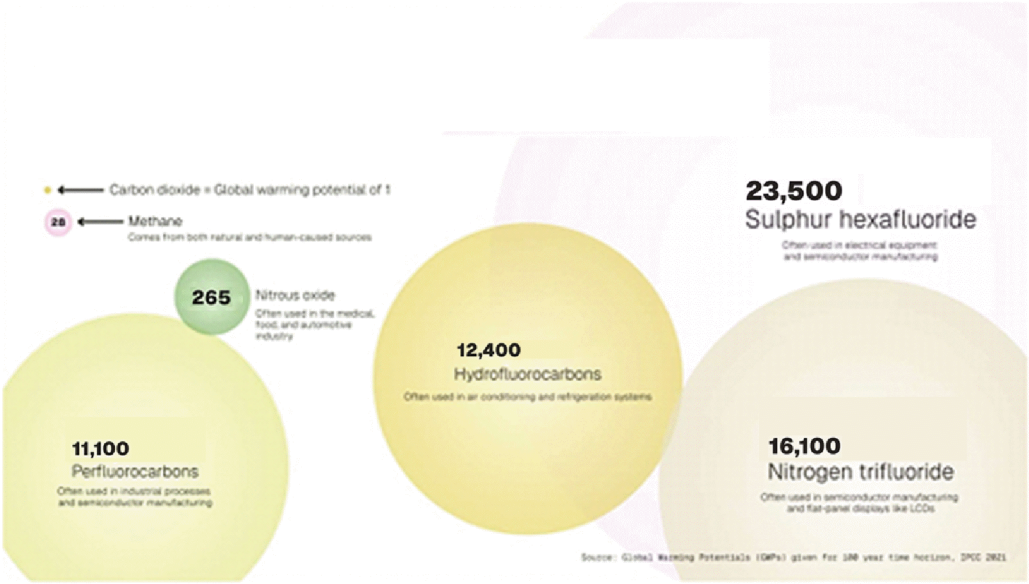


Figure 14.5: Relative warming potential of the most important GHGs

14.6 CLIMATE CHANGE MITIGATION AND ADAPTATION

Before going to discuss different mitigation and adaptation process, let us first get the concept of mitigation and adaptation.

Climate change mitigation focuses on reducing the causes of climate change by lowering greenhouse gas emissions. As for example, use of solar and wind energy instead of burning fossils fuels, planting more trees to absorb carbon dioxide, and encouraging electric vehicles are mitigation strategies because they reduce the amount of harmful gases released into the atmosphere.

Climate change adaptation, on the other hand, focuses on reducing the negative effects of climate change and adjusting to its impacts. For example, building flood barriers in coastal areas to protect against rising sea levels, growing drought-resistant crops in areas facing water shortages, and developing early warning systems for extreme weather events are adaptation strategies because they help people cope with climate change.

Measures of Climate Change mitigation and adaptation

Some mitigation measures for changing climate

1. Use of renewable energy instead of burning fossil fuels
2. Promotion of Sustainable mobility as according to the International Energy Agency (IEA), road transport is currently responsible for approximately a quarter of all greenhouse gas emissions worldwide.
3. Follow 3Rs (Reduce, Reuse, Recycle).
4. Application of Carbon Tax (Carbon tax is a penalty business must pay for excessive greenhouse gases emissions)

Sustainable Mobility: Sustainable mobility means transportation system that includes cycling, walking, public transport, electric vehicles etc.

Example of Adaptation measures

1. Erecting environment friendly buildings
2. Planting more trees, restoring damaged ecosystem.
3. Investigating and developing innovative solutions to prevent and manage natural catastrophes.

Technology-Based Solutions for Climate Change Mitigation

1. Renewable and Clean Energy Technologies

With modern economic growth, population increase, globalization, and rapid industrialization dependency on fossil fuels such as coal, oil, and natural gas are also increasing. Despite they support modern lifestyles; their use has serious environmental and health costs. As already discussed above, the whole supply chain of fossil fuels right from the extraction to transportation cause damage to the environment.

Renewable energy sources include solar, wind, water (hydropower), biomass, and geothermal energy. These natural resources can be converted into clean energy. Renewable energy is expected to become the world's main source of electricity by 2027. Currently, hydropower provides most large-scale renewable electricity, but it is limited by location and high costs. Solar and wind energy are growing rapidly and made up most new renewable installations in 2022. Solar energy is expected to exceed coal power capacity by 2027 (Wang et al., 2023)

However, renewable energy sources like solar and wind are not always available, so large-scale energy storage technologies are needed. Important storage technologies

include lithium-ion batteries, flow batteries, lead-acid batteries, supercapacitors, flywheels, compressed air storage, and hydropower storage (Yang et al. 2011)

2. Carbon Capture, Utilization, and Storage (CCUS)

Carbon capture, utilization, and storage (CCUS) is a technology that captures carbon dioxide (CO_2) from industries or power plants, uses it for different purposes, or stores it underground for long-term storage. It is considered as an important method for reducing greenhouse gas emissions and slowing climate change.

According to the Intergovernmental Panel on Climate Change, CCUS could reduce global CO_2 emissions by 3–6.8 billion tons per year by 2050. The International Energy Agency estimates that CCUS could provide about 15% of the emission reductions needed to achieve net-zero emissions by 2070 (IEA, 2020).

14.7 INTERNATIONAL AGREEMENT, PROTOCOLS AND POLICIES ON CLIMATE CHANGE

Major International Agreement on Climate changes are:

1. UNFCCC: The United Nations Conference on Environment and Development held in Rio de Janeiro in 1992 showed that countries around the world agreed on the need to address climate change. During this meeting, the United Nations Framework Convention on Climate Change was established. It was first signed by 166 countries, came into force on 21 March 1994, and has now been ratified by 198 countries. The main aim was to stabilize green house gas concentrations in the atmosphere. UNFCCC is the parent of major agreement Paris agreement and Kyoto Protocol.
2. Montreal Protocol: It is an important global agreement that controls the production and use of ozone-depleting substances (ODS). These human made chemicals damage the Earth's ozone layer, which protects living beings from harmful ultraviolet radiation. This was adopted on 16 September 1987.
3. Kyoto Protocol: The Kyoto Protocol is an international agreement adopted in 1997 under the United Nations Framework Convention on Climate Change to reduce greenhouse gas emissions and combat climate change. It sets legally binding emission reduction targetsfor developed countries based on the principle of "common but differentiated responsibilities." The protocol came into force in 2005 and introduced mechanisms such as carbon trading, clean development projects, and joint implementation to help countries meet their targets.
4. Paris Agreement: The Paris Agreement is a legally binding international treaty adopted in 2015 at the United Nations Climate Change Conference (COP21) to address climate change through global cooperation. It aims to limit global temperature rise to well below 2°C above pre-industrial levels, reduce greenhouse gas emissions, support developing countries with climate finance, and promote adaptation and transparency. The agreement came into force on 4 November 2016 and has been joined by nearly all countries worldwide.

Climate Changes policies and initiatives by India

The climate change policy framework in India includes a number of national programs, legislations, and international commitments to reduce emissions and build climate resilience. The key components are as follows:

1. National Action Plan on Climate Change (NAPCC) – 2008
   This is a broad policy framework that provides a structure for climate action in India through eight national missions, including
   a. National Solar Mission
   b. National Mission for Enhanced Energy Efficiency
   c. National Mission on Sustainable Habitat
   d. National Water Mission
   e. National Mission for Sustaining the Himalayan Eco-system
   f. National Mission for a Green India
   g. National Mission for Sustainable Agriculture
   h. National Mission on Strategic Knowledge for Climate Change
2. State Action Plans on Climate Change (SAPCCs)
   These are state-level climate plans that are aligned with the NAPCC and address regional environmental and agricultural issues.
3. Nationally Determined Contributions (NDCs)
   These are the commitments of India to the United Nations Framework Convention on Climate Change, which include:
   - Reduction of emission intensity of GDP
   - Increase in non-fossil fuel energy capacity
   - Increase in forest carbon sinks
4. Paris Agreement Commitments
   India, under the Paris Agreement, commits to achieve net-zero emissions by 2070.
5. National Adaptation Fund for Climate Change (NAFCC)
   This is a financial mechanism for supporting climate change adaptation projects, with a focus on agriculture, water, and rural development.
   Renewable Energy Policies
6. These policies promote solar, wind, and other forms of renewable energy to decrease dependence on fossil fuels.

14.8 CARBON PRICING AND EMISSION TRADING SYSTEMS

Carbon markets allow countries or companies to trade carbon credits proportional to their carbon dioxide emissions. Carbon pricing involves giving a financial value to carbon emissions, thereby making polluters pay for the costs involved in the environmental damage caused by them.

The carbon pricing policies currently cover 28 percent of the total global greenhouse gas emissions, and in 2024, they rose over USD 100 billion. The funds raised are steadily being used for actions that support climate action and sustainable development, such as actions that promote social equity and support Indigenous Peoples.

Emissions trading, established under Article 17 of the Kyoto Protocol, enables countries that emit less than their assigned emission limits to sell their unused emission

units to countries that exceed their targets. In this way, countries with surplus allowances can transfer them to those that need additional capacity to meet their commitments.

As carbon dioxide is the main greenhouse gas, this system is commonly referred to as carbon trading. Emission reductions and removals are treated as tradable commodities, creating what is known as the "carbon market," where carbon credits are bought and sold like other market goods.

Emissions trading systems (ETSs) are expanding worldwide, with 38 systems operating in 2025 and about 20 more under development. Around 23% of global greenhouse gas emissions are now covered by ETSs. Emerging economies such as Brazil, India, Indonesia, Turkey and Vietnam are leading new ETS initiatives. At the same time, existing systems are being strengthened for example; China has expanded its ETS beyond the power sector to include steel, cement, and aluminum, significantly increasing emissions coverage. To address concerns over carbon leakage, tools like Carbon Border Adjustment Mechanisms are being introduced, especially in the EU and the UK. Overall, ETSs are increasingly seen as an important policy tool for achieving net-zero goals. (International Carbon Action Partnership, 2025).

India's Position in Global Carbon Pricing Landscape

India is gradually strengthening its position in the global carbon pricing market by developing a structured, domestically driven carbon trading framework aligned with international trends. According to the Press Information Bureau, India has notified the Carbon Credit Trading Scheme (CCTS), which adopts rate-based emissions trading approach rather than an absolute emissions cap, making it suitable for a fast-growing economy. The scheme initially targets energy-intensive sectors and allows industries that outperform emissions intensity benchmarks to earn and trade carbon credits. Alongside this compliance mechanism, India is also building a voluntary carbon market covering sectors such as renewable energy, energy efficiency, green hydrogen, and afforestation. This dual approach positions India as a key emerging economy in global carbon markets and it enables cost-effective emission reductions, supports development goals and future integration with international carbon pricing systems (Press Information Bureau, Government of India)

CHECK YOUR PROGRESS

Q1: Is renewable energy completely free from environmental impact?
Q2: Does energy production affect the environment only during combustion?
Q3: Which energy source dominates India's total energy supply?
Q4: What percentage of anthropogenic greenhouse gas emissions comes from energy use?
Q5: What does CO_2e mean?
Q6: What is climate change mitigation?
Q7: Which agreement aims to limit global temperature rise below 2°C?
Q8: Which protocol controls ozone-depleting substances?

14.9 LET US SUM UP

- Energy production and utilization affect the environment through pollution, resource extraction, and waste generation.
- The energy sector is a major source of greenhouse gas emissions, while climate change also impacts energy production and demand.
- Greenhouse gases contribute to global warming, and their impacts are measured using Global Warming Potential (GWP) and Carbon Dioxide Equivalent (CO_2e).
- Climate change can be addressed through mitigation and adaptation measures, supported by renewable energy and CCUS technologies.
- Global climate action is guided by agreements such as the UNFCCC, Montreal Protocol, Kyoto Protocol, and Paris Agreement, along with India's climate policies.
- Carbon pricing and Emission Trading Systems (ETS) promote emission reduction by assigning a cost to carbon emissions and enabling carbon credit trading.

14.10 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: No

Ans to Q2: No, it affects the environment at all stages (extraction, processing, transport, and use).

Ans to Q3: Coal

Ans to Q4: 75%

Ans to Q5: Carbon dioxide equivalent, a measure to compare different greenhouse gases based on their warming impact.

Ans to Q6: Actions taken to reduce greenhouse gas emissions.

Ans to Q7: The Paris Agreement.

Ans to Q8: The Montreal Protocol.

14.11 FURTHER READING

- International Carbon Action Partnership. (2025). *Emissions trading worldwide: ICAP status report 2025*. International Carbon Action Partnership. https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2025
- International Carbon Action Partnership. (2025). *Emissions trading systems*. https://icapcarbonaction.com/en/about-emissions-trading-systems
- International Energy Agency. (2020). *Energy technology perspectives: Special report on carbon capture, utilisation and storage (CCUS) in clean energy transitions*. IEA

- Open Oregon Educational Resources. *Challenges and impacts of energy use*. https://openoregon.pressbooks.pub/envirobiology/chapter/11-1-challenges-and-impacts-of-energy-use/
- Powell, L., & Sati, A. (2025). *The energy transition and climate change: Manifesto from the Global South*. Observer Research Foundation. https://www.orfonline.org/public/uploads/posts/pdf/20250312153901.pdf
- Wang, F., Harindintwali, J.-D., Wei, K., et al. (2023). Climate change: Strategies for mitigation and adaptation. *The Innovation Geoscience, 1*(1), 100015. https://doi.org/10.59717/j.xinn-geo.2023.100015
- World Energy Council. (2014). *Climate change implications for the energy sector: Summary from IPCC AR5*. https://www.worldenergy.org/assets/images/imported/2014/06/Climate-Change-Implications-for-the-Energy-Sector-Summary-from-IPCC-AR5-2014-Full-report.pdf
- Yang, Z., Zhang, J., Kintner-Meyer, M. C. W., et al. (2011). Electrochemical energy storage for green grid. *Chemical Reviews, 111*, 3577–3613. https://doi.org/10.1021/cr100290v
- PressInformationBureau,GovernmentofIndia.(2025, June 23).*Carbonpricingin India* [Press release]. https://www.pib.gov.in/PressNoteDetails.aspx?NoteId=154721&ModuleId=3&reg=3&lang=2

14.12 MODEL QUESTIONS

Q1: Discuss the environmental effects of energy production and utilization with reference to fossil fuels and renewable energy sources.

Q2: Examine the relationship between energy use and climate change, highlighting its two-way impacts.

Q3: Explain the greenhouse effect and global warming. Discuss the role of major greenhouse gases and the concepts of Global Warming Potential (GWP) and Carbon Dioxide Equivalent (CO_2e).

Q4: Differentiate between climate change mitigation and adaptation. Describe major strategies and technological solutions for each.

Q5: Analyze major international agreements, protocols, and policy instruments related to climate change, with special reference to carbon pricing and emission trading systems.

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UNIT 15: FUTURE TRENDS

UNIT STRUCTURE

15.1 Learning Objectives
15.2 Introduction
15.3 Role of AI/ML in Hybrid Renewable Optimization
15.4 Smart Charging Systems: V2G, V2V, V2X
15.5 Let Us Sum Up
15.6 Answers to Check Your Progress
15.7 Further Reading
15.8 Model Questions

15.1 LEARNING OBJECTIVES

After going through this unit, you will be able to:

- discuss the role of Artificial Intelligence (AI) and Machine Learning (ML) in optimising hybrid renewable energy systems
- Explain the concept and functioning of smart charging systems, with particular reference to Vehicle-to-Grid (V2G), Vehicle-to-Vehicle (V2V) and Vehicle-to-Everything (V2X) technologies.
- Analyse the benefits and challenges associated with AI-driven renewable integration and smart charging infrastructure

15.2 INTRODUCTION

In the previous unit, we studied the environmental effects of energy production and utilization of renewable energy. Building on this foundation, this unit introduces the role of Artificial Intelligence (AI) and Machine Learning (ML) in optimizing hybrid renewable energy systems. It also provides a brief overview of smart charging technologies, including Vehicle-to-Vehicle (V2V), Vehicle-to-Grid (V2G), and Vehicle-to-Everything (V2X) systems, which support efficient energy management and the integration of renewable energy.

15.3 ROLE OF AI/ML IN HYBRID RENEWABLE OPTIMIZATION

The use of Artificial Intelligence (AI) and Machine Learning (ML) techniques in the field of Renewable Energy is a relatively newer concept. AI refers to the ability of machines or computer systems to perform tasks that normally require human intelligence. Such intelligence involves the steps as- learning, reasoning, decision-making and problem-solving. While ML is a subset of AI, that enables systems to learn from data and improve their performance over time, without being explicitly programmed. It uses algorithms to identify patterns and make predictions or decisions based on data. The data that is used for training ML models are obtained from experimental results.

In simple terms, AI is the broader concept of intelligent machines, while ML is a technique that allows these machines to learn from experience.

Key Roles of Artificial Intelligence (AI) and Machine Learning (ML) in Renewable Energy Systems

Following are the key roles played by Artificial Intelligence and Machine Learning based systems in the field of Renewable Energy.

a) **Demand and Generation Forecasting**
   AI models (e.g., neural networks, LSTM) predict Solar irradiance and wind speed as well as the Load demand patterns. Accurate forecasting improves scheduling and reduces energy wastage. ML models analyse historical and real-time data to predict demand and renewable output with high accuracy. Seasonal variation of demand and generation are also taken into consideration through historical data.

b) **Optimal Energy Management**
   AI enables real-time optimisation of Power dispatch between sources, Battery charging/discharging, Load prioritisation etc. AI-driven optimisation improves grid stability, reduces operational cost, and enhances efficiency. It allows the properscheduling of charging/discharging, based on the time of the day, demand of electricity at that moment and the availability of power from the sources at that moment.

c) **Smart Grid Integration**
   AI helps in Load balancing, Voltage regulation and Fault detection. Intelligent algorithms enable adaptive control in dynamic grid environments. Smart grids handle bulk data from all the connected sources and loads in a grid. Hence the use of AI is a must, to do the analysis and reach to some inference in short span of time, while handling a lot of data.

d) **Predictive Maintenance**
   ML detects anomalies in Solar panels, Wind turbines and Batteries. This reduces downtime and increases system reliability. The prediction of conditions is done based on previous data and records. This helps prevent outages of the systems and make them more reliable.

e) **Renewable Energy Utilisation**
   AI maximises renewable penetration by scheduling energy usage during peak generation, reducing dependency on fossil fuel backup. AI-based frameworks significantly increase renewable energy utilisation and reduce peak loads. Since the availability of renewable energy is highly variable in nature, use of AI in predicting the availability of such sources is a must.

Figure 15.1 shows a larger picture of the role of AI/ML techniques in optimization of various parameters of a Hybrid Renewable Energy Systems.

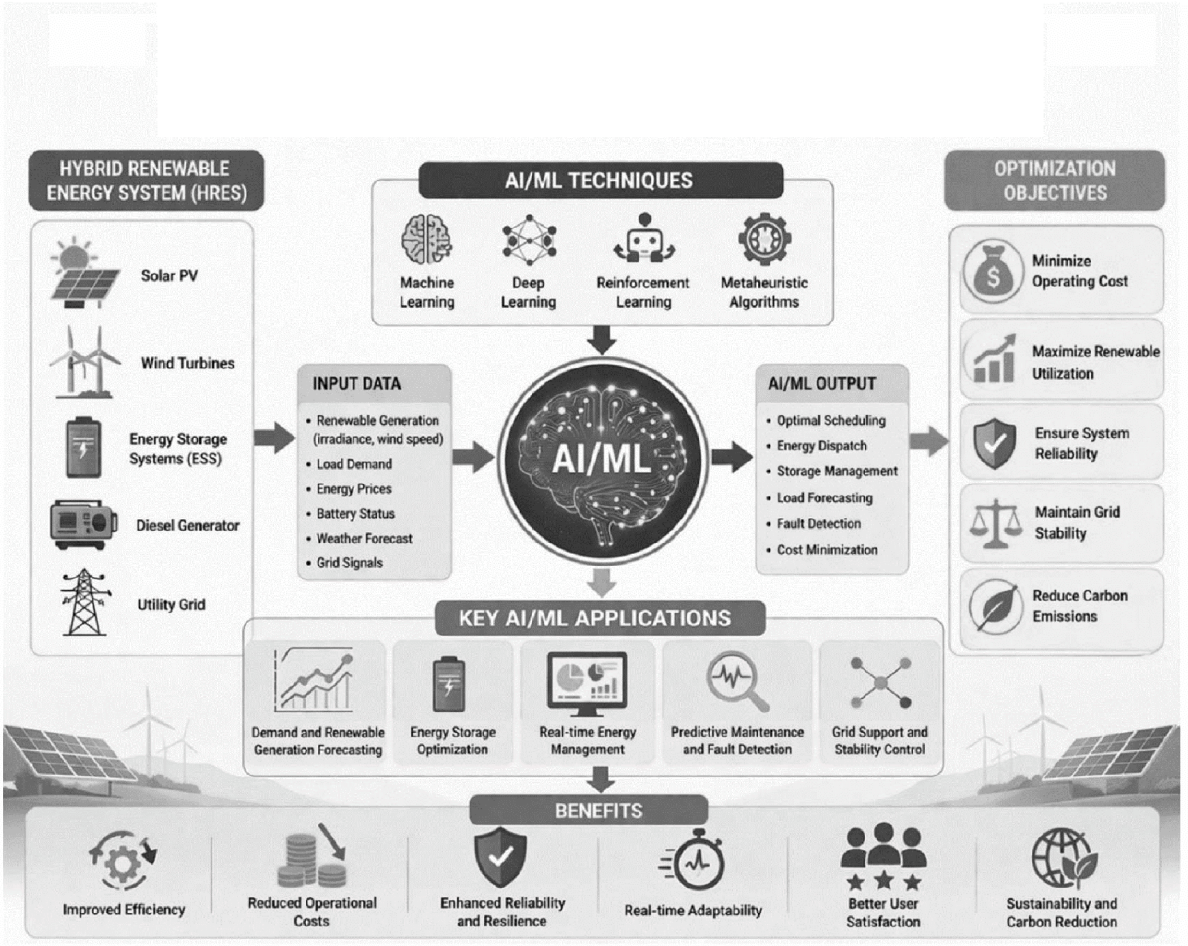


Figure 15.1: Role of AI/ML in Hybrid Renewable Optimization

Common AI techniques used in Renewable Energy Systems

The most common AI techniques used in renewable energy prediction, monitoring and control are-

- Machine Learning (Regression, SVM)
- Deep Learning (LSTM, CNN, Transformers)
- Reinforcement Learning (RL)
- Metaheuristic Algorithms (Genetic Algorithm, PSO)

Machine Learning enables systems to learn renewable energy availability patterns from previous data and make predictions. Regression techniques are used to model relationships between variables and predict continuous values, such as energy demand or solar output. Support Vector Machines (SVM) are supervised learning models used for classification and regression tasks. These are known for their effectiveness in handling high-dimensional data and identifying optimal decision boundaries.

Deep Learning is an advanced subset of Machine Learning that uses neural networks with multiple layers to process complex data. Long Short-Term Memory (LSTM) networks are particularly useful for time-series forecasting, such as predicting energy demand. Convolutional Neural Networks (CNN) are widely used for image and pattern recognition, including fault detection in energy systems. Transformers are powerful

models designed for handling sequential data and capturing long-range dependencies, making them suitable for advanced forecasting and optimisation tasks.

Reinforcement Learning is a type of Machine Learning where an agent learns to make decisions by interacting with its environment. It receives rewards or penalties based on its actions and gradually learns optimal strategies over time. In energy systems, RL is used for real-time optimisation, such as managing energy storage, controlling grid operations and improving efficiency under dynamic conditions.
Metaheuristic algorithms are optimisation techniques inspired by natural processes. Genetic Algorithms (GA) are based on the principles of natural selection and evolution, where solutions evolve over generations to find optimal results. Particle Swarm Optimisation (PSO) mimics the behaviour of birds flocking or fish schooling to search for the best solution. These algorithms are widely used in hybrid renewable systems for optimal energy scheduling, system design and cost minimisation.

Advantages of AI/ML in HRES
The integration of Artificial Intelligence and Machine Learning in Hybrid Renewable Energy Systems (HRES) offers significant advantages by enhancing overall system performance. These technologies improve efficiency and reliability by enabling accurate forecasting and intelligent energy management. They help reduce operational costs through optimal utilisation of resources and minimisation of energy wastage. Additionally, AI-driven systems contribute to enhanced grid stability by maintaining a balance between supply and demand. One of the key strengths of AI/ML is real-time adaptability, allowing systems to respond dynamically to changing conditions. This ultimately leads to better user satisfaction through reliable and cost-effective energy supply.

Challenges of implementing AI/ML in HRES
Despite their benefits, the implementation of AI and ML in HRES is associated with several challenges. These systems are highly dependent on large volumes of quality data, which may not always be readily available. Moreover, the computational cost of deploying advanced AI models can be quite high, requiring significant processing power and infrastructure. Cybersecurity concerns also arise, as increased connectivity makes systems more vulnerable to potential attacks.

Future Scope
The future of AI/ML in hybrid renewable energy systems is highly promising, with several emerging developments shaping the next generation of energy solutions. AI-driven autonomous grids are expected to operate with minimal human intervention, ensuring efficient and reliable energy distribution. The concept of digital twins will enable virtual modelling of energy systems for better monitoring, analysis and optimisation. Edge AI is likely to support decentralised control by processing data closer to the source, improving response times and efficiency. Furthermore, the integration of these technologies with the Internet of Things (IoT) and smart cities will create a connected, intelligent and sustainable energy ecosystem.

15.4 SMART CHARGING SYSTEMS: V2G, V2V, V2X

Vehicle-to-Grid (V2G)

Vehicle-to-Grid (V2G) is an advanced technology that enables bidirectional energy flow between electric vehicles (EVs) and the power grid. In this system, EVs not only draw electricity for charging their batteries, but can also supply stored energy back to the grid when required. Typically, an EV charges during periods of low electricity demand and lower tariffs and discharges energy back to the grid during peak demand. This dynamic interaction helps in stabilising the grid, reducing peak load pressure and lowering overall energy costs. As a result, V2G plays a vital role in balancing energy supply and demand while supporting the effective integration of renewable energy sources. Figure 15,2 shows a smart charging system using V2G.

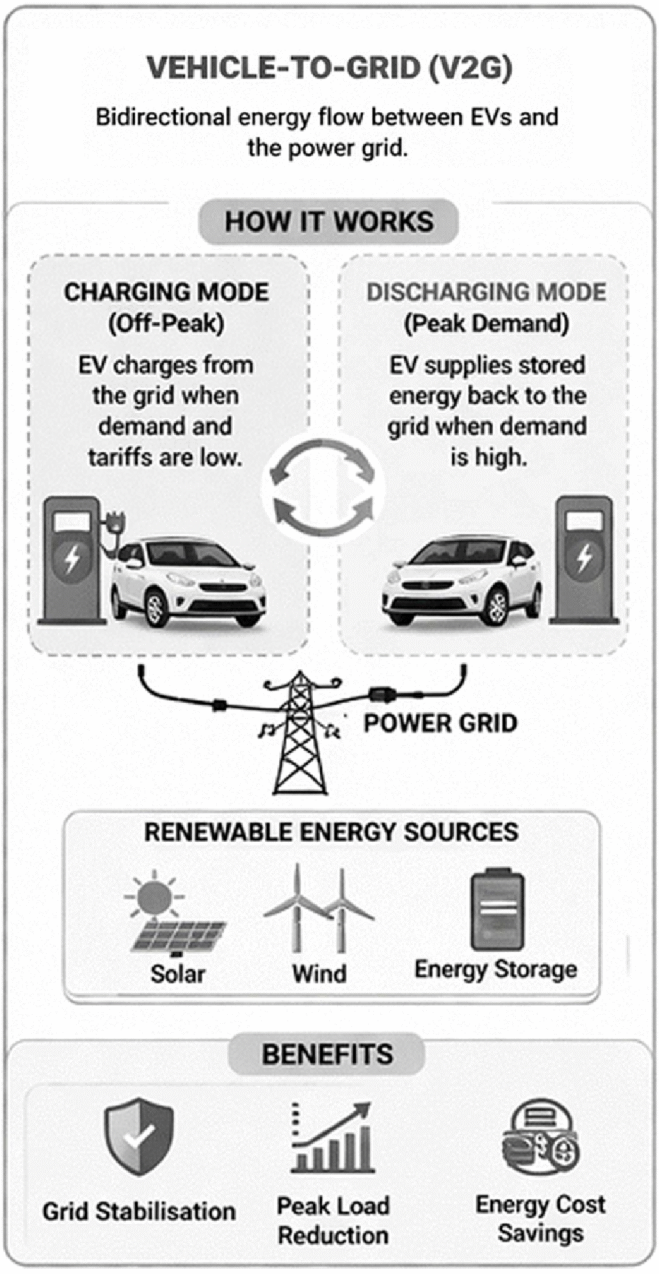


Figure 15.2: A smart charging systems using V2G

Vehicle-to-Vehicle (V2V)

Vehicle-to-Vehicle (V2V) technology allows direct energy transfer between electric vehicles without involving the main power grid. In this system, one EV can supply energy to another, which is particularly useful in situations such as emergency charging or in isolated microgrids. This approach enhances flexibility in energy usage and ensures continuity of power in critical situations. V2V systems also reduce dependency on grid infrastructure and promote efficient utilisation of stored energy, making them a valuable component of decentralised energy systems.

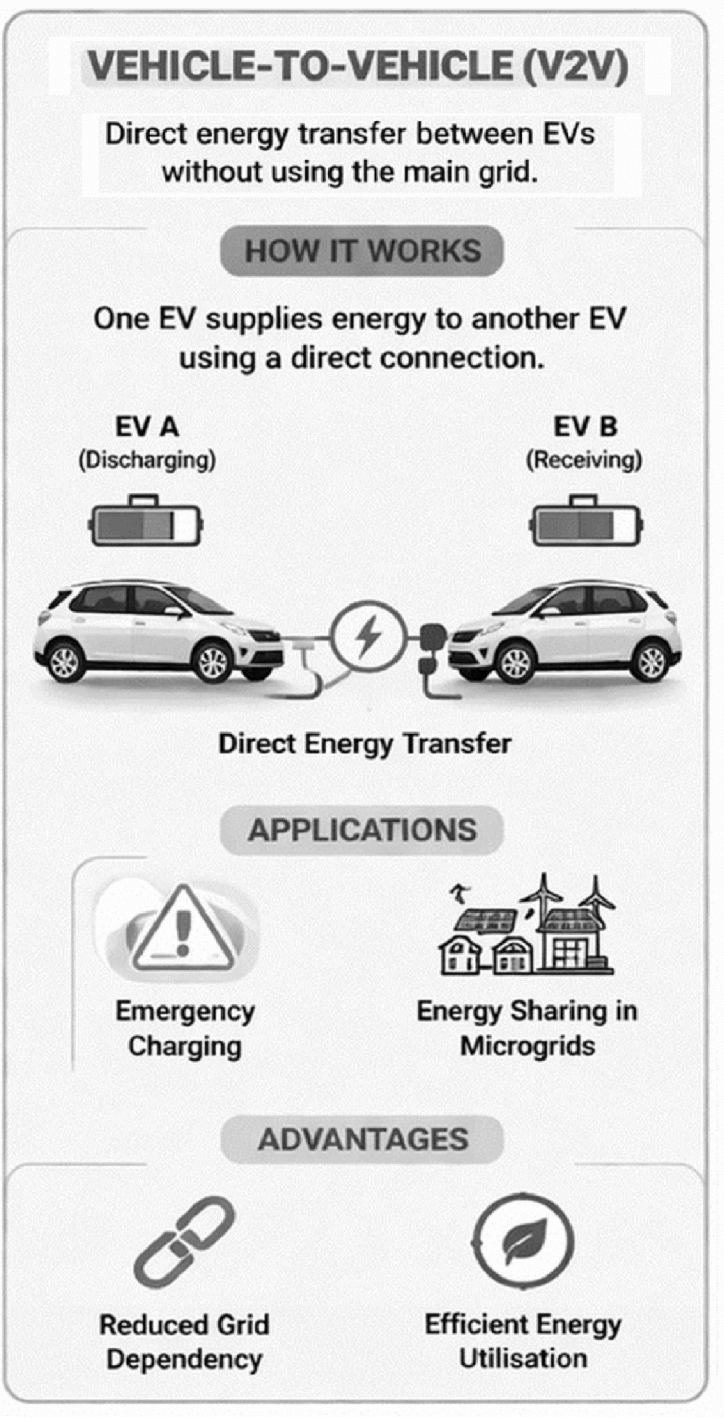


Figure 15.3: A smart charging systems using V2V

Vehicle-to-Everything (V2X)

Vehicle-to-Everything (V2X) is a comprehensive framework that extends the concept of energy exchange beyond individual interactions. It enables electric vehicles to

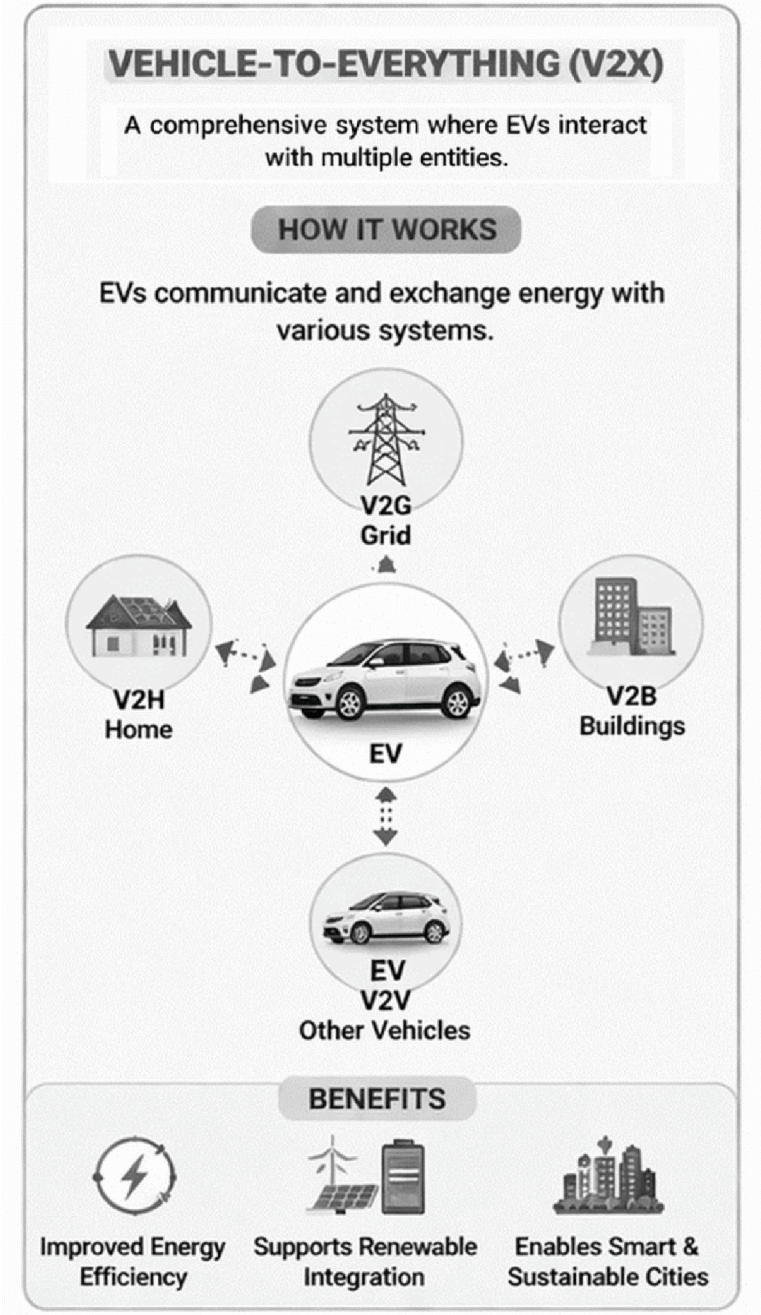


Figure 15.4: A smart charging systems using V2X

communicate and exchange energy with multiple entities, including the grid (V2G), homes (V2H), buildings (V2B) and other vehicles (V2V). Through this interconnected system, EVs function as mobile energy storage units within a decentralised energy ecosystem. V2X enhances overall energy efficiency, supports renewable energy integration and contributes to the development of smart and sustainable energy networks. Figure 15.4 shows a smart charging system using V2X.

Smart Charging Mechanism: AI-Based Predictive Charging

Smart charging mechanisms utilise Artificial Intelligence to optimise the charging behaviour of electric vehicles. AI-based predictive charging systems analyse various factors such as driving behaviour, weather conditions, electricity prices and grid demand to determine the most suitable charging schedule. By processing both historical and real-time data, these systems can accurately anticipate future energy requirements and grid conditions. As a result, AI selects the most efficient time slots for charging, ensuring cost-effectiveness and reducing stress on the power grid while maintaining user convenience.

Benefits of Smart Charging Systems

Smart charging systems offer numerous advantages that contribute to the efficiency and stability of modern energy networks. They enable load shifting and peak shaving by distributing energy demand more evenly over time, thereby reducing pressure on the grid during peak hours. These systems also help in lowering electricity costs by allowing users to charge during off-peak periods. Furthermore, smart charging enhances the integration of renewable energy by aligning charging activities with periods of high renewable generation. It also improves battery life through controlled charging cycles and strengthens overall grid reliability by maintaining a balanced supply-demand relationship.

Integration with Hybrid Renewable Systems

Smart charging plays a crucial role in the effective integration of electric vehicles with hybrid renewable energy systems. It aligns EV charging schedules with the availability of renewable sources such as solar and wind energy, thereby maximising the use of clean energy. Additionally, EVs can function as distributed energy storage units, storing excess energy and supplying it when needed. This capability supports the operation of microgrids and enhances energy resilience, especially in decentralised systems. As a result, smart charging contributes to a more flexible and sustainable energy ecosystem.

Challenges

Despite its advantages, the implementation of smart charging systems faces several challenges. Infrastructure limitations, such as the lack of widespread charging stations, can hinder large-scale adoption. Communication complexity between vehicles, charging stations and grid systems requires advanced coordination and reliable networks. Battery degradation is another concern, as frequent charging and discharging cycles may affect battery lifespan. Additionally, regulatory and market barriers, including policy constraints and lack of standardisation, can slow down the deployment of these technologies.

Future Trends

The future of smart charging systems is shaped by rapid technological advancements and increasing demand for sustainable energy solutions. AI-controlled autonomous charging networks are expected to optimise charging processes without human intervention. Blockchain-based energy trading may enable secure and transparent peer-to-peer transactions between users. The development of fully integrated smart cities will allow seamless coordination between transportation and energy systems.

Moreover, decentralised peer-to-peer energy exchange is likely to empower consumers to actively participate in energy markets.

CHECK YOUR PROGRESS

Q1: Which AI technique is commonly used for time-series forecasting in renewable energy systems?
Q2: What type of energy flow is enabled by Vehicle-to-Grid (V2G) technology?
Q3: Which Machine Learning technique is used to detect faults before system failure?
Q4: What does V2X stand for?
Q5: Which technology allows electric vehicles to exchange energy directly with other vehicles?
Q6: Fill in the blanks:

i. AI helps in improving_____ and_____ in hybrid renewable systems.
ii. V2G enables_____ energy flow between electric vehicles and the grid.
iii. In smart charging, EVs act as_____ energy storage units.
iv. _____ learning is used to detect faults and predict maintenance needs in energy systems.

15.5 LET US SUM UP

- Artificial Intelligence (AI) and Machine Learning (ML) improve hybrid renewable energy systems through accurate forecasting, energy management, and predictive maintenance.
- AI techniques help optimise renewable energy utilisation, enhance grid stability, and improve the reliability and efficiency of hybrid energy systems.
- Smart charging systems enable intelligent charging of electric vehicles based on grid demand, electricity prices, and renewable energy availability.
- V2G, V2V, and V2X technologies support bidirectional energy exchange, efficient energy sharing, and better integration of electric vehicles with energy systems.
- AI-based smart charging and hybrid renewable systems promote efficient energy use, renewable energy integration, and sustainable power management.
- Future energy systems are expected to be more intelligent, decentralised, and sustainable through the combined use of AI, smart grids, and electric mobility.

15.6 ANSWERS TO CHECK YOUR PROGRESS

Ans to Q1: LSTM

Ans to Q2: Bidirectional

Ans to Q3: Predictive maintenance

Ans to Q4: Vehicle-to-Everything

Ans to Q5: V2V

Ans to Q6:

i. efficiency, reliability
ii. bidirectional
iii. distributed
iv. Machine

15.7 FURTHER READING

- International Energy Agency (IEA) – Digitalisation and Energy https://www.iea.org/reports/digitalisation-and-energy
- MDPI Energies Journal – AI in Smart Grids and Renewable Systems https://www.mdpi.com/journal/energies
- Neeraja B, Mrs. KiranmayeeJampala, Dr. Mohammad Irshad, Dr. T. Hussain, Grid Integration of Electric Vehicles, BR Publications, 2025.
- Dan Bahadur Pal, Ashish Kapoor, Smart Energy Technologies Towards a Sustainable Future, CRC Press, 2026.

15.8 MODEL QUESTIONS

Q1: Explain the significance of Artificial Intelligence in improving the efficiency of hybrid renewable energy systems.
Q2: Discuss how Machine Learning techniques can be applied for demand forecasting in renewable energy systems.
Q3: Analyse the role of AI in enabling smart grid operations and maintaining grid stability.
Q4: Describe the concept of smart charging and its importance in modern power systems.
Q5: Compare and contrast V2G, V2V, and V2X technologies in terms of their functionality and applications.
Q6: Evaluate the advantages and limitations of integrating electric vehicles into energy systems through smart charging.
Q7: Illustrate how electric vehicles can act as distributed energy storage units in a decentralised energy system.
Q8: Discuss the challenges associated with implementing AI-based optimisation in hybrid renewable energy systems.
Q9: Examine the future prospects of AI-driven energy systems in achieving sustainability and carbon neutrality.
Q10: Explain the role of predictive maintenance in enhancing the reliability of renewable energy infrastructure.

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