LECTURE NOTES

Subject Name	RENEWABLE AND DISTRIBUTED ENERGY TECHNOLOGIES
Year / Branch	III Year /EEE
Regulation	R23
Prepared By	Dr.V. Maheswari

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PRE-REQUISITE: Basic electrical engineering

COURSE EDUCATIONAL OBJECTIVES:
1. To explores each of the principal renewable energy sources in turn.
2. To know the different technology is examined in terms of the relevant physical principles potential
renewable resource.
3. This Distributed Generation course is intended.
4. To provide knowledge of the benefits of renewable energy generation, availability of distributed generation technology, electricity generation technologies, issues related to grid interconnection.
5. To analyzing the methods of technical and economic feasibility

UNIT-1: ENERGY SCENARIO AND SOLAR ENERGY: (09)

Introduction: Fundamentals of renewable energy sources, Types of energy, Renewable and Non- renewable energy, SWOT analysis, Global warming and climate change, World energy transformation by 2050, Prospects of renewable energy in the world, Renewable energy availability in India. Solar Energy Fundamentals: Solar Spectrum, propagation of solar radiation from the sun to earth; solar radiation geometry: sun-earth geometry, extra-terrestrial and terrestrial radiation. Solar Thermal: Solar Collectors, Solar parabolic trough, Solar tower, Solar cooker, Solar water heater, Solar dryer, Solar Pond. Solar Electric Power Generation: A Generic PV Cell, PV Materials, Equivalent Circuits for PV Cells, Modules and Arrays; I-V Curve under Standard Testing Conditions; Impact of Temperature and Insolation on I-V curves; Shading Impacts on I-V curves; Maximum Power Point Trackers (MPPT).

UNIT-2: WIND AND OTHER ENERGY SYSTEMS: (09)

Wind Energy: Air, Wind, Global and Local Wind, availability of wind energy in India, wind velocity and power from wind; major problems associated with wind power, Classification of wind energy conversion system (WECS)- Horizontal axis- single, double and multiblade system. Vertical axis- Savonius and darrieus types. Biomass Energy: Introduction; Photosynthesis Process; Biofuels; Biomass Resources; Biomass conversion technologies-fixed dome; Urban waste to energy conversion; Biomass gasification (Downdraft). Tidal Power: fundamental characteristics of tidal power, harnessing tidal energy, advantages, and limitations

UNIT-3: ENERGY STORAGE AND GREEN ENERGY: (09)

Energy Storage: Stationary Battery Storage – Basics of Lead-Acid batteries, Battery Storage Capacity, Coulomb efficiency instead of energy efficiency, Battery Sizing. Different Battery storage technologies and comparison of their performance. Introduction to Super capacitors. Green Energy: Historical Development, Basic Operation of a Fuel Cell, Fuel Cell Thermodynamics, Entropy and the theoretical efficiency of Fuel Cells, Gibbs Free Energy and Fuel Cell efficiency, Electrical output of an Ideal Cell, Electrical Characteristics of Real Fuel Cells, Types of Fuel Cells, H2: Operating principles, Zero energy Concepts. Benefits of hydrogen energy, hydrogen production technologies (electrolysis method only), hydrogen energy storage, applications of hydrogen energy, problem associated with hydrogen energy.

UNIT-4: INTRODUCTION TO DG AND ITS GRID INTEGRATION: (09)

Introduction: Need for Distributed generation, renewable sources in distributed generation, current scenario in Distributed Generation, Planning of DGs – Siting and sizing of DGs – optimal placement of DG sources in distribution systems. Grid integration of DGs: Different types of interfaces - Inverter based DGs and rotating machine-based interfaces - Aggregation of multiple DG units. Energy storage elements: Batteries, ultracapacitors, flywheels.

UNIT-5: Technical Impact, Economic and Control aspects of DG (9)

Technical impacts of DGs: Transmission systems, Distribution systems, De-regulation – Impact of DGs upon protective relaying – Impact of DGs upon transient and dynamic stability of existing distribution systems Economic and control aspects of DGs: Market facts, issues, and challenges - Limitations of DGs. Voltage control techniques, Reactive power control, Harmonics, Power quality issues. Reliability of DG based systems – Steady-state and Dynamic analysis.

COURSE OUTCOMES:

On successful completion of the course, students will be able to		POs related to COs
CO1	Understood the different types of power plants, operation of power plants	PO1,PO2,PO3
CO2	Understood the concepts of distribution systems, underground cables, economic aspects and tariff	PO1,PO2, PO3
CO3	Understood various substations that are located in distribution systems	PO1,PO2, PO3
CO4	Applied the above concepts to illustrate different power generation layouts	PO1,PO2,PO3
CO5	Analyzed various economic aspects related to power generation and distribution	PO1,PO2,PO3

TEXT BOOKS:

1. Muhammad Kamran, Muhammad Rayyan Fazal, "Renewable Energy Conversion Systems", First Edition, Elsevier Academic Press, 2021.

2. G. D. Rai, Non-Conventional Sources of Energy, Khanna Publisher, 2004

REFERENCE BOOKS:

1. G N Tiwari, Solar Energy: Fundamentals, Design, Modeling and Applications, Narosa, 2002.

2. Mukund R Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd

3. H. Lee Willis, Walter G. Scott, —Distributed Power Generation – Planning and Evaluation‖, Marcel Decker Press, 2000.

4. Gilbert M. Masters, —Renewable and Efficient Electric Power Systems‖, 2nd Edn., IEEE Press, Wiley, 2013.

5. N. Jenkins, J.B. Ekanayake and G. Strbac, —Distributed Generation‖, 1st Edn, The Institution of Engineering and Technology, London, 2010.

REFERNCE LINK:

1. **https://archive.nptel.ac.in/courses/121/106/121106014/#**

2. **https://onlinecourses.nptel.ac.in/noc22_ch27/preview**

3. **https://www.nptelvideos.com/lecture.php?id=8517**

CO-PO MAPPING:

CO-PO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO.1	3	3	2									
CO.2	3	3	2									
CO.3	3	3	2									
CO.4	3	3	2									
CO.5	3	3	2									
CO*	3	3	2									

Faculty In charge
(Dr.V.Maheswari)

UNIT-1: ENERGY SCENARIO AND SOLAR ENERGY:

Course Objectives:

1. **Understand the global and national energy scenario** including renewable and non-renewable energy resources and their environmental impacts such as global warming and climate change.

2. **Explain the fundamentals of solar radiation** including solar spectrum, sun–earth geometry, and the propagation of solar energy from the sun to the earth.

3. **Study solar thermal technologies** such as solar collectors, solar parabolic troughs, solar towers, solar cookers, solar dryers, solar ponds, and solar water heaters.

4. **Analyze solar photovoltaic (PV) systems** including PV cell materials, equivalent circuits, modules, and array configurations.

5. **Evaluate the performance of solar PV systems** considering I-V characteristics, effects of temperature and insolation, shading impacts, and maximum power point tracking (MPPT) techniques.

RENEWABLE AND DISTRIBUTED ENERGY TECHNOLOGIES

UNIT-1: ENERGY SCENARIO AND SOLAR ENERGY: (9)

Introduction: Fundamentals of renewable energy sources, Types of energy, Renewable and Non- renewable energy, SWOT analysis, Global warming and climate change, World energy transformation by 2050, Prospects of renewable energy in the world, Renewable energy availability in India.

Solar Energy Fundamentals: Solar Spectrum, propagation of solar radiation from the sun to earth; solar radiation geometry: sun-earth geometry, extra-terrestrial and terrestrial radiation.

Solar Thermal: Solar Collectors, Solar parabolic trough, Solar tower, Solar cooker, Solar water heater, Solar dryer, Solar Pond.
Solar Electric Power Generation: A Generic PV Cell, PV Materials, Equivalent Circuits for PV Cells, Modules and Arrays; I-V Curve under Standard Testing Conditions; Impact of Temperature and Insolation on I-V curves; Shading Impacts on I-V curves; Maximum Power Point Trackers (MPPT).

Fundamentals of renewable energy sources

❑ Fundamentals of renewable energy involve harnessing naturally replenishing sources like sun, wind, water, and Earth's heat to generate power, offering a sustainable, low-carbon alternative to finite fossil fuels, which including Solar (photovoltaic/thermal), Wind (turbines), Hydro (dams/tides), biomass (organic matter), and Geothermal (Earth's heat), each working on different principles but sharing the benefit of inexhaustible fuel and reduced pollution.

❑ **Natural Replenishment:** Energy comes from sources that renew naturally over short timescales (days, years), unlike fossil fuels that take millions of years to form.

❑ **Sustainability:** These sources are virtually inexhaustible, ensuring long-term energy availability.

❑ **Low/Zero Emissions:** They produce significantly fewer greenhouse gases and pollutants compared to burning coal, oil, and gas, combating climate change.

❑**Solar Energy:** Captures sunlight using photovoltaic (PV) cells for electricity or solar thermal systems for heat.

❑**Wind Energy:** Uses kinetic energy from wind to spin turbine blades, generating electricity.

❑**Hydropower:** Harnesses the energy of flowing or falling water (rivers, tides).

❑**Biomass:** Burns organic matter (plants, waste) or converts it into biofuels (ethanol, biodiesel) for energy.

❑**Geothermal Energy:** Utilizes heat from within the Earth for direct heating or electricity generation.

TYPES OF ENERGY, RENEWABLE AND NON- RENEWABLE ENERGY:

- There are two major categories of energy: renewable and non-renewable.

- Non-renewable energy resources are available in limited supplies, usually because they take a long time to replenish. The advantage of these non-renewable resources is that power plants that use them are able to produce more power on demand. The non-renewable energy resources are:

❑ Coal
❑ Nuclear
❑ Oil
❑ Natural gas

Renewable resources, on the other hand, replenish themselves. The five major renewable energy resources are:

❑Solar

❑Wind

❑Water, also called hydro

❑Biomass, or organic material from plants and animals

❑Geothermal, which is naturally occurring heat from the earth

❑While renewable energy resources have the advantage of unlimited supply over the long haul, they are limited in their availability at any given moment.

❑For example, the sun rises each day, but its ability to generate power is limited when its cloudy. Another disadvantage is that power plant operators can't crank up renewable energy production when people are consuming more power, such as on a hot day when many people are running air conditioners at the same time.

❑States like California are trying to solve this problem by using energy storage, like large batteries, to collect electricity from renewable sources when demand is low in order to use it later when demand goes up.

Non-renewable Energy and Climate Change:

❑When coal, natural gas and oil are burned to produce energy, they emit heat-trapping gases such as carbon dioxide. This process of trapping heat is what drives climate change, and the failure to address this problem is what's catalyzing the current climate crisis.

❑Fossil fuels are hydrocarbon-containing materials like coal or gas that are found in the Earth's crust and formed in the geological past from the remains of living organisms. These energy sources account for the majority of the world's greenhouse gas emissions.

❑If emissions continue unrestrained, the atmosphere could warm by as much as 2.7 degrees Fahrenheit above preindustrial levels by the year 2040.

According to the latest report from the Intergovernmental Panel on Climate Change, a group of international scientists empowered by the United Nations to advise world leaders.

Scientists say this increase in the temperature would threaten life on the planet in a myriad of ways, including severe water shortages; more air pollution; rising sea levels, habitat loss; heat waves; melting ice sheets in West Antarctica and Greenland; and destruction of the world's coral reefs.

• Over the last 150 years, humans are responsible for the vast majority of the increase of these gases in the atmosphere, and the burning of fossil fuels through activities like driving a car is the largest source of these emissions.

❑There is a vocal group of environmentalists and researchers —Stanford's Mark Jacobson, who developed a state-by-state 100% renewable <u>plan</u> for one — who argue that the power grid should be supported only by renewable resources.

❑Policy makers who invest in renewable energy often do so with the goal of generating power without emitting these planet-warming gases.

SWOT Analysis

❑SWOT analysis identifies the Strengths, Weaknesses, Opportunities, and Threats related to a project or position. In the context of global renewable energy development, a general SWOT analysis would be:

❑**Strengths:** Abundant natural resources (solar, wind, hydro), declining technology costs, no greenhouse gas (GHG) emissions during operation, improved energy security, and job creation (e.g., 42 million jobs globally by 2050).

❑**Weaknesses:** Intermittency of sources (sunlight, wind), high initial capital costs, need for advanced energy storage and smart grid infrastructure, and potential personal biases in analysis.

❑**Opportunities:** Meeting climate change targets (Paris Agreement), growing global electricity demand (especially in developing economies), technological advancements (e.g., green hydrogen), economic growth, and governmental policies/incentives.

❑**Threats:** Inadequate infrastructure, policy conflicts (e.g., import duties), geopolitical instability, competition from established fossil fuel industry, and the high cost of capital.

Global Warming and Climate Change

❑It is primarily caused by the increase in greenhouse gas (GHG) emissions, especially CO_2, from burning fossil fuels. This leads to:

❑Rising global temperatures and extreme weather events.

❑The urgent need for a transition to clean, low-carbon energy sources to limit warming to 1.5°C.

World Energy Transformation by 2050

The global energy transformation seeks to shift from fossil fuels to sustainable sources.

Key aspects include:

❑**Decarbonization:** Aiming for net-zero emissions by 2050.

❑**Increased Renewables Share**: Renewables are projected to provide 70-85% of global electricity by 2050.

❑**Electrification:** Electricity's share of final energy consumption is expected to nearly double to around 40-50% by 2050, driven by electric vehicles and heat pumps.

❑**Efficiency:** A significant increase in energy efficiency improvements is necessary.

Prospects of Renewable Energy in the World

The prospects for renewable energy globally are strong and driven by several factors:

❑Declining costs of solar and wind technologies make them increasingly attractive.

❑Policy support and international climate agreements (**Paris Agreement**) push for greater adoption.

❑Renewable energy can meet new electricity demands, such as for AI data centres, and offer energy independence.

Renewable Energy Availability in India

- India has significant renewable energy availability and is making great strides in its deployment:

- **Installed Capacity:** As of October 2024, 46.3% of India's total installed energy capacity comes from renewable sources (over 200 GW).

- **Global Ranking:** India **ranks fourth globally** in total renewable installed capacity.

- **Targets:** India aims to have **500 GW** of renewable energy capacity by **2030** and potentially achieve a largely **(90%)** renewable-based economy by **2050.**

- **Key Sources:** Solar and wind energy are the primary focus areas, with solar accounting for the majority of new capacity additions.

- **Challenges:** India faces the dual challenge of meeting a rapidly growing energy demand (fastest among major economies) while transitioning away from its reliance on coal.

Solar Energy Fundamental(UNIT-1) Syllabus

Solar Spectrum, propagation of solar radiation from the sun to earth; solar radiation geometry: sun-earth geometry, extra-terrestrial and terrestrial radiation.

Solar Spectrum

- The solar spectrum is the range of electromagnetic radiation emitted by the sun, extending from the ultraviolet to the infrared region.

- It is composed of photons with various wavelengths, which define the spectrum's shape and intensity.

- It can be defined in terms of **solar radiation** or solar irradiance. Solar radiation is the **direct emission of energy** from the sun while **solar irradiance** is the **amount of energy that reaches the Earth's surface**.

- The solar spectrum can be **divided into three main regions:** the ultraviolet (UV), visible, and infrared (IR).

❑The UV includes light with a wavelength shorter than 400 nanometers (nm).

❑UV photons have energies ranging from approximately 3 to 5 electron Volts (eV).

❑The visible region extends from 400 to 700 nm. This region contains photons with energies of 1.8 to 3 eV.

❑Finally, the IR region comprises of light of wavelengths longer than 1000 nm, and its photons have energies between approximately 0.35 eV and 1.8 eV.

❑The intensity of the solar spectrum received on Earth is strongly dependent on the Earth-Sun distance, the angle at which the sun's rays reach the Earth's atmosphere, the weather, and the amount of air pollution.

❑Solar cells, which use photovoltaic technology to convert solar radiation into electricity, are highly sensitive to the shape of the solar spectrum and the intensity of the radiation.

❑Therefore, researchers and engineers working on solar cells must be knowledgeable about the solar spectrum in order to achieve optimal performance and efficiency.

❑Therefore, the solar spectrum is an important phenomenon to consider when designing and working with solar cells.

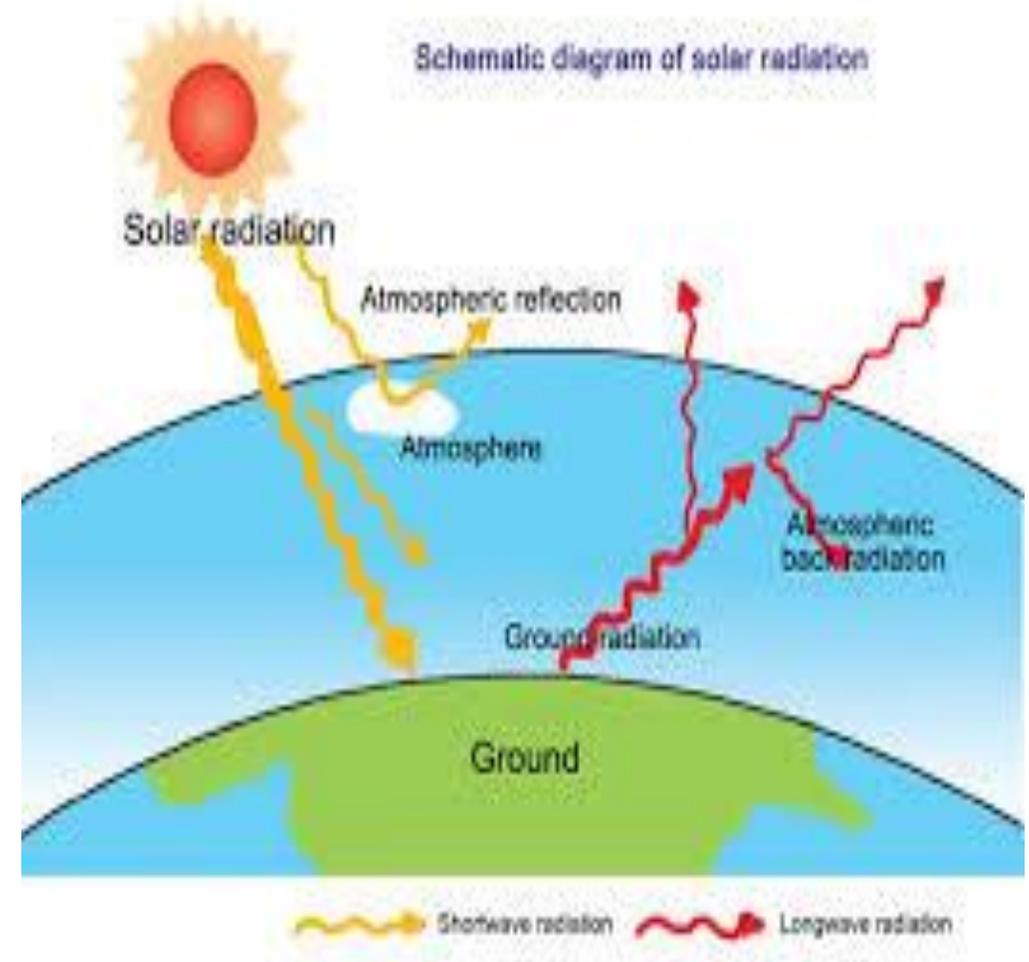# Propagation of solar radiation from the sun to earth

❑Solar radiation propagates as electromagnetic waves (including visible light, infrared, and ultraviolet) at the speed of light through the vacuum of space, requiring no medium, and takes about 8 minutes to reach Earth.

❑Upon entering Earth's atmosphere, some radiation travels directly (beam radiation) while much of it is scattered, reflected, or absorbed by air molecules, clouds, dust, and pollutants (diffuse radiation) before reaching the surface as global radiation.

Solar radiation:

EXTRATERRESTRIAL / TERRESTRIAL SOLAR RADIATION

Scattered

Diffuse

Beam

Albedo

M.KARTHIKEYAN AP/MECH AAACET SIVAKASI

Schematic diagram of solar radiation

Solar radiation

Atmospheric reflection

Atmosphere

Atmospheric back radiation

Ground radiation

Ground

Shortwave radiation   Longwave radiation
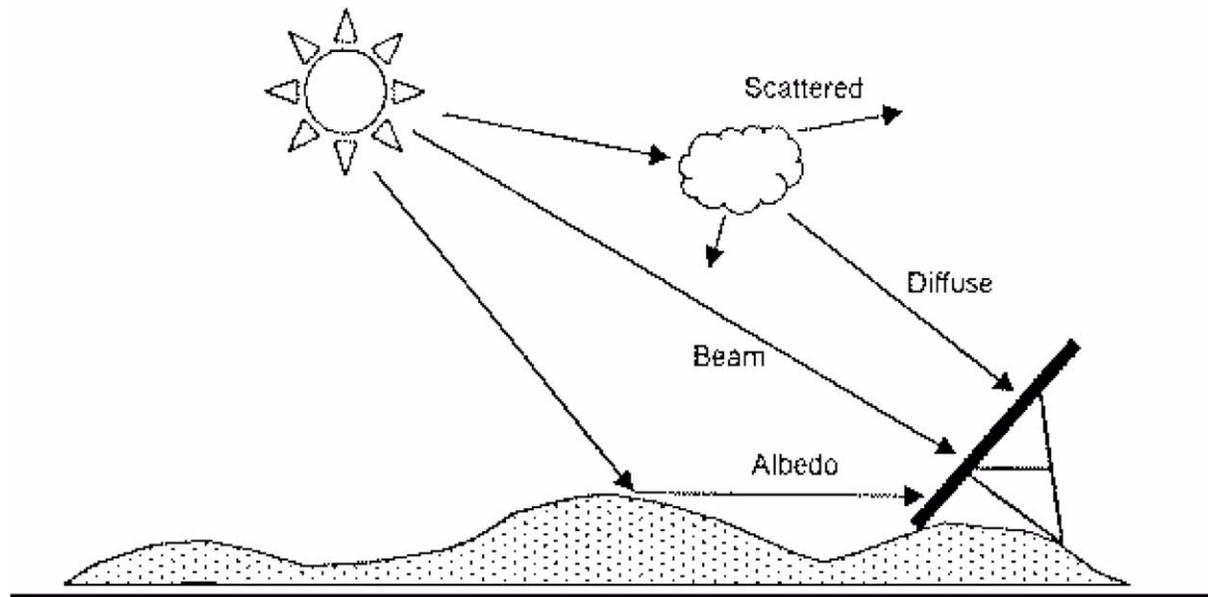
1. **Journey Through Space (Extraterrestrial)**

- **Energy Form:** The Sun emits energy as electromagnetic radiation (photons) across a spectrum, including infrared (heat), visible light (what we see), and ultraviolet (UV) light.

- **Travel:** This energy travels as waves through the vacuum of space at the speed of light.

- **Duration:** It takes approximately 8.3 minutes (8 1/3 minutes) for this energy to cover the ~150 million km distance from the Sun to Earth.

2. Interaction with Earth's Atmosphere (Terrestrial)

- **Direct vs. Diffuse:**

- **Direct Beam Radiation:** Sunlight that travels straight through the atmosphere to the surface.

- **Diffuse Radiation**: Sunlight scattered by atmospheric components like water vapor, gases, dust, and clouds, appearing as skylight.

- **Global Radiation**: The sum of direct and diffuse radiation.

- **Atmospheric Effects:**

- **Absorption:** The ozone layer absorbs most harmful UV-C radiation; other molecules absorb UV-B and some infrared.

- **Scattering:** Air molecules and particles scatter shorter wavelengths (blue light), making the sky appear blue.

- **Reflection:** Clouds and surfaces reflect radiation back to space, reducing heating.

3. Reaching the Surface

- **Uneven Heating:** The angle at which sunlight hits the Earth's surface varies, with direct rays (near the equator) delivering more concentrated energy than angled rays (near the poles), causing temperature differences.

- **Energy Transformation:** Absorbed radiation is converted into heat, driving Earth's climate, weather, and the water cycle.

Solar Radiation Geometry:

❑ Solar radiation geometry deals with the relative position of the Sun with respect to the Earth and a given location on Earth.

❑ Understanding this geometry is essential for estimating solar energy availability, designing solar collectors, and performance analysis of photovoltaic and thermal systems.

Solar Radiation:

❑ The sun is a spherical source of about 1.39 million km diameter, at an average distance of 149.6 million km from earth.

❑ Radiation from the sun sustains life on earth and determines the climate.

❑ The solar radiation can be divided into two types, extraterrestrial and terrestrial

Sun–Earth Geometry:

- The Earth revolves around the Sun in an elliptical orbit, while rotating about its own axis. The Earth's axis is tilted at 23.45° with respect to the plane of its orbit (ecliptic plane). This tilt is responsible for seasons, variation in solar angles, and day length.

- **Earth's Orbit:** Earth orbits the Sun in an ellipse, not a perfect circle, causing variations in distance (affecting solar constant) and seasons.

- Key Angles:

- **Declination Angle (δ):** Angle between the Sun-Earth line and Earth's equatorial plane, causing seasons.

- **Hour Angle (ω):** Angle representing time, changing 15° per hour.

- **Latitude (φ):** Angular distance north or south of the equator.

- **Zenith Angle (θz) & Altitude Angle (α):** Angles defining the Sun's height and direction relative to the local horizon.

Extraterrestrial Radiation:

- Radiation received outside Earth's atmosphere.

- Considered constant (Solar Constant ~1367 W/m²), though it varies slightly due to Earth's elliptical orbit.

- Has a broad spectrum (UV, Visible, Near-Infrared).

- **Extraterrestrial solar radiation (H)** is the solar radiation which falls on a surface normal to the rays of the sun outside the atmosphere of the earth. A typical spectral distribution of extraterrestrial radiation is shown in Figure 2-1. The curve rises sharply with the wavelength and reaches the maximum value of 2074 W/m2-μm at a wavelength of 0.48 μm. It then decreases asymptotically to zero.

Spectral distribution of extraterrestrial radiation
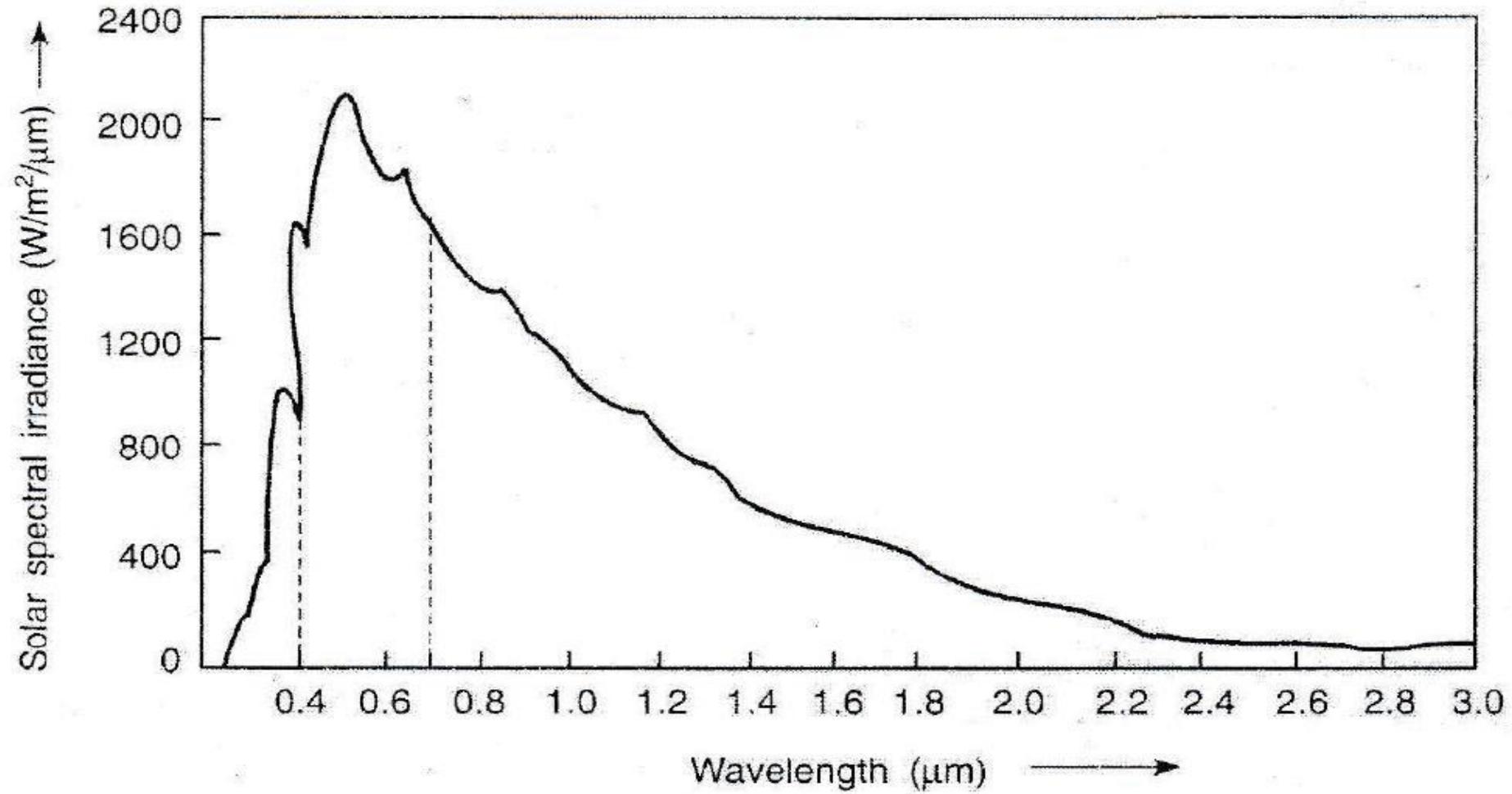
- This extraterrestrial solar radiation at the mean earth sun distance, D_0, is called the **solar constant, H_0**.

- Using the value obtained by measurements from NASA, the solar constant is said to be 1353 W/m^2. Thus, the extraterrestrial solar radiation, H, can be calculated by using the following

Equation : $$H = H_O\left(1 + 0.034 Cos\left(\frac{360.d_n}{365.25}\right)\right)$$

Where dn is the day's number from year .

Terrestrial Radiation:

- Solar radiation that reaches Earth's surface after passing through the atmosphere.

- **Components:**

  - **Direct:** Unscattered radiation from the sun's disk.

  - **Diffuse:** Scattered by atmosphere (aerosols, clouds) and reflected from ground.

  - **Global:** Sum of direct + diffuse.

- **Atmospheric Effects:** Absorption (water vapor, ozone) and scattering (molecules, particles) reduce intensity.

- **Insolation** Energy received per unit area per unit time (W/m²) or energy (J/m², kWh/m²).

Terrestrial Solar Radiation

❑ Solar radiations pass through the earth's atmosphere and are subjected to scattering and atmospheric absorption.

❑ A part of scattered radiation is reflected back into space. Short wave ultraviolet rays are absorbed by ozone and long wave infrared rays are absorbed by CO_2 and water vapours.

❑ Scattering is due to air molecules, dust particles and water droplet that cause attenuation of radiation as detailed in Figure.

❑ Minimum attenuation takes place in a clear sky when the earth's surface receives maximum radiation.

Solar radiation atmospheric mechanisms
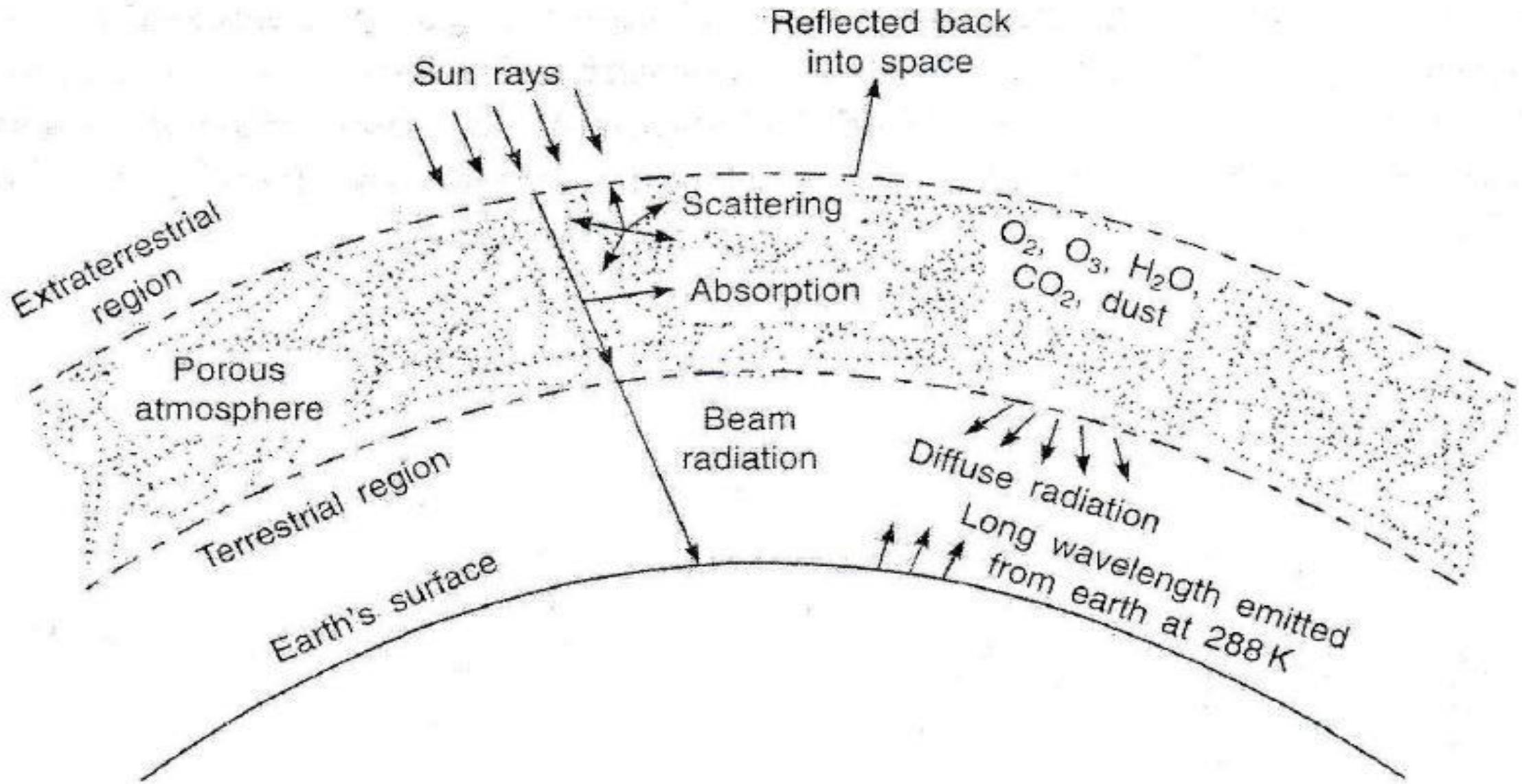
- **Beam radiation (*Hb*):** Solar radiation received on the earth's surface without change in direction.

- **Diffuse radiation (*Hd*):** The radiation received on a terrestrial surface (scattered by aerosols and dust) from all parts of the sky dome.

- **Total radiation (*Ht*):** The sum of beam and diffuse radiations (*Hb* + *Hd*). When measured at a location on the earth's surface, it is called **solar**

- **insolation** at the place. When measured on a horizontal surface, it is called **global radiation (*Hg)*.**

- **Irradiance (W/m2):** The rate of incident energy per unit area of a surface.

- **Albedo:** The solar radiation that reflects from the earth's surface.

- **Sun at zenith:** It is the position of the sun directly overhead.

- **Air mass (AM):** It is the ratio of the path length of beam radiation through the atmosphere to the path length if the sun were at zenith

Solar Thermal (UNIT-1) Syllabus

- **Solar Thermal:** Solar Collectors, Solar parabolic trough, Solar tower, Solar cooker, Solar water heater, Solar dryer, Solar Pond.

- **Solar Electric Power Generation:** A Generic PV Cell, PV Materials, Equivalent Circuits for PV Cells, Modules and Arrays; I-V Curve under Standard Testing Conditions; Impact of Temperature and Insolation on I-V curves; Shading Impacts on I-V curves; Maximum PowerPoint Trackers (MPPT).
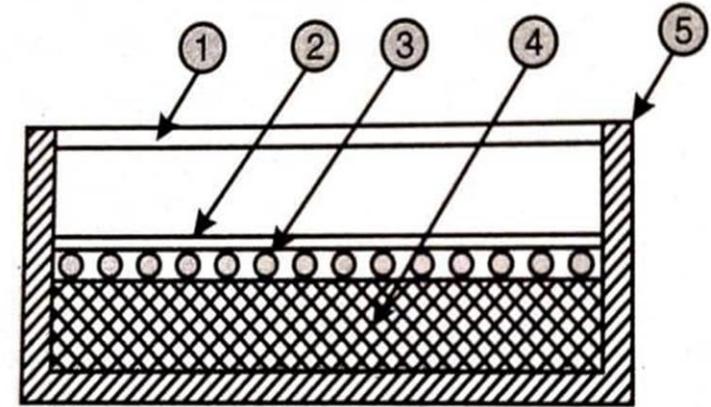
Solar Collector:

- Solar energy collectors are crucial for converting solar radiation into usable forms like heat or electricity. There are two main types of collectors: non-concentration and concentrating collectors.

- In **non-concentration** collectors, the **collector area and absorber area are the same**. These collectors intercept solar radiation and absorb it without concentrating it.

- **Concentrating collectors**, however, **have a larger area for intercepting solar radiation compared to the absorber area**. They use mirrors and lenses to focus the sun's rays on a boiler, allowing for much higher temperatures. This type of collector is more efficient than non-concentration collectors.

- To maximize efficiency, it is important to mount the collectors in a way that they face the sun as it moves across the sky.

- Overall, solar energy collectors play a vital role in harnessing solar radiation and converting it into proper energy forms. There are mainly **two types** of collectors:

- **Non Concentrating Collectors**

- **Concentrating Collectors.**

1. Non Concentrating Collectors

- In these collectors, the area of the collector to intercept the solar radiation is equal to the absorber plate and has a concentration ratio of 1. These collectors are further classified as:

- **Flat Plate Collectors:** Fixed tilted non-concentration collectors are used for temperatures below 100 °C. They can utilize both direct and diffuse solar radiation. These collectors are installed in a fixed tilted position, ideally facing the equator, to maximize efficiency and capture sunlight throughout the day.

The main parts of a flat plate collector are:

1. **A see-through cover:** This can be made of glass or a transparent plastic sheet that allows sunlight to pass through.

2. **Tubes, fins, passages, or channels:** These are connected to the absorber plate or integrated with it. They carry water, air, or another fluid to transfer heat.

3. **The absorber plate:** It is usually made of metal or has a black surface. It absorbs the solar energy and converts it into heat. Different materials can be used for air heaters.

4. **Insulation:** This is placed at the back and sides of the collector to minimize heat loss. Common insulating materials like fiberglass or styrofoam are used for this purpose.

5. **The casing or container:** It encloses all the other components and protects them from the weather.

Liquid Collector:
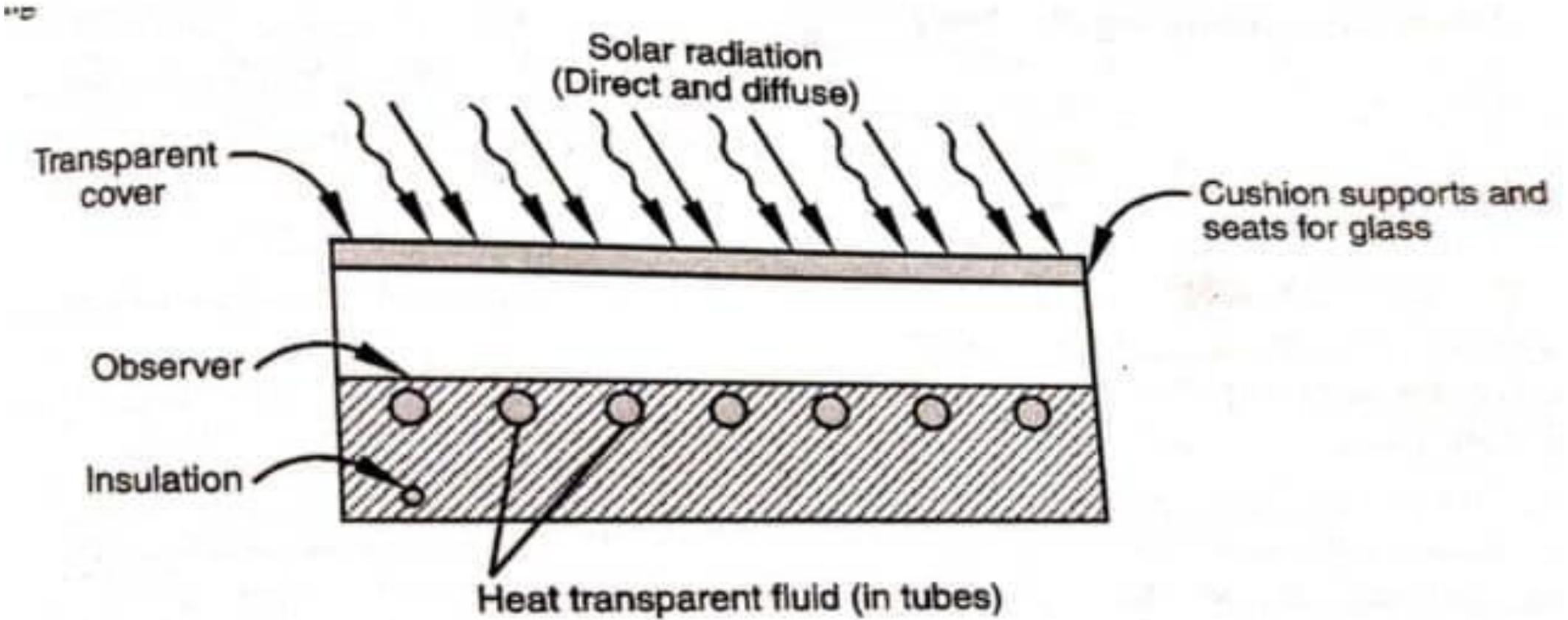
Liquid Collector:

- A liquid collector is a type of solar collector that consists of a flat surface designed to absorb solar radiation.

- The absorbing surface is typically a metal plate made of materials like copper, steel, or aluminum, with copper tubes in thermal contact with the plate.

- The absorber plate is usually 1 to 2 mm thick, while the tubes range in diameter from 1 to 1.5 cm. They are connected to the bottom of the absorber plate with a spacing of 5 to 15 cm.

- To transfer heat to a point of use, fluid (typically water) is circulated across the solar-heated surface.

- Thermal insulation, usually 5 to 10 cm thick, is placed behind the absorber plate to minimize heat loss. Insulation materials such as mineral wool, glass wool, or fiberglass are commonly used.
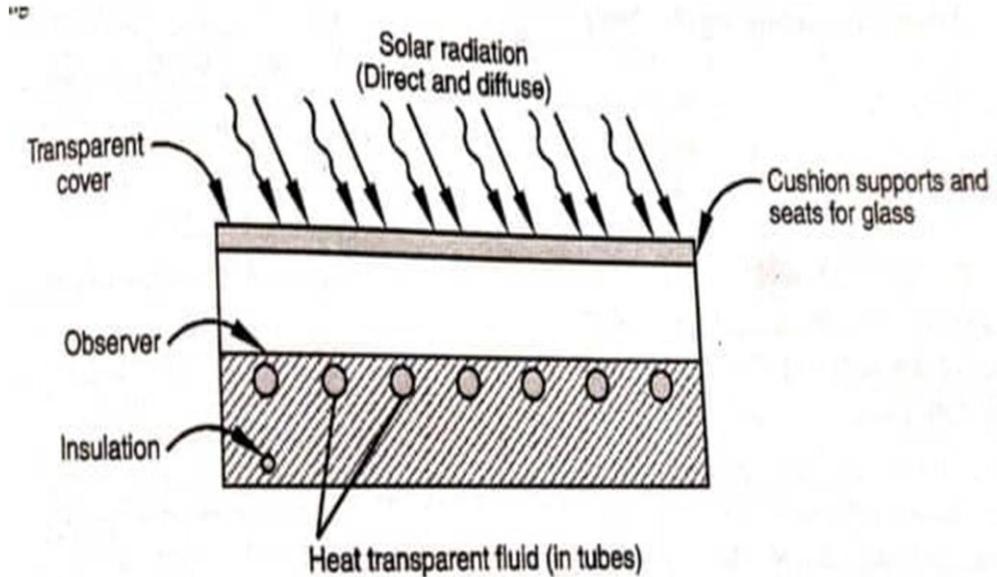
- The front cover, usually made of glass or transparent plastic, allows solar radiation to enter but blocks infrared re-radiation from the absorber. The glass cover acts as a shield against convection losses from the absorber plate. Glass is the preferred material, typically with a thickness of 3 to 4 mm. However, certain plastic films may also be suitable.

- In summary, a liquid collector consists of an absorbing surface made of a metal plate and tubes, fluid circulation for heat transfer, insulation to reduce heat loss, and a front cover (usually glass) that allows solar radiation to pass through while minimizing convection losses.

3. Typical Air collectors or Solar Air Heater:

❑A flat plate collector used for heating an air stream consists of a plate with attached fins on the back side to increase contact surface area.

❑The back side of the collector is heavily insulated with materials like mineral wool.

❑The most favorable orientation for heating purposes is facing due south, inclined at an angle equal to the latitude plus 15°.

Solar Air Heater:
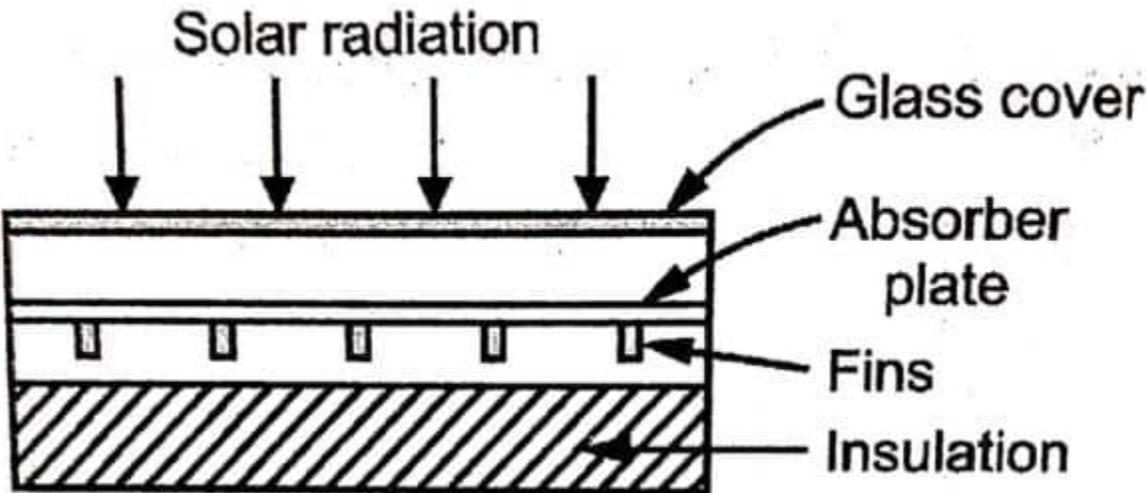
❑Air is sometimes used as the heat transport medium in solar collectors, offering advantages over water.

❑To reduce the power needed for air circulation, wider flow channels are used, such as spaces between the absorber plate and insulator with baffles creating a zig-zag flow path.

❑Air eliminates freezing and corrosion issues and small air leaks are less concerning than water leaks. Additionally, heated air can be directly used for space heating.

❑However, air requires larger duct sizes, higher flow rates, and increased pumping power than water. Heat transfer from air to water in a hot water supply system is also inefficient.

❑Solar air heaters are essential for utilizing solar energy and find applications in drying agricultural products, space heating, dehumidifying agent regeneration, timber seasoning, and curing industrial products like plastics.

Applications of Solar Air Heater:

❑Heating buildings.

❑Drying agricultural produce and lumber.

❑Heating greenhouses.

❑Air conditioning buildings utilizing desiccant beds or absorption refrigeration process.

❑Using air heaters as the heat sources for a heat engine such as a Brayton or Stirling cycle

2. Concentrating Collectors

- A focusing collector is designed to capture solar energy with high intensity by using optical systems like reflectors or refractors.

- It is a modified version of a flat plate collector, where a reflecting or refracting surface (known as a concentrator) is introduced between the solar radiation and the absorber.

- These collectors can significantly increase the radiation intensity from a low value to a much higher value, sometimes up to 10,000 times.

- They focus the solar radiation from a large area onto a smaller receiver or absorber. This concentration of energy allows fluids to be heated to temperatures of 500 °C or even higher.

Types of Concentrating Collectors

Two general categories of concentrating collectors are:

(A) Line-focusing types

(B) Point focusing types The line is a collector pipe and the point is a small volume through which the heat transport fluid flows.

As per the number of concentrating collector geometries, the main types of concentrating collectors are

(a) Parabolic trough collectors.

(b) Mirror strip reflector.

(c) Fresnel lens collector.

(d) Flat plate collector with adjustable mirrors.

(e) Compound parabolic concentrator (C.P.C.)

A) Line-focusing collectors:

- **1. Parabolic Trough Reflector:** In concentration, collectors like the parabolic trough collector, solar radiation is collected and concentrated at the focus of a parabolic reflector.

- The reflector is shaped like a trough with a parabolic cross-section, causing the solar radiation to be focused along a line.

- The absorber, usually a collector pipe with a selective absorber coating, is placed at the focus to capture the concentrated solar energy.

- Parabolic trough collectors can vary in size, with reflector units typically being 3 to 5 meters long and 1.5 to 2.4 meters wide. Multiple units are often connected in a row or in parallel. Reflectors are commonly made of polished aluminum or silvered glass.
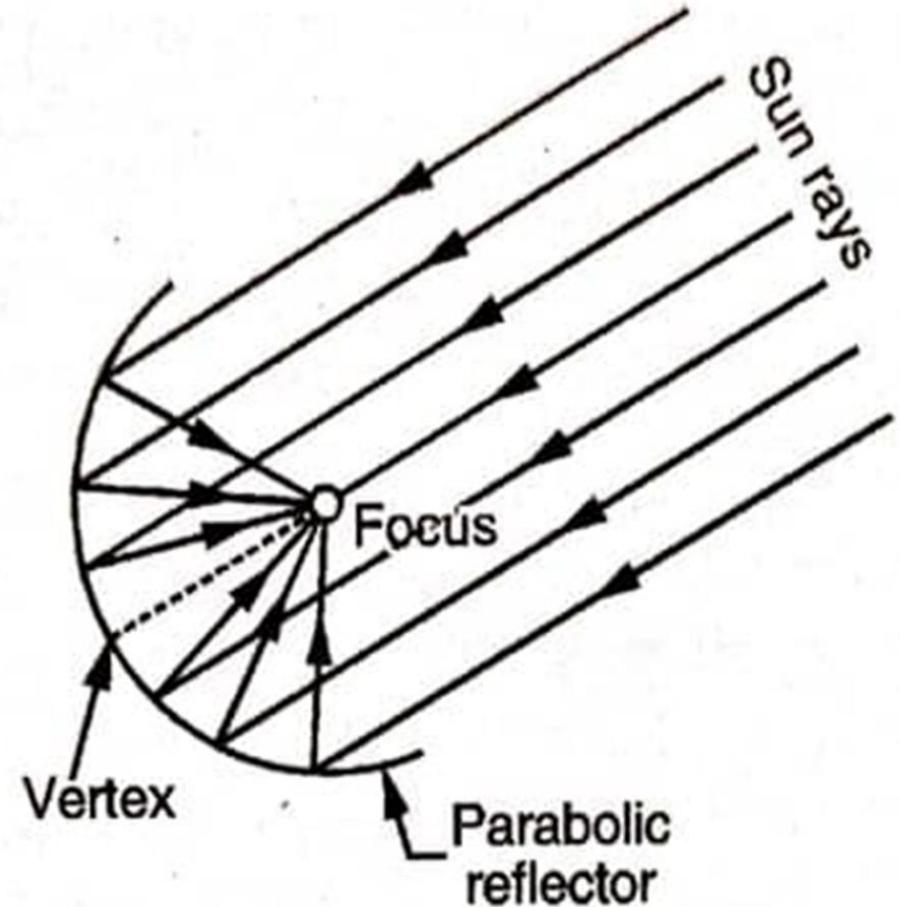
Mirror Strip Reflector:

- A solar trough concentrator consists of a plane or slightly curved mirrors mounted on a flat base, reflecting solar radiation onto a fixed focal line.

- The mirrors are adjusted to account for changes in the sun's elevation, while the collector pipe remains in the focal line.
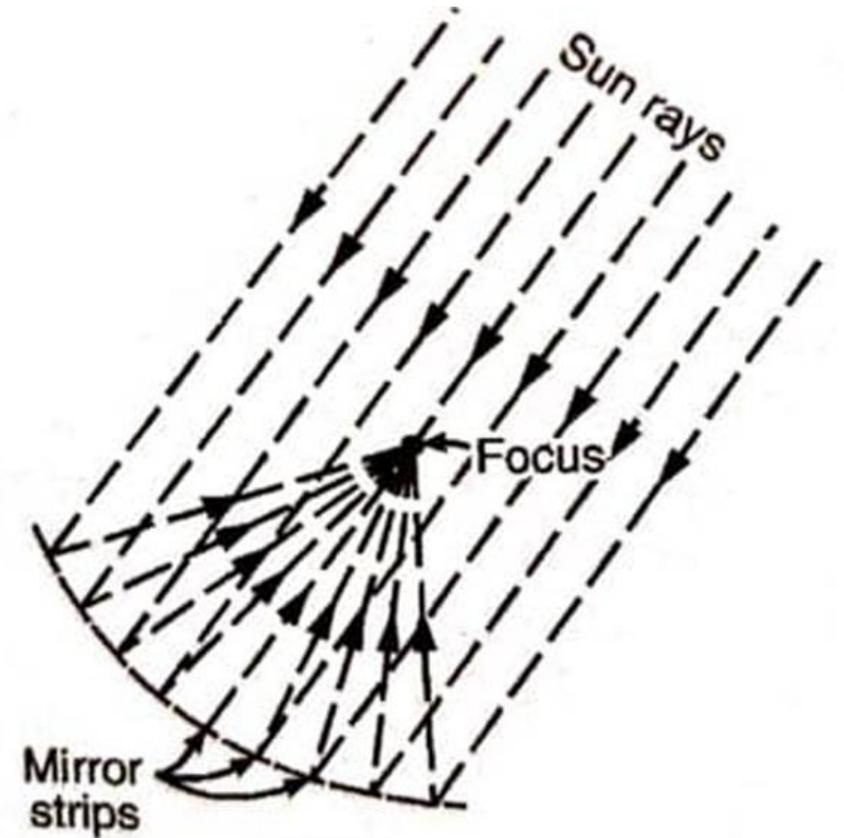
Fresnel Lens Collector:

- Fresnel lens-based collectors use the focusing effect of a rectangular lens, typically 4-7 meters long and 0.95 meters wide. The lens is made in sections from acrylic plastic and is cost-effective. The trough container does not contribute to concentrating solar energy.

-
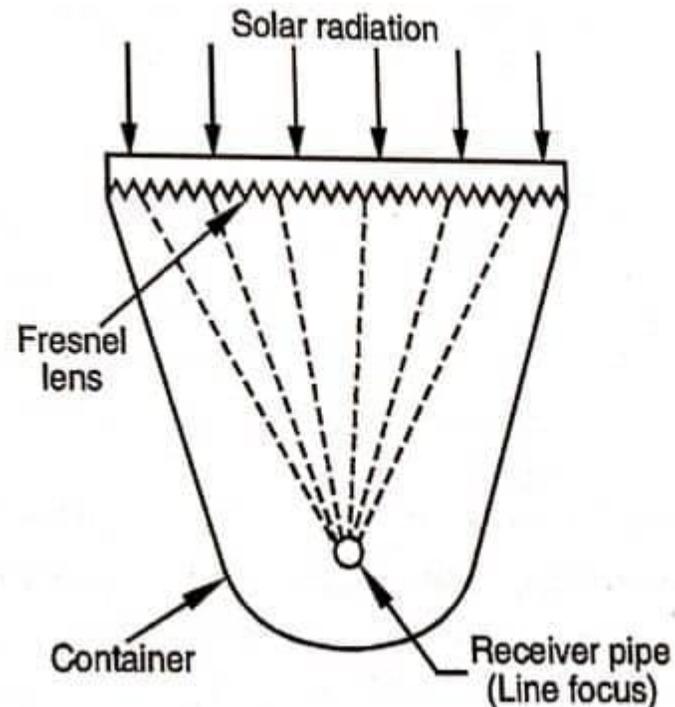
B) Point focusing collector (Paraboloidal Type):

- A paraboloidal dish collector concentrates solar radiation by bringing it to a focus at a small central volume.

- The dish, about 6-6 meters in diameter, is made of curved mirror segments forming a paraboloidal surface.

- The absorber cavity, located at the focus, is made of a zirconium copper alloy with a selective coating.

- The collector tracks the sun to maintain alignment with the focus, allowing for continuous solar tracking.


Absorber (focus)

Paraboloid dish
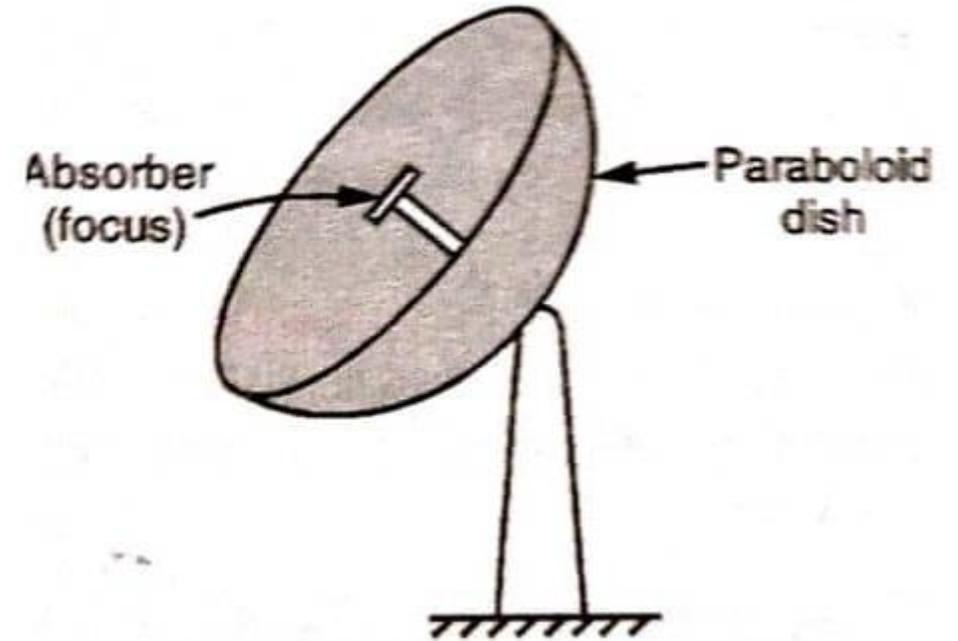
4. Concentrating Collectors, Non-Focusing type:

❏ A reflective flat plate collector consists of a south-facing flat plate with mirrors attached to its north and south edges. When the mirrors are set at the correct angle, they reflect solar radiation onto the absorber plate.

❏ This allows the absorber plate to receive both direct solar radiation and reflected radiation from the mirrors. By reflecting and redirecting scattered radiation onto the absorber, the mirrors enhance the concentration effect.

❏ The main advantage comes from the increased direct radiation reaching the absorber plate, resulting in improved efficiency.
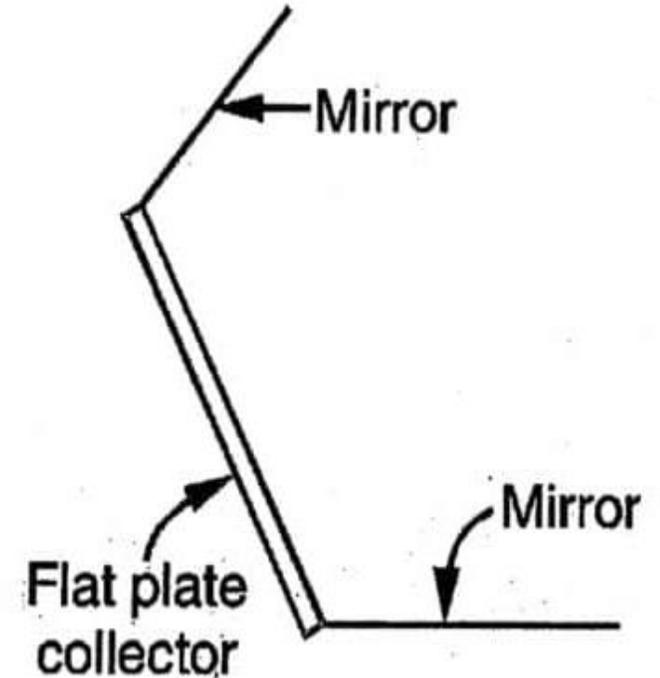
Compound Parabolic Concentrator (C.P.C.):

- The C.P.C. (Compound Parabolic Concentrator) is a trough-like arrangement of two parabolic mirrors.

- Unlike single parabolic troughs, the C.P.C. collects solar radiation from various directions, including diffuse radiation, concentrating it on a small area.

- It offers a moderate concentration in the east-west direction without constant sun tracking.
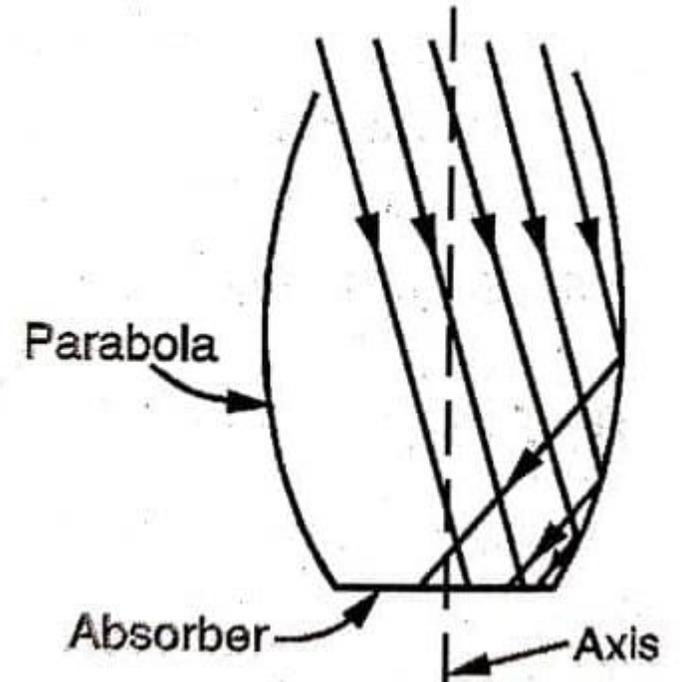
Advantages of Solar Collector

- **Renewable Energy:** Solar collectors use energy from the sun, which is a limitless and renewable resource.

- **Good for the Environment:** They help reduce pollution and lessen the need for fossil fuels, making the planet cleaner.

- **Saves Money:** Solar collectors can cut down on energy bills, especially in sunny areas.

- **Energy Independence:** They reduce the need to rely on outside energy sources, making you more self-sufficient.

- **Long Lasting:** With proper care, solar collectors can work efficiently for many years.

- **Government Support:** Many places offer financial help, like rebates and tax credits, for installing solar collectors.

Solar Cooker

- Solar Cooker is a device that harnesses heat from solar energy and use it for cooking and heating.

- Unlike the gas stove and other cooking devices which use conventional and non-renewable forms of energy, solar cooker uses renewable and non pollution form of energy.

- It is a non-polluting and clean device that doesn't cause any emission.

- It concentrate sunlight falling on it which causes the increase in temperature and thus helps in cooking.

- Although it slowly cooks the food but save the nutrition of the food.

- Because of its good properties, government of India provides subsidy on Solar Cooker to promote it
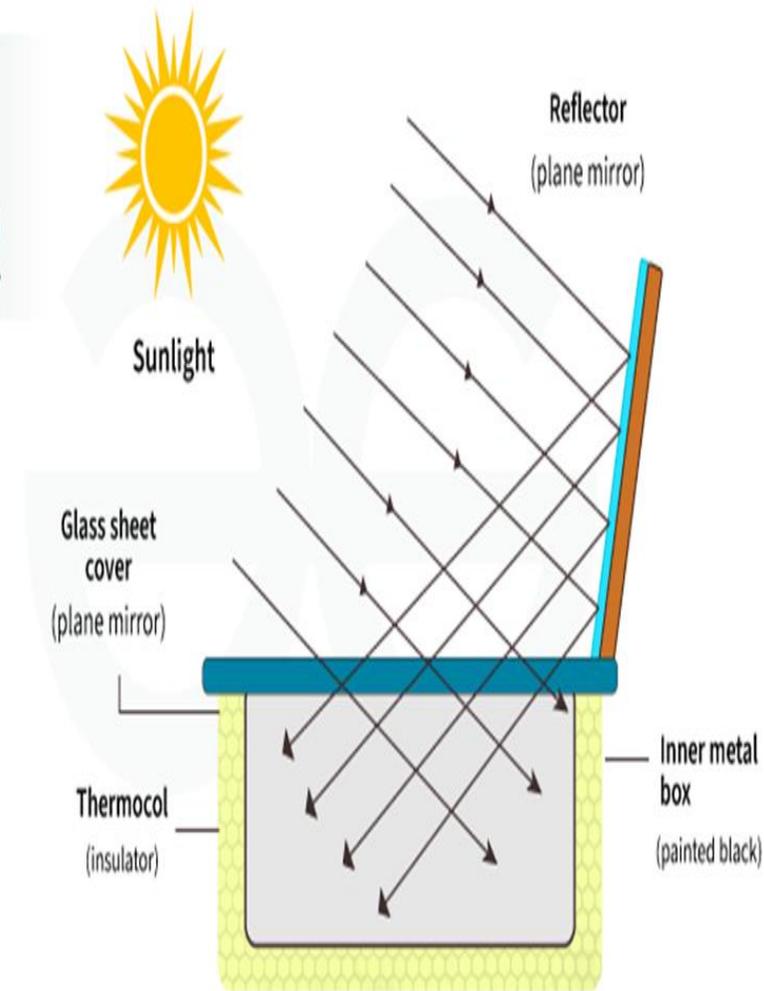
Working Principle of Solar Cooker

Using Mirrors to Focus Sunlight or Concentrate Sunlight

• A highly reflective concave mirror surface is used for cooking by using sunlight. The concave mirror concentrates and directs the sunlight into a small cooking area. This helps to increase the magnitude of the sunlight, which produces a high temperature, enough to cook. The solar cookers are designed to achieve temperatures ranging from 65°C to 400°C, which is enough for cooking.

Converting Light Energy to Heat

• The concentrated sunlight is directed onto a receiver that is a cooking pot. The light energy transforms into heat by the interaction between the light and the material of the receiver. This process is known as conduction. The conversion can be maximized by improving the conducting materials and retain heat. To absorb maximum light , black painted pot is used in Solar Cooker.

Trapping Heat

- Once we retain heat in Solar Cooker, we have to keep it inside as much as we can. For this , we have to minimize the effects of convection. By isolating the air inside the Solar cooker from the external air, we can reduce the effects of convection. By using a glass lid on the cooking pot we can reduce the loss of heat through convection along with enhances light absorption from the top of the solar cooker. The glass lid is used to hold heat inside the cooker and captures incoming sunlight.

Types of Solar Cooker

- Solar Cookers are generally four types

- Panel Cooker

- Parabolic Cooker

- Evacuated Tube Cooker

- Box Cooker

Application of Solar Cooker:

- Applications of Solar Cooker are as follows -
- Solar cooker is used to Roasting coffee beans , popcorns and peanuts for commercial purposes.
- Water Distillation is done by Parabolic Solar Cooker. Water distillation is done by boiling the water constantly.
- Many industries can achieve more than 2400°C from solar cooker which melts iron very easily.
- Separation of Beeswax and melting the capping
- Melting of Wax is done by solar cooker.
- Sterilization of Medical apparatus such as needles, gauge bandages.
- It is also used for Ironing. Even it is not a conventional way on ironing. Iron is heated by parabolic solar cooker and then it is used for ironing cloths.
- Purification of Water . Solar cooker is used for water purification by heating water.
- Solar cooker is used for Dehydrating foods. The lid of the cooking pot is partially opened , so that it prevents from the excess heating.

Advantages of Solar Cooker

Solar Cooker is used in household purposes as well as commercial purposes. The followings are the advantages of Solar Cooker -

- Solar Cooker keeps environment pollution free. It doesn't affect on environment.
- Fuel is not required for cooking in Solar Cooker.
- The food that is cooked in Solar Cooker, contains high nutrition value.
- Solar Cooker is available in various sizes. So that a family can buy solar cooker according to the number of their family members.
- Solar Cooker is a government scheme, so a reasonable subsidy will be provided to the buyers.

Disadvantages of Solar Cooker

Solar Cooker has a few limitations or disadvantages. These are given below -

- Solar Cooker takes too much time to cook any food.
- Solar Cooker is working only in the presence of sunlight. At night Solar Cooker is not working.
- In cloudy weather, it is very hard to cook food by using solar cooker.
- During strong winds, solar cooker's working process is less effective

Solar water heater:

Solar Thermal Devices:

❑ The solar water heater consists of a solar collector, insulated stainless steel tank and piping connections.

❑ The total system can be mounted on the roof top, on one side the piping connects it to the overhead tank and on the other side to the usage points.

❑ The smallest capacity available is 100 liters per day at 60° C temperature, suitable for a family of 4-6 members.

Solar water heater:

❑ The solar water heating systems come with a solar collector of 25 sq. m area for solar tank of 100liter capacity. It occupies an area of 35 sq. ft on the roof top.

❑ The water is loaded in the daytime and is stored in the storage tank for a period of 48 hours.

❑ This system can be connected to bathrooms and kitchen. Generally, the life of the system is about 15 years and it requires no maintenance

- The collector is having 20gauge G.I. corrugated sheet as absorber with 12 mm.

- G.I. pipes as heat exchanger laid in the corrugations of the sheet in serpent fashion.

- The absorber and the pipes are painted black and embedded in a wooden box insulated at the bottom and sides.

- The ends of the pipe are connected to the insulated storage drum which is kept just above the collector.

- The collector is kept on an angle iron stand such that the flat plate is at 11° slope facing south. Hot water temperature is 55 - 63° C on a typical sunny day and heat loss due to over night storage is about 4 to 8°C.

SOLAR WATER HEATER

Fig : solar water heater.

Dimensions in mm
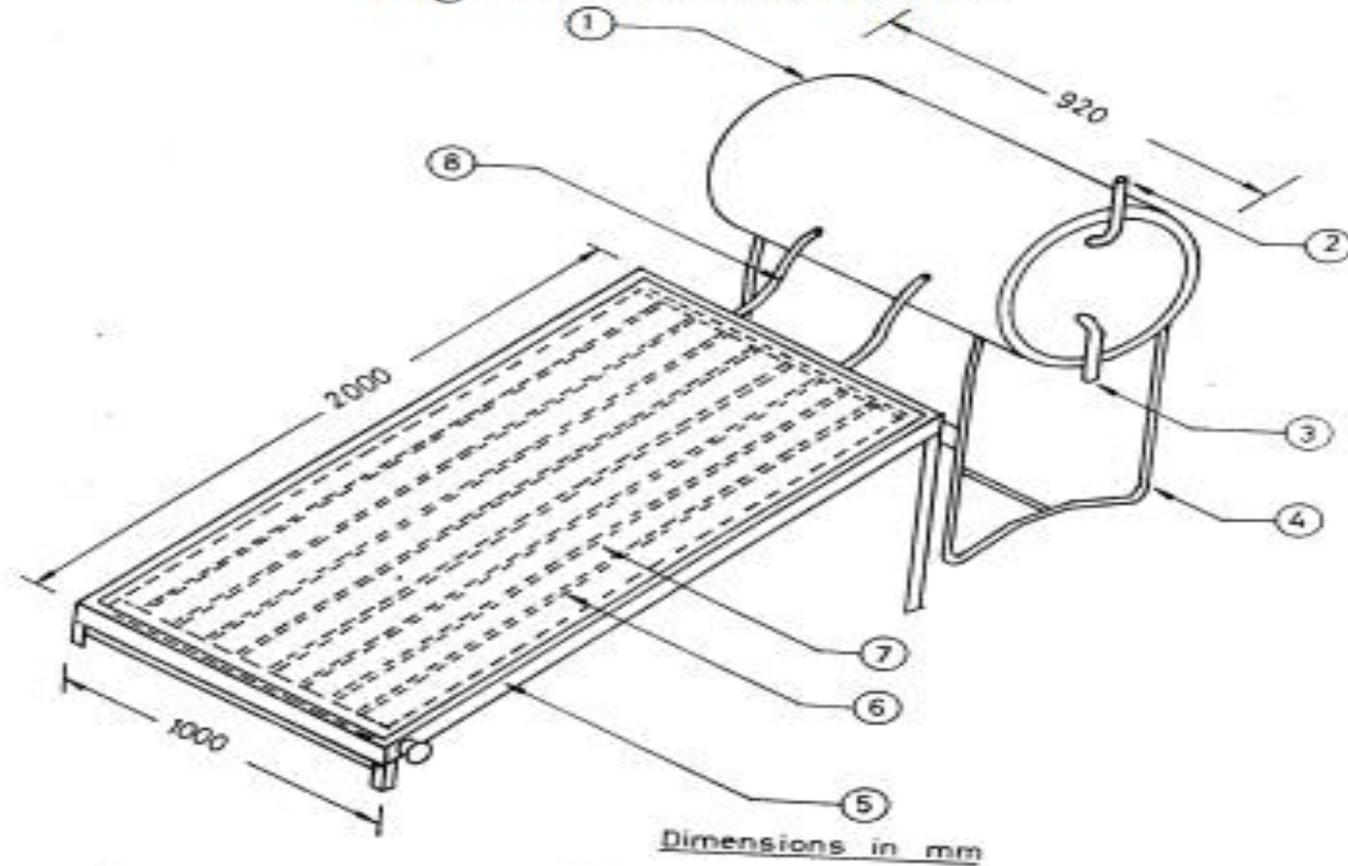
1. Insulated water tank
2. Water inlet
3. Water outlet
4. Tank support
5. Frame
6. Liquid pipe
7. Absorber
8. Water line

Solar water heater is based on the principle of converting solar energy into electrical energy and then into heat energy, using solar electric panels, so called solar cells or Photovoltaic cells.

Construction

It consists of a solar thermal panel in which collector is used to collect, capture and retain the heat radiations from the sun
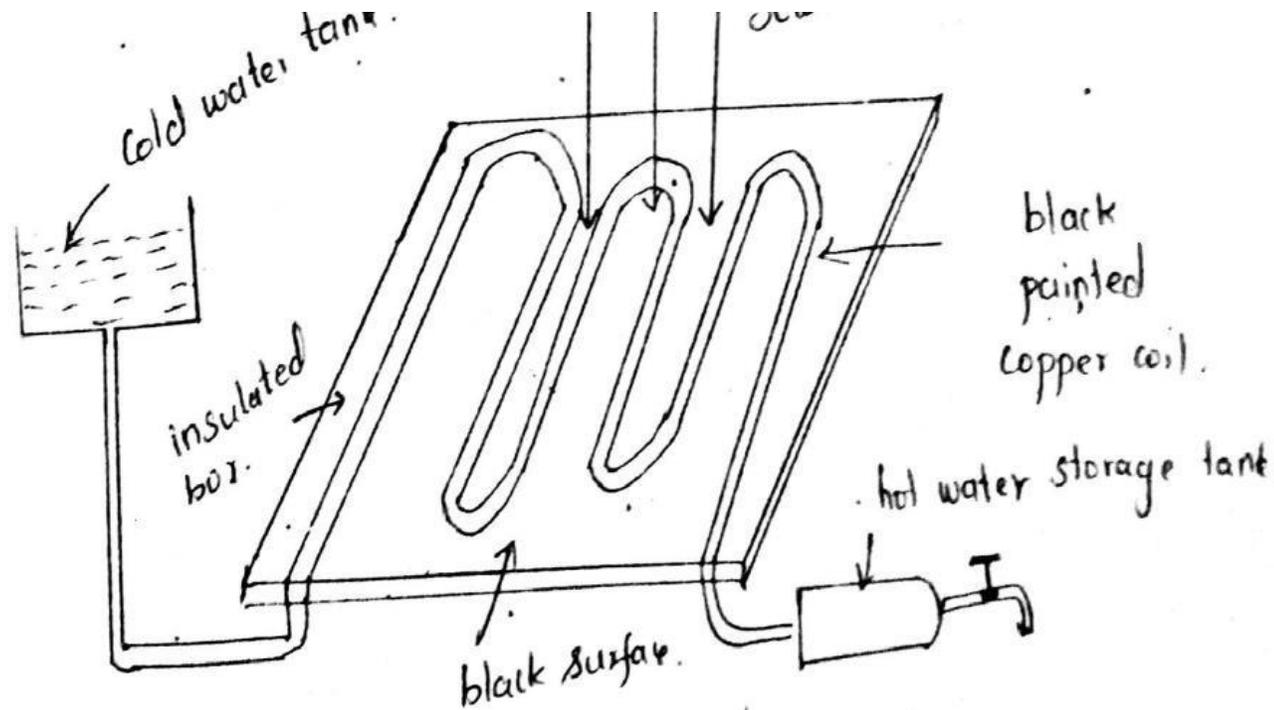
❑The heat exchanger is made up of coil of copper pipes and is kept inside the water tank.

❑Heat exchanger is used to transfer the heat energy from the hot water passing through the copper pipe in the heat exchanger to the cold water in the water tank.

❑An electric pump is used to pump the cold water coming out from the heat exchanger to the collector of the thermal panel.

❑The total system is controlled by the controller unit, which is used to

- Fill the water with Auto cut-off in the tank.

- Switch on/off the electric pup, whenever required.

Working

❑ With the help of the electric pump, cold is pumped to the collector in the solar thermal panel.

❑ Now, due to the thermal radiations that fall on the thermal panel, the water in the collector is heated up.

❑ This hot water is allowed to pass through the water tank with the help of the heat exchangers

❑ The heat exchanger, which is made up of coil of copper pipes, transfers the heat energy from the water inside the copper coils, to the water present in the water tank and therefore the water in the water tank becomes hot.

❑ The water coming out from the heat exchanger, after transferring the energy, become cold water and enters into the electric pump again.

❑ Thus we can run off hot water from the tank at any time without affecting the panel's

Advantages

Solar energy is free and abundant.

Solar thermal panel occupies less space.

Solar thermal panels are more efficient.

We can save money by paying less electricity bill.

It is a Eco-friendly way to heat water for the domestic need.

Disadvantages

Capital investment and installation cost in high.

Annual maintenance is required to check the working of pump, antifreezing etc.

It occupies space and depends on the availability of direct sun light.

It is not useful during rainy or foggy days.

It will take about 10 to 15 years to get back the money we spent.

solar pond:

- A solar pond is a solar energy collector, generally large in size, that looks like a pond. This type of solar energy collector uses a large, salty lake as a kind of a flat plate collector that absorbs and stores energy from the Sun in the warm, lower layers of the pond. These ponds can be natural or man-made, but generally speaking the solar ponds that are in operation today are artificial

Solar radiation

Relatively fresh water

Insulation zone:
Increasing salt

Storage zone:
Saturated salt water
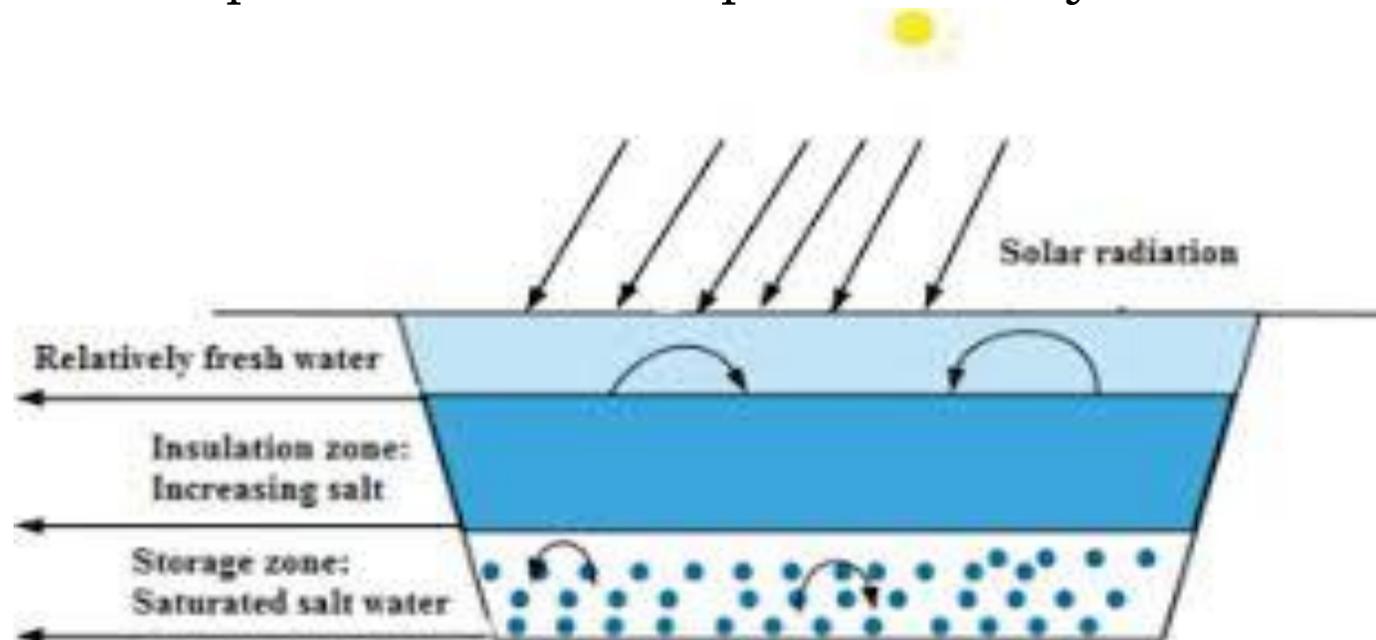
- **SOLAR POND POWER PLANTS**

❑Solar ponds are power plants that utilize the effect of water stratification as a basis for the collector.

❑A basin filled with brine (i.e. a water/salt mixture) functions as collector and heat storage.

❑The water at the bottom of the solar pond serves as primary heat storage from which heat is withdrawn.

❑The deeper water layers and the bottom of the solar pond itself serve as absorber for the impinging direct and diffuse solar radiation.

❑Due to the distribution of the salt concentration within the basin, which increases towards the bottom of the basin, natural convection and the ensuing heat loss at the surface due to evaporation, convection and radiations minimized.

❑ This is why heat of an approximate temperature between 80 and 90 °C (approximate stagnation temperature 100 °C) can be extracted from the bottom.

Heat can then be used for power generation

* Pond collector
* Heat Exchangers
* Thermal Engine

Pond collector:

* Pond collectors are either natural or artificial lakes, ponds or basins that act as a flat plate collector because of the different salt contents of water layers due to stratification.

* The upper water layers of relatively low salt content are often provided with plastic covers to inhibit waves.

* This upper mixing zone of such pond collectors usually is approximately 0.5 mthick.

* The adjacent transition zone has a thickness of 1 to 2 m, and the lower storage zone is of 1.5 to 5 m thickness.

- **Mechanism:**

❏If deeper layers of a common pond or lake are heated by the sun, the heated water rises up to the surface since warm water has a lower density than cold water.

❏The heat supplied by the sun is returned to the atmosphere at the water surface.

❏This is why, in most cases, the mean water temperature approximately equals ambient temperature.

❏In a solar pond, heat transmission to the atmosphere is prevented by the salt dissolved in deeper layers, since, due to the salt, water density at the bottom of the pond is that high, that the water cannot rise to the surface, even if the sun heats up the water to temperatures that are close to the boiling point.

❏The salt concentration of the different layers must thus increase with increasing depth.

- In a first phase, this ensures stable water stratification.

- The upper, almost salt-less layer only acts as transparent, heat-insulating cover for the cooling, heat-storing deeper layers at the pond bottom.

Heat Exchanger:

- Basically, there are two methods to withdraw heat from a solar pond: The working fluid of the thermal engine flows through tube bundle heat exchangers installed within the storage zone of the solar pond, and is there by heated up.

- The hot brine can also be pumped from the storage zone by means of an intake diffuser, subsequently be transmitted to the working fluid of the thermal engine and eventually be re-supplied to greater depths of the pond by another diffuser, once the brine has cooled down.

- The technical approach allows adjusting the position of the intake diffuser to the depth of the highest temperature.

- Secondly, heat losses by the pond bottom are reduced, since the cooled water is recycled to the pond near the bottom.

Thermal Engine:
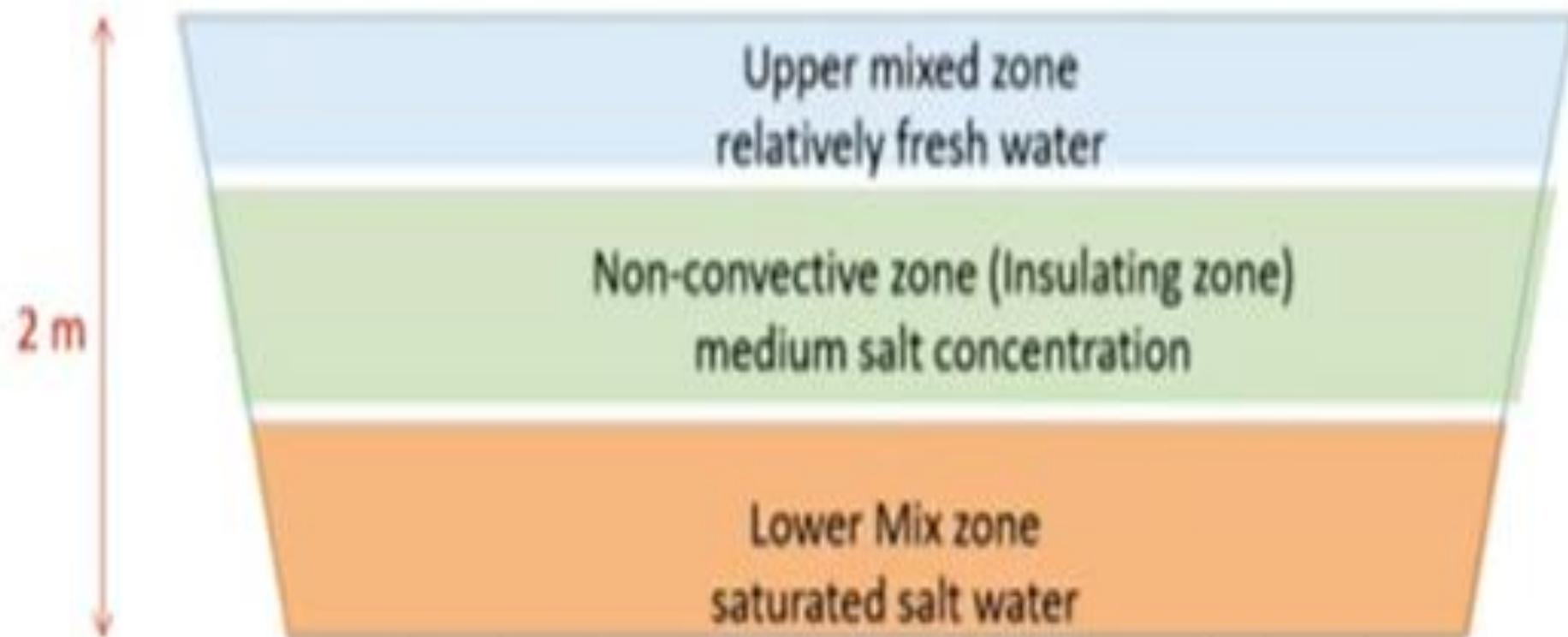
❑To convert solar thermal energy into mechanical and afterwards in electrical energy, usually Organic Rankine Cycles (ORC) processes are applied.

❑These are basically steam cycles which utilize a low-boiling, generally organic, cycle fluid.

❑Such processes permit to provide electrical energy also at low useful temperature differences.

Plant Concepts:

❑Plant diagram of a solar pond power plant

❑The water absorbs the incident direct and diffuse radiation, similar to the absorber of a conventional solar collector, and is heated up.

❑The technically adjusted salt concentration prevents natural convection and the resulting heat loss at the surface due to evaporation, convection and radiation.

❑ Water can thus be withdrawn from the storage zone at the bottom at an approximate temperature of 80 – 90°C.

❑This heat can subsequently be used for power generation by an ORC process

Clear natural Pond

Here it losses heat to the ambient air

2 m

Upper mixed zone
relatively fresh water

Non-convective zone (Insulating zone)
medium salt concentration

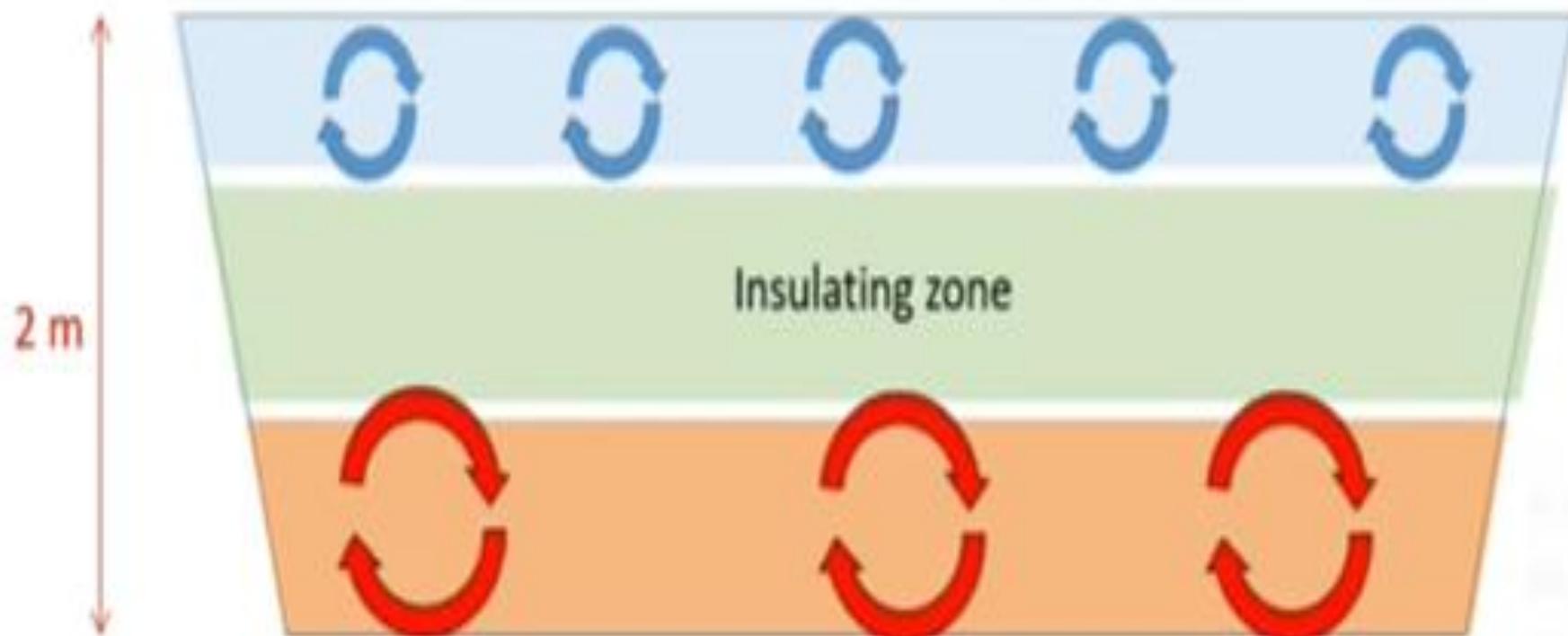Lower Mix zone
saturated salt water

This solar radiation absorbed at the bottom of the pond
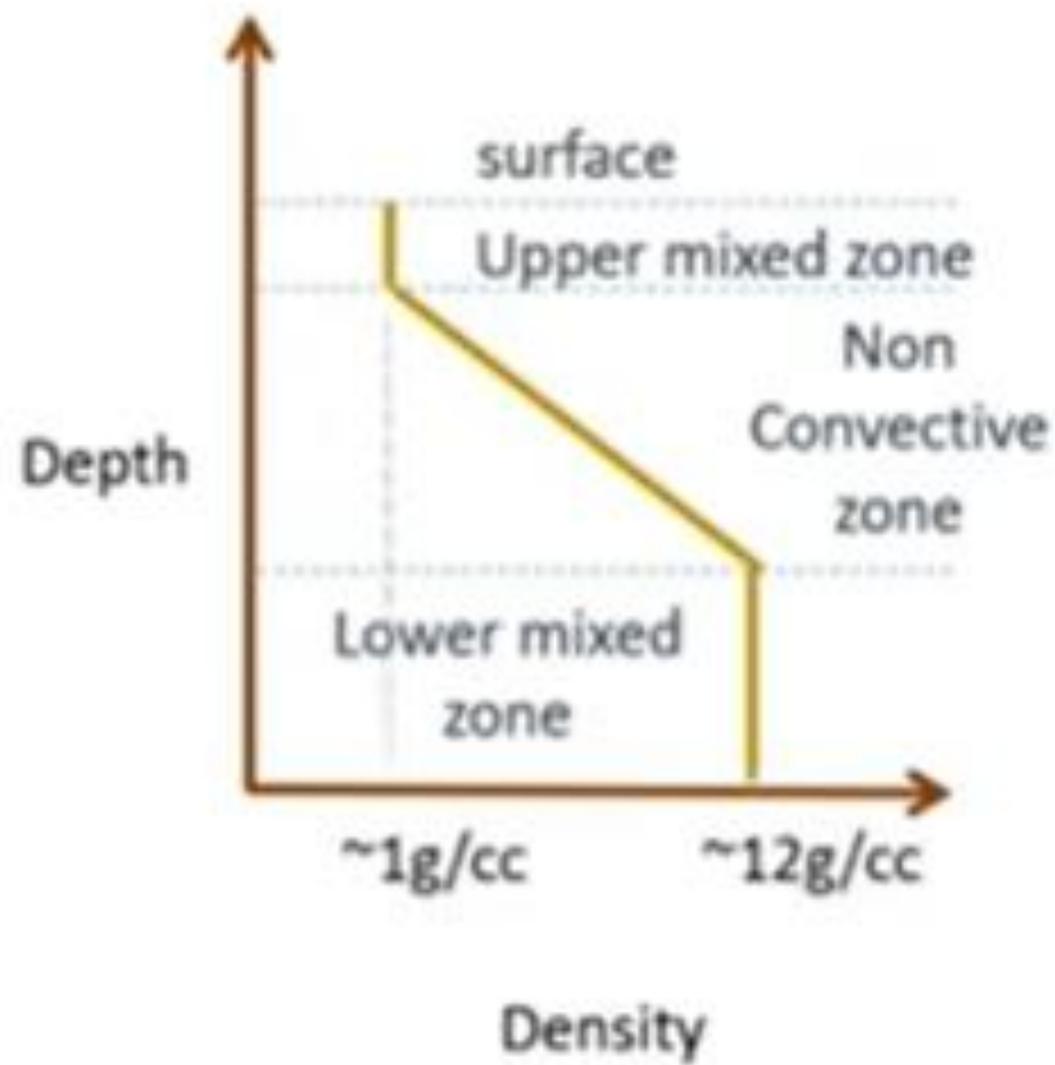The hotter at the bottom becomes lighter

Clear natural Pond

Here it losses heat to the ambient air

Insulating zone

2 m

This solar radiation absorbed at the bottom of the pond

Different zones in Solar pond
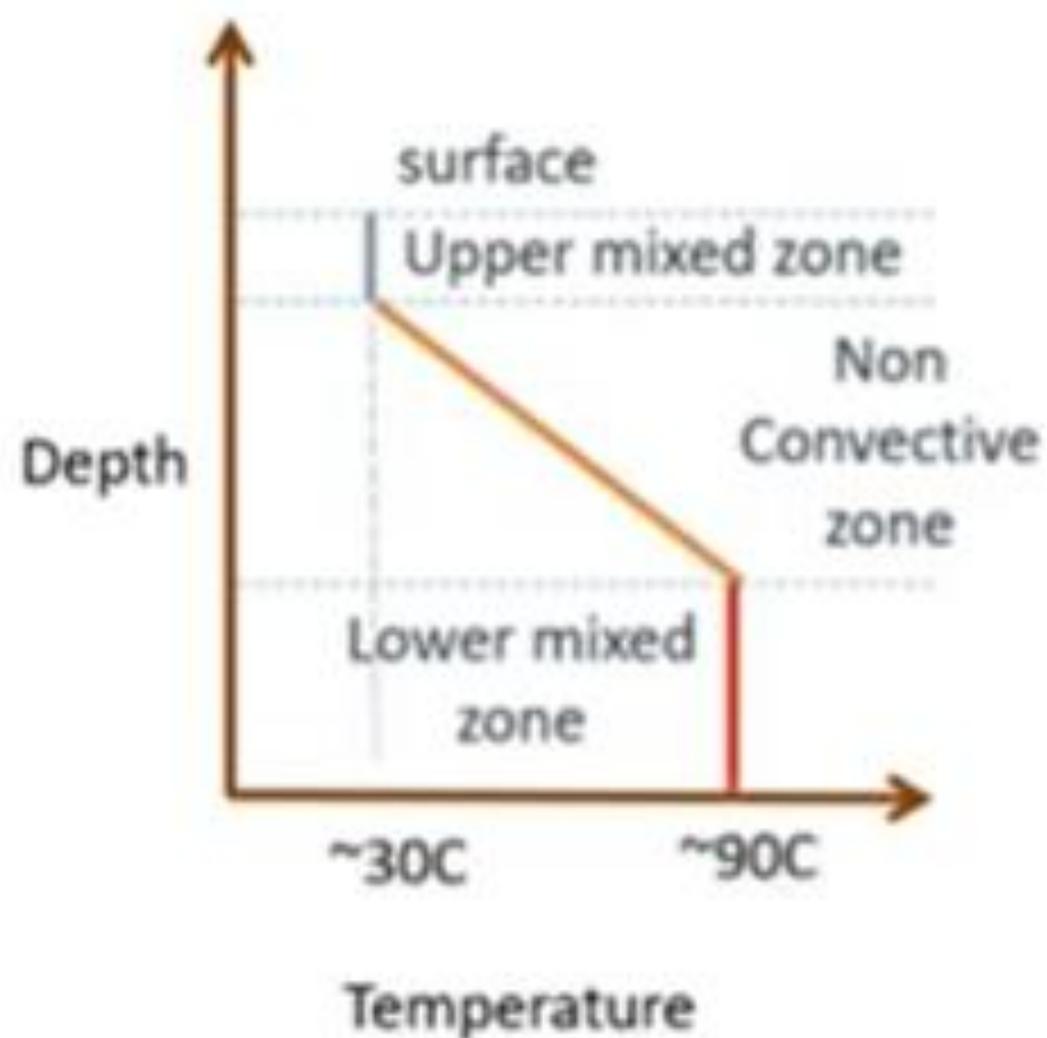
Application (electricity generation)
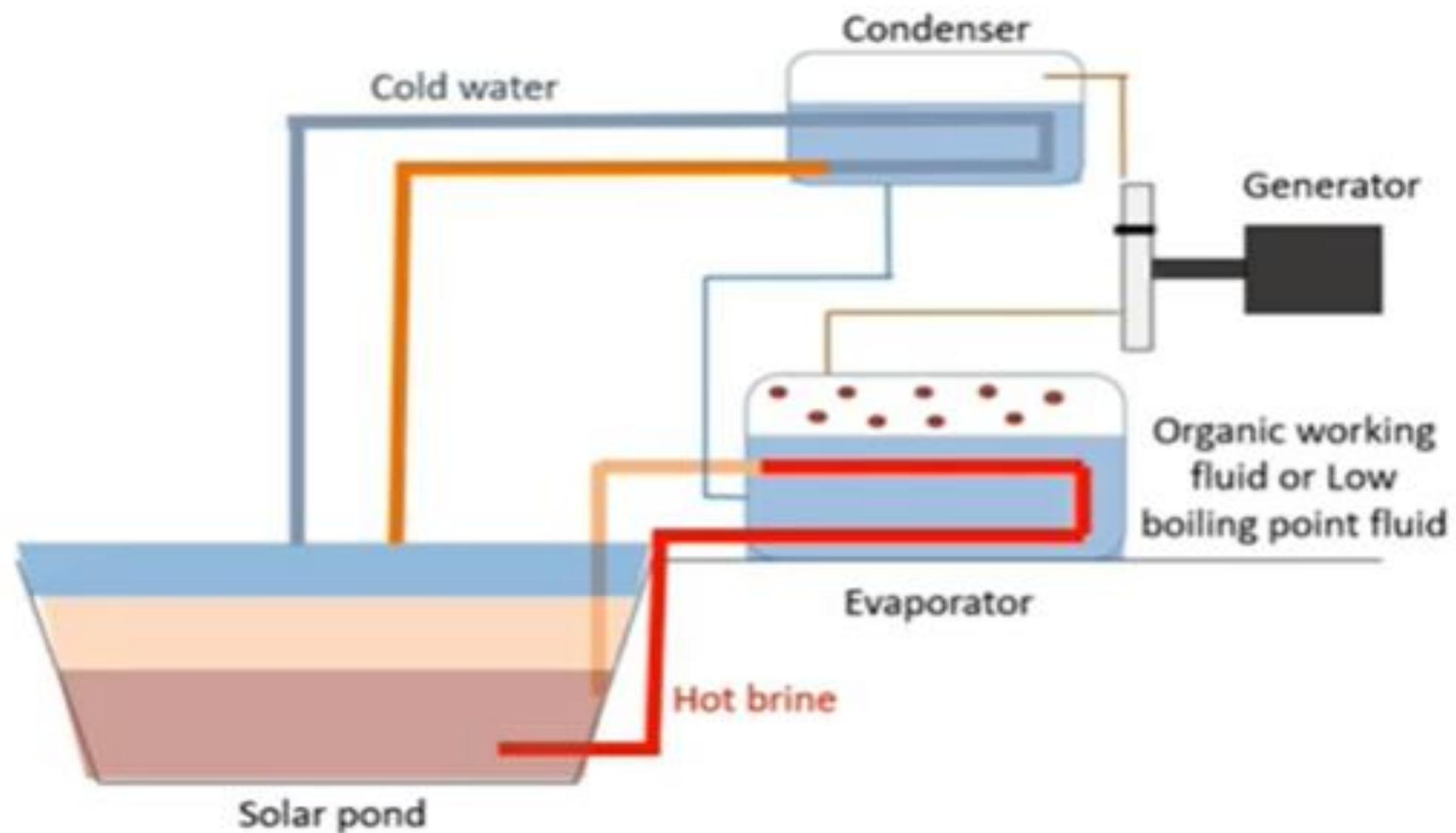
Solar Ponds in India

Location	Area(m^2)	Depth (m)	Main objective	Achievement
Bhavnagar (India)	1210	1.2	Operating experience and behaviour of materials	Max. Temp. 80°C in 1972. worked for 2 years
Bhavnagar (India)	1600	2.3	Operating experience and application for power production	Getting heated, designed to supply 20KW. Rankine cycle turbines.
Pondicherry (India)	100	2.0	Experience, material behaviour, monitoring & modeling.	Built in 1980
Bhuj (India)	6000	3.0	Operating experience, material and behaviour and possible application	Supplying process heat to a dairy

APPLICATIONS:

❑The heat from solar ponds can be used in a variety of different ways.

❑They are ideal for use in heating and cooling buildings as they can maintain a fairly stable temperature.

❑These ponds can also be used to generate electricity either by driving athermo- electric device or some organic Rankine engine cycle - simply a turbine powered by evaporating a fluid (in this case a fluid with a lower boiling point).

Solar Dryer and its Types

- Food products such as pickles, chillies, amlas, fish, fruits, and spices tend to have a longer life after they have been dried. Drying is a process that removes moisture content from food products and prevents the growth of microorganisms such as bacteria, yeast, and other moisture-related reactions in the product. Other benefits of drying include a reduction in the weight and volume of the food products, which will minimize time and cost associated with its (i) packaging, (ii) storage, and (iii) transportation. Drying also makes food products more sustainable under ambient conditions.

- **Methods of Drying:**

- **Natural drying** process is usually done using direct sunlight, ie., the sun's rays hit the product and remove its moisture through natural air circulation. This method is a slow process and has certain disadvantages such as dust contamination, insect infestation, and spoilage due to unexpected rain. These problems can be eliminated by using a mechanized method of drying.

- In mechanised drying methods, the most commonly used dryers are either (i) biomass-fired or (ii) electrically operated.

- (i) A [biomass-fired dryer](#) consists of a burner and a drying chamber. Food products to be dried are placed in the drying chamber and coconut shells or briquettes which are used as fuel are placed in the burner. Once the fuel is ignited, the drying chamber is maintained at a temperature of 80-degree Celsius. The burner manages to retain heat for 6 hours which ensures effective drying of the food products.

- (ii) <u>Electrically operated dryers</u> contain the following parts: (a) an evaporator, (b) a condenser, (c) a blower, and (d) a drying chamber.

- Air enters the dryer through the evaporator and gets heated when it flows over the condenser. It further gets supplied to the drying chamber as regulated by the blower. Once the food products in the drying chamber have dried completely, humid air leaves the dryer, through the holes provided on top of the chamber.

- **Solar Drying**

- Unlike mechanised methods of drying, solar drying is environment-friendly and is done using solar dryers. Solar dryers help provide more heat than the atmospheric temperature. In a solar dryer, air enters the drying chamber through the process of natural convection or through an external source like fan, pump, suction device, etc. Air gets heated as it passes through the chamber and then partially cools as it absorbs moisture from the food product placed in the chamber. Then, the humid air is removed by an exhaust fan or chimney.

- **Advantages of solar drying**
- The rate of drying increases with higher temperature and movement of air in the chamber.
- Food is enclosed in the dryer and therefore protected from dust, insects, birds, and animals.
- Higher temperature prevents insect infestation and the faster drying rate reduces the risk of spoilage by microorganisms.
- The dryers are waterproof, therefore, the food does not need to be moved during the rainy season.
- A dryer can be constructed from locally available materials at a relatively low cost.
- Solar dryers last longer. A typical dryer can last 15-20 years and will need minimum maintenance.
- **Limitations with solar drying**
- Can be only used during day time when an adequate amount of solar energy is present.
- Lack of skilled personnel for operation and maintenance.
- Takes longer as compared to the modern type of electric dryers.
- A backup heating system is necessary for products requiring continuous drying.

- **Different types of solar dryers**

- Integrated Solar Dryers: In this type, the solar energy collection and drying takes place in a single unit. Some of the examples for this category includes step type dryers, cabinet dryers, rack dryers, tunnel dryers, greenhouse dryers, and multi-rack dryers.

- Distributed Solar Dryers: In this type, the solar energy collection and drying takes place in two different units namely, a flat plate air-heater and a drying chamber. The flat plate heater can be placed on the roof of a building or on the ground or the place where the Sun's intensity is high. Air is heated in the flat plate heater and with the help of a blower, the heated air gets circulated in the drying chamber.

- Mixed Mode dryer: In this type, the solar energy collection takes place at both the flat plate air heater as well as a drying chamber and the drying takes place only at the drying chamber. The outer part of the dryer will also get solar energy; this helps to remove the moisture quickly.
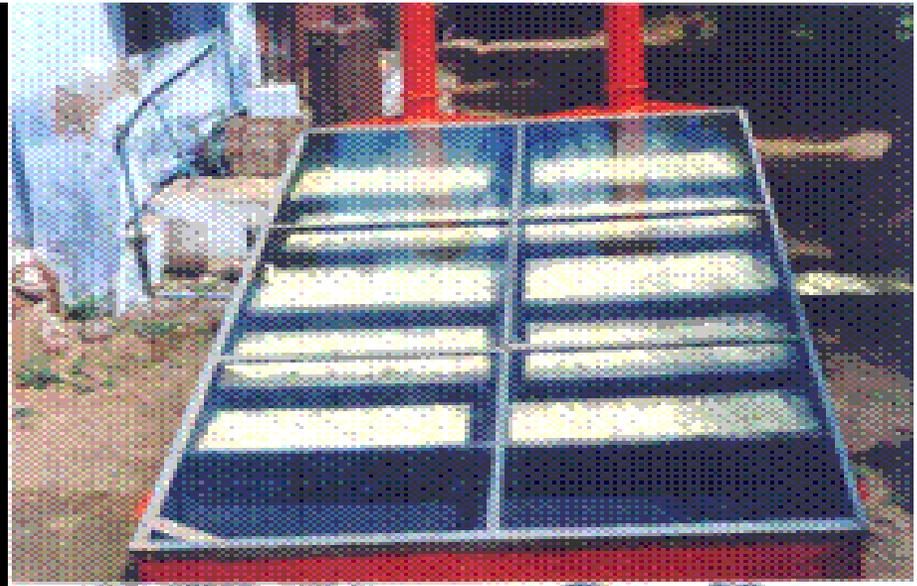
Solar tower

A solar tower (or power tower) is a large Concentrated Solar Power (CSP) plant using an array of mirrors (heliostats) to focus sunlight onto a receiver atop a tall tower, heating a fluid (like molten salt or water) to generate steam, which then drives turbines for electricity, often with thermal storage for 24/7 power. These systems offer high efficiency and energy storage but require large land areas and careful siting due to environmental impacts like bird mortality.
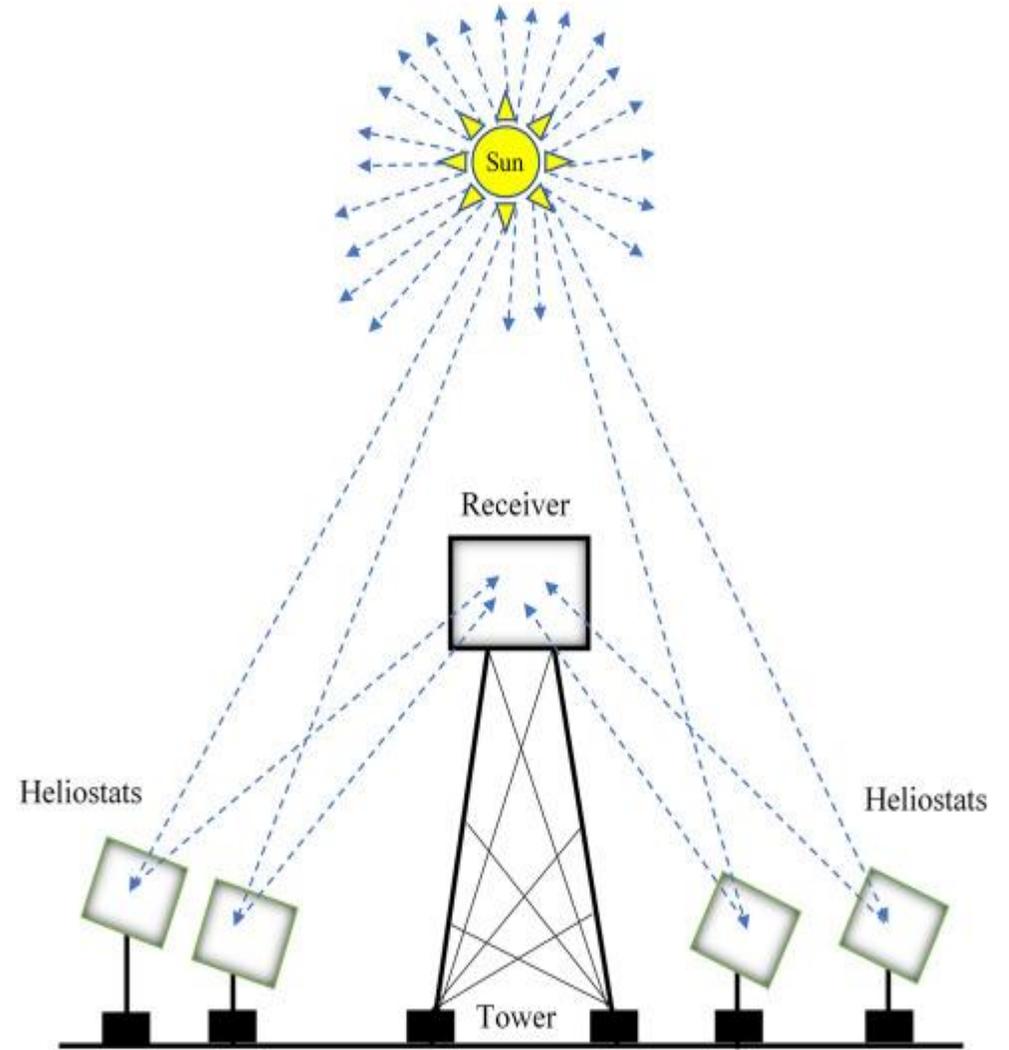
- Solar tower power plants are large-scale solar energy generation setups that use mirrors called heliostats to capture sunlight. Since solar towers rely entirely on sunlight, they are one of the most sustainable and greenest options for energy generation.

- However, you may be thinking, can they work in the absence of sunlight? The answer is yes! Since solar towers contain a heat-storing medium (water or molten salts), they can continue working without sunlight.

How It Works

- Firstly, you should know that solar towers are a part of solar power plants. These solar towers are basically central towers that receive the captured sunlight from the surrounding mirrors.

- A solar tower stands in the middle of a sizable arrangement of mirrors. These mirrors can be curved or flat. However, most solar tower power plants use flat mirrors due to their cost efficiency. These mirrors catch the directly falling sunlight as they follow the sun's rays.

- Afterward, the captured sunlight is reflected or redirected to the solar tower. Many of these mirrors concentrate a significant quantity of solar radiation onto the receiver, a small area of the tower where water is heated.

- Older solar towers used water as a direct heat-transferring medium. However, newer and more advanced solar towers use molten salts with significantly higher efficiency to heat water. Water plays a significant role in energy generation; once heated, it generates steam which turns the turbine. Consequently, this process generates electricity
- Mirrors capture sunlight.
- The sunlight is directed to the solar tower.
- The sunlight is used to heat the stored fluid (water or liquid sodium).
- Steam is generated from heating the fluid.
- The steam moves the turbine.
- The rotation of the turbine produces electricity.

Advantages

- The primary benefit of solar towers is that they do not use fossil fuels for operation. The entire process of energy generation is reliant on sunlight. Therefore, it produces no emissions.

- Moreover, newer solar towers that use molten salts for energy storage can continue producing electricity even without sunlight. Hence, solar towers can work 24/7 without any interruptions due to the weather, making them a very reliable energy source.

Drawbacks of Solar Towers

- Solar tower power plants are indeed highly beneficial and a green source of energy generation. However, they still have certain drawbacks as well.

- Solar towers need a constant water supply to generate steam that can turn the turbine to produce electricity.

- The overall temperature around the solar tower can reach up to 550 °C, which is harmful to wildlife.

- The components of the solar tower, such as heliostats, can produce harmful byproducts during manufacturing.

Applications of Solar Tower Power Plants

- Solar tower power plants are large-scale setups, making them perfectly suitable for commercial applications. Among the most notable solar tower plants, one of the biggest solar towers produces 650 GWh of energy per year.

- In addition to commercial applications, there have been numerous attempts to use them for other innovative applications as well.

- Using solar energy in both domestic and commercial spaces can significantly reduce yearly carbon emissions.

- In addition, systems generating solar energy, like the solar tower power plant, are sustainable and comparatively cheaper than conventional **Photovoltaic systems**.

Syllabus

- **Solar Electric Power Generation:** A Generic PV Cell, PV Materials, Equivalent Circuits for PV

- **Cells, Modules and Arrays;** I-V Curve under Standard Testing Conditions; Impact of Temperature and Insolation on I-V curves; Shading Impacts on I-V curves; Maximum Power Point Trackers (MPPT).

Solar Electric Power Generation

Construction of Solar Cell

- A solar cell functions similarly to a junction <u>diode</u>, but its construction differs slightly from typical p-n junction diodes. A very thin layer of <u>p-type semiconductor</u> is grown on a relatively thicker <u>n-type semiconductor</u>. We then apply a few finer <u>electrodes</u> on the top of the p-type semiconductor layer.

- These electrodes do not obstruct light to reach the thin p-type layer. Just below the p-type layer there is a <u>p-n junction</u>. We also provide a current collecting electrode at the bottom of the n-type layer. We encapsulate the entire assembly by thin glass to protect the **solar cell** from any mechanical shock.

Solar Radiation (Photon-light)

Metallic Conducting Strips

i

Electron Flow

Glass Lens

V Approx. 0.58V DC

N-type Silicon

Depletion Layer

-ve Electrons

P-type Silicon

Substrate Base

+ve Holes

PV Cell Symbol
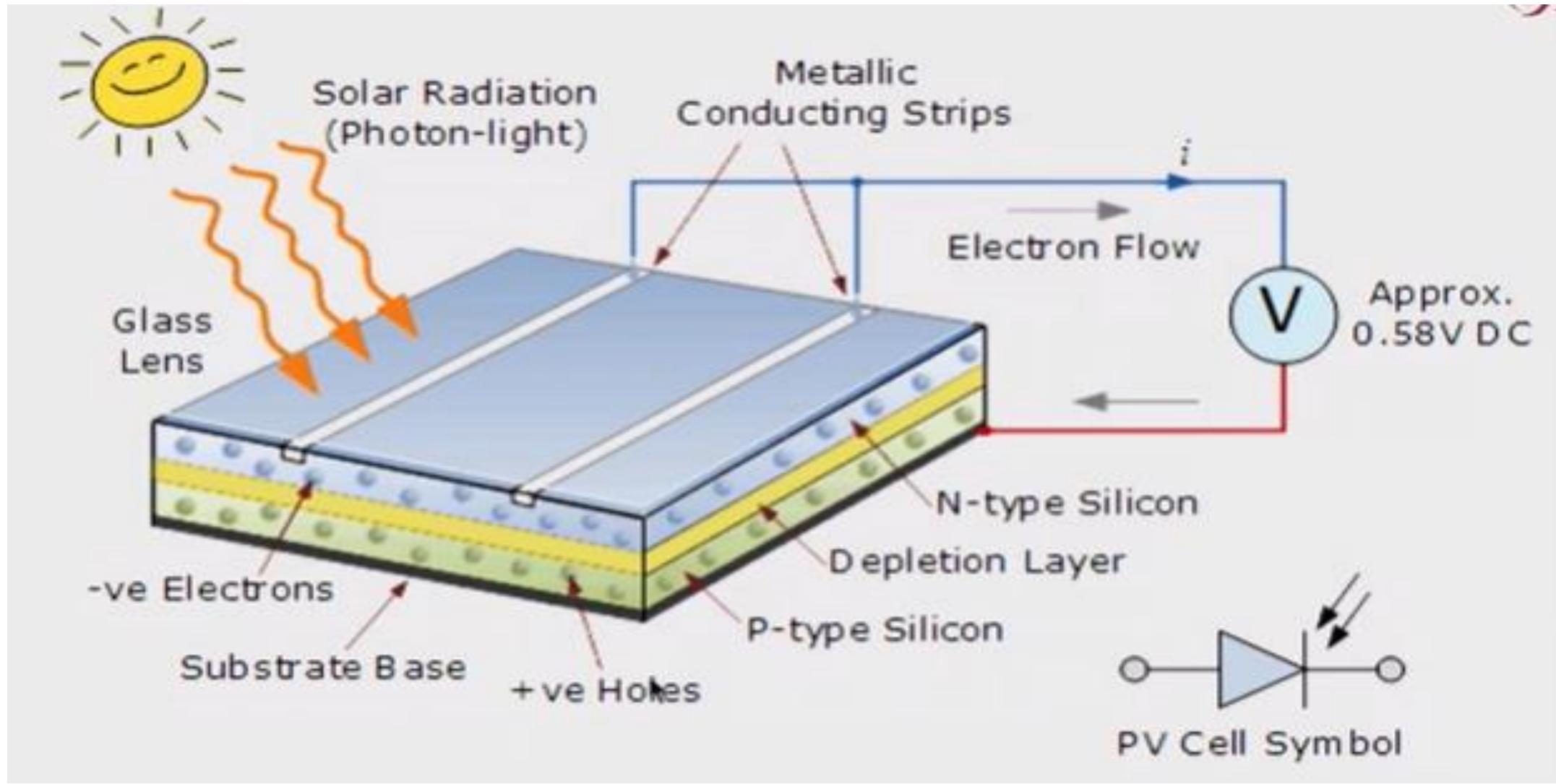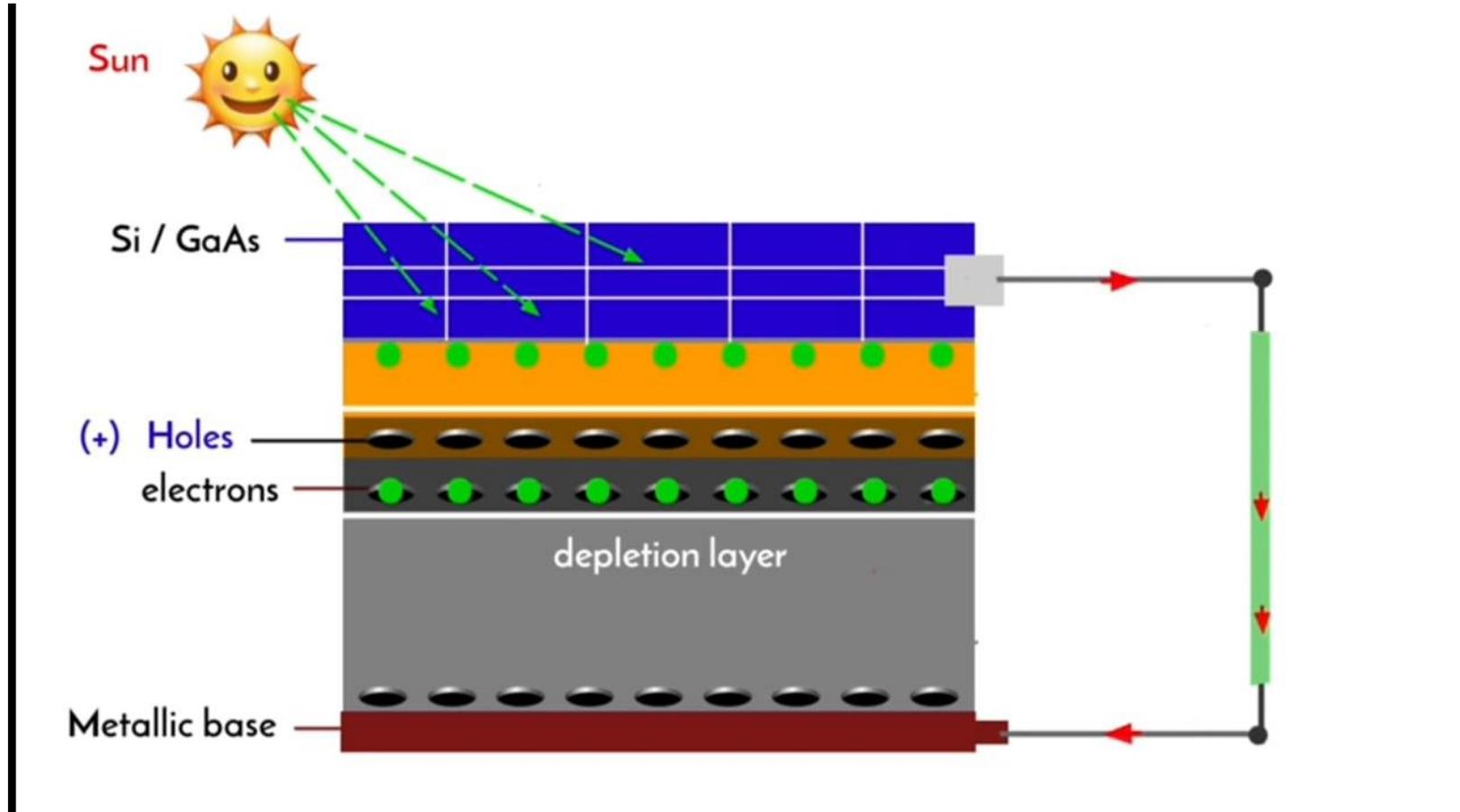
Solar cell working :

Working Principle of Solar Cell

- When light photons reach the p-n junction through the thin p-type layer, they supply enough energy to create multiple electron-hole pairs, initiating the conversion process. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.

- Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.

- Once the newly created holes reach the p-type side, they cannot cross back over the junction due to the barrier potential. This separation of electrons and holes across the p-n junction allows it to function like a small battery cell.

- A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.

V-I Characteristics of a Photovoltaic Cell:

Photovoltaic Array Voltage / Current Characteristic
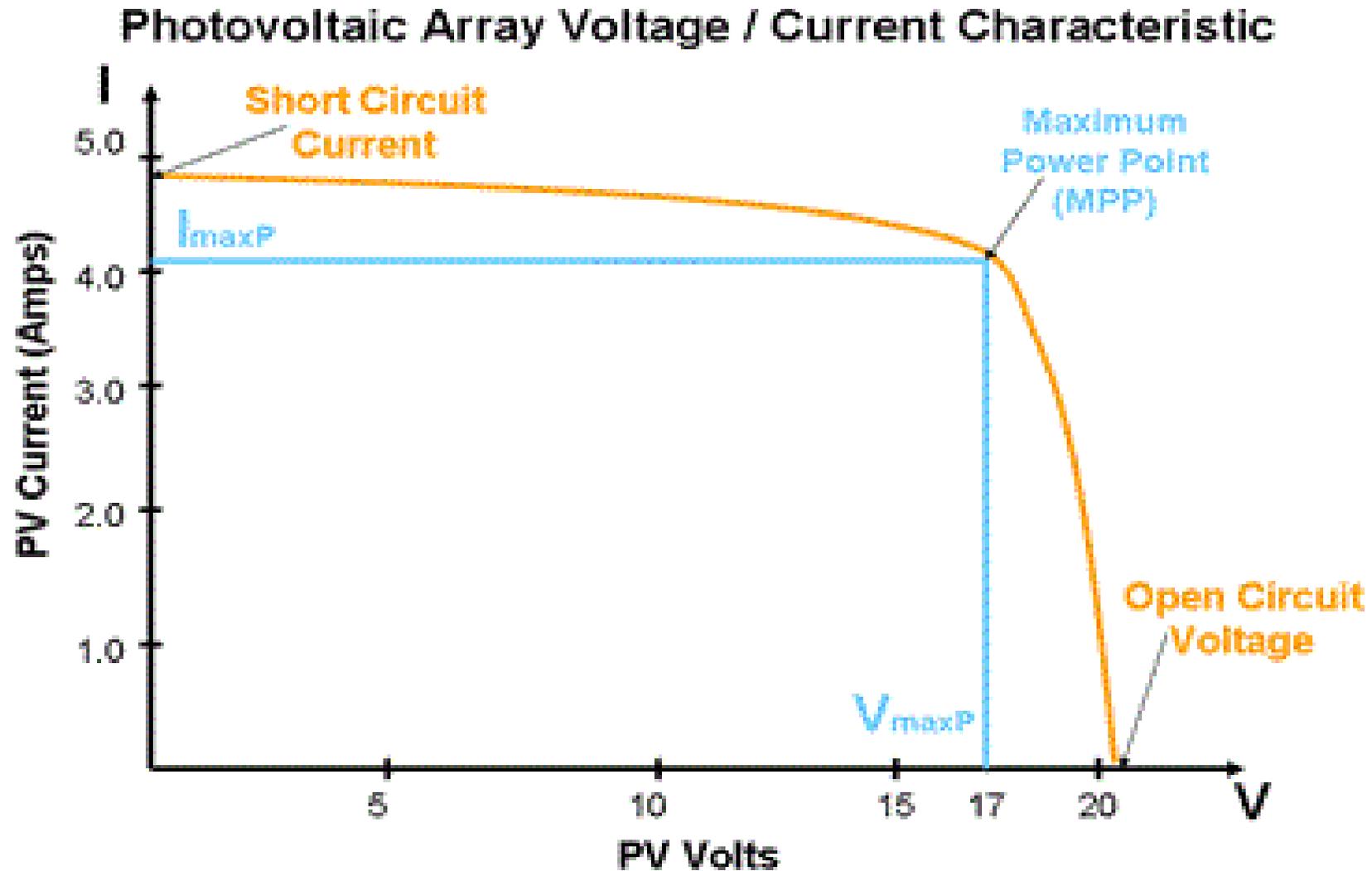
Photovoltaic Materials

- **Monocrystalline & Polycrystalline:** Made from purified silicon, offering high efficiency and long life, forming the bulk of today's solar panels.
- **Amorphous Silicon (a-Si):** Thin-film silicon deposited on a substrate, often used in flexible applications.

Thin-Film Materials:

- **Cadmium Telluride (CdTe):** Second most common after silicon, known for cost-effective manufacturing.
- **Copper Indium Gallium Diselenide (CIGS):** A chalcopyrite semiconductor offering good properties for thin films.

Emerging Materials:

- **Perovskites(Ca Tio3):** Show rapid efficiency gains and tunable properties, ideal for next-gen solar, but stability is a research focus.
- **Organic Photovoltaics (OPVs):** Solution-processable conjugated polymers for low-cost, flexible, and large-area cells.
- **Gallium Arsenide (GaAs):** Used in high-efficiency, specialized applications like satellites.

Equivalent Circuit of PV Cell:

A PV (Photovoltaic) cell's equivalent circuit models its electrical behavior, typically featuring a current source (photocurrent) in parallel with a diode, representing light-generated current and internal losses, respectively, with a shunt resistor (Rsh) for leakage and a series resistor (Rs) for material/contact resistance, all connected to a load. The output current is the source current minus diode and shunt currents, capturing real-world inefficiencies like recombination and resistance.
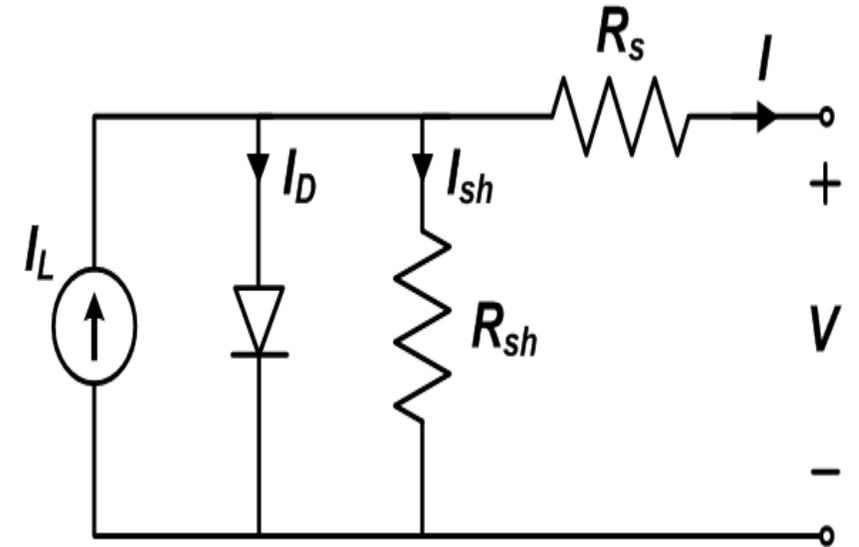
- Governing Current Equation,

- Using Kirchhoff's Current Law (KCL), the output current of a solar cell is written as:

$$I = I_L - I_D - I_{sh}$$

Meaning of each term:

- $I \rightarrow$ Output current of the solar cell

- $I_L \rightarrow$ Light-generated (photocurrent)

- $I_D \rightarrow$ Diode current (represents recombination losses)

- $I_{sh} \rightarrow$ Shunt (leakage) current due to imperfections in the cell

2. The Physics of the Diode

The "Shockley Equation" is used to model the diode current (I_D). This describes the non-linear relationship between voltage and current in a p-n junction:

$$I_D = I_0 \left[\exp\left(\frac{V + IR_s}{nV_T}\right) - 1 \right]$$

- I_0 **(Saturation Current):** A measure of the "leakage" of the diode in the dark.

- n **(Ideality Factor):** Usually between 1 and 2, representing how closely the cell follows ideal diode theory.

- V_T **(Thermal Voltage):** Calculated as $V_T = \frac{kT_c}{q}$. It shows how the cell's performance is sensitive to temperature (T_c).

3. Resistance Factors

The model includes two types of electrical resistance that reduce efficiency:

Series Resistance (Rs): Caused by metal contacts and the semiconductor material itself. Ideally, this should be zero.

Shunt Resistance (Rsh): Caused by manufacturing defects that provide a shortcut for the current. Ideally, this should be infinite.

4. The Complete Governing Equation

By combining all the terms, the final equation provides the full I-V (current-voltage) characteristic of the solar cell:

$$I = I_L - I_0 \left[\exp\left(\frac{V + IR_s}{nV_T}\right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

- The equation represents the single-diode model of a practical solar PV cell, describing the relationship between output current and voltage.
- I_L is the light-generated current, produced by solar radiation, and is approximately equal to the short-circuit current.
- The exponential term represents the diode current, accounting for the PN-junction behavior and recombination losses.
- R_s (series resistance) model's internal resistive losses, while R_{sh} (shunt resistance) represents leakage current paths in the cell.
- The output current is equal to the generated current minus diode and shunt loss currents, giving a realistic I–V characteristic of a PV cell.

Solar Array

If *photovoltaic solar panels* are made up of individual photovoltaic cells connected together, then the **Solar Photovoltaic Array**, also known simply as a **Solar Array** is a system made up of a group of solar panels connected together.

A *photovoltaic array* is therefore multiple solar panels electrically wired together to form a much larger PV installation (PV system) called an array, and in general the larger the total surface area of the array, the more solar electricity it will produce.

Most manufactures produce standard PV panels with an output voltage of 12V or 24V. By connecting many single PV panels in series (for a higher voltage requirement) and in parallel (for a higher current requirement) the PV array will produce the desired power output.

PV Cell – a single Solar Cell
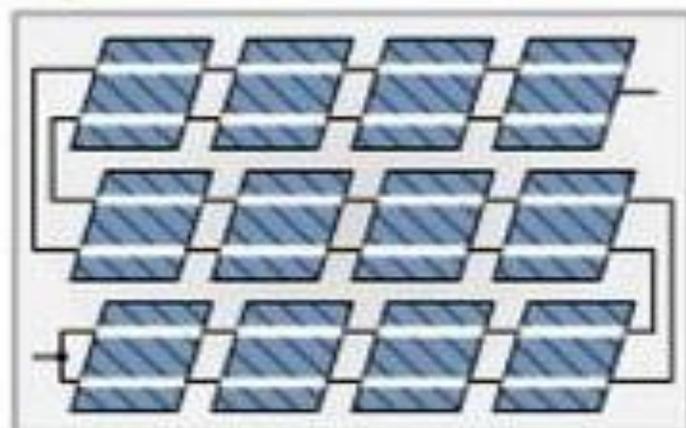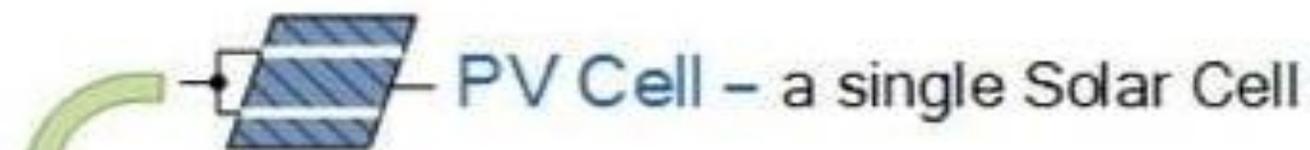
PV Panel - a collection of single solar cells connected together
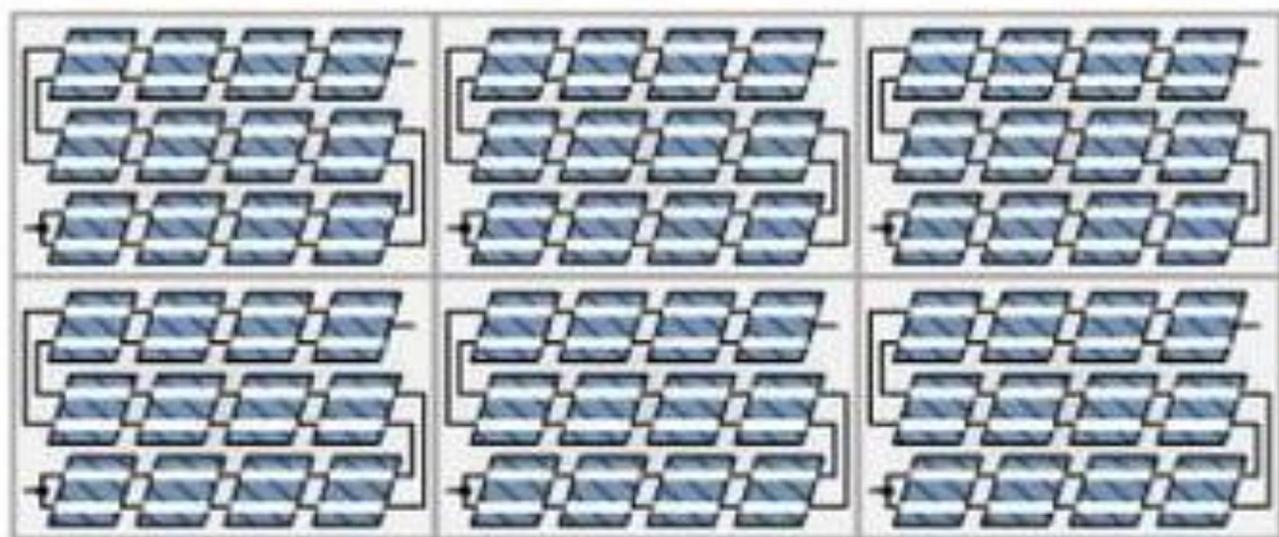
PV Array - a number of individual PV panels electrically connected together

Cell

PV Module

PV Array

- No of cell in series and parallel combination
- Watt from 0-1 kW

- No of module in series and parallel

The array consists of four identical PV modules, each rated at 12 V. **The modules are arranged as:**

Two modules in series in the left string (A)Two modules in series in the right string (B)The two series strings are then connected in parallel.

This is called a series–parallel PV array.

$$I_T = I_A + I_B$$

Photovoltaic Array
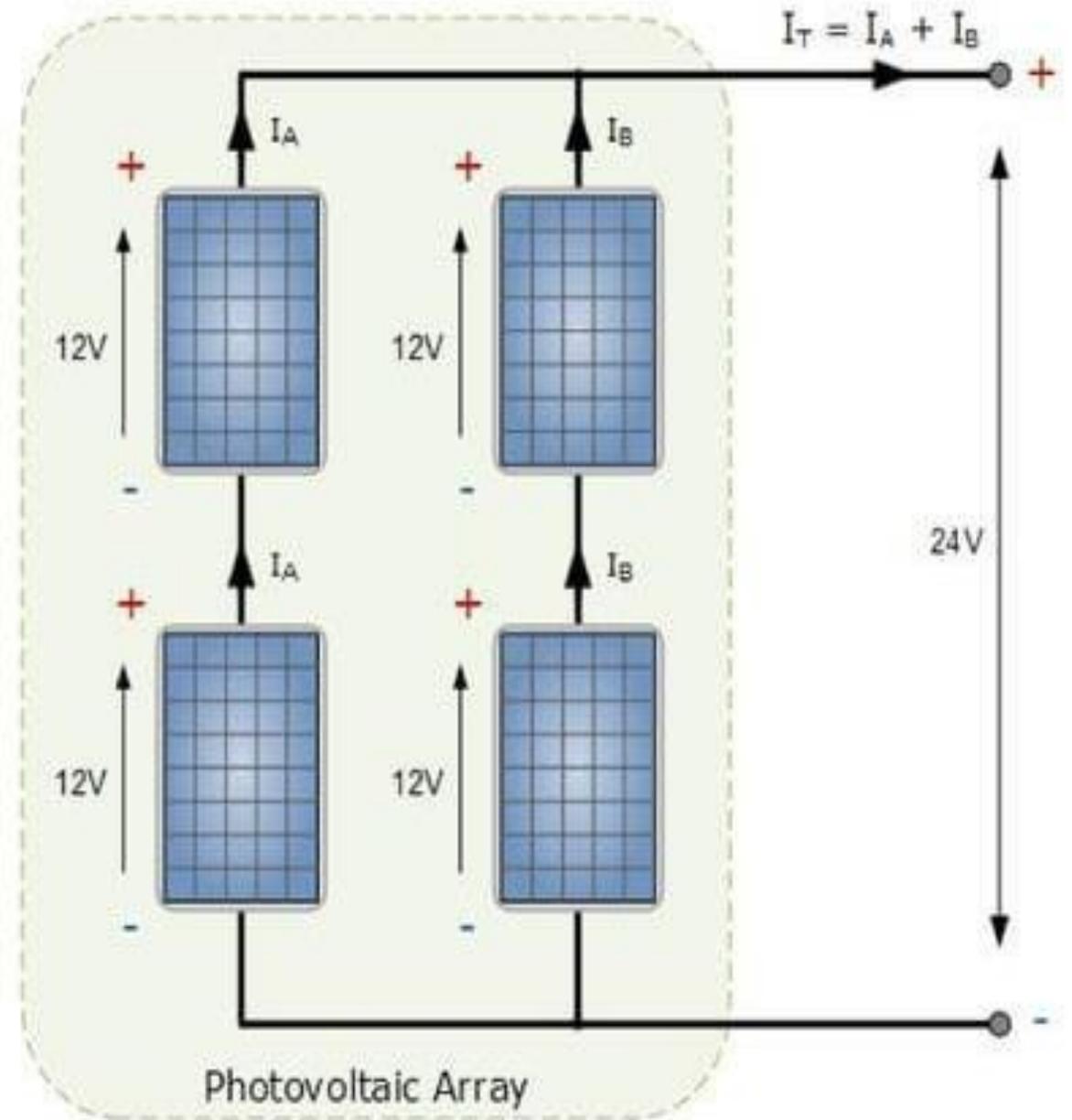
Characteristics of solar cell
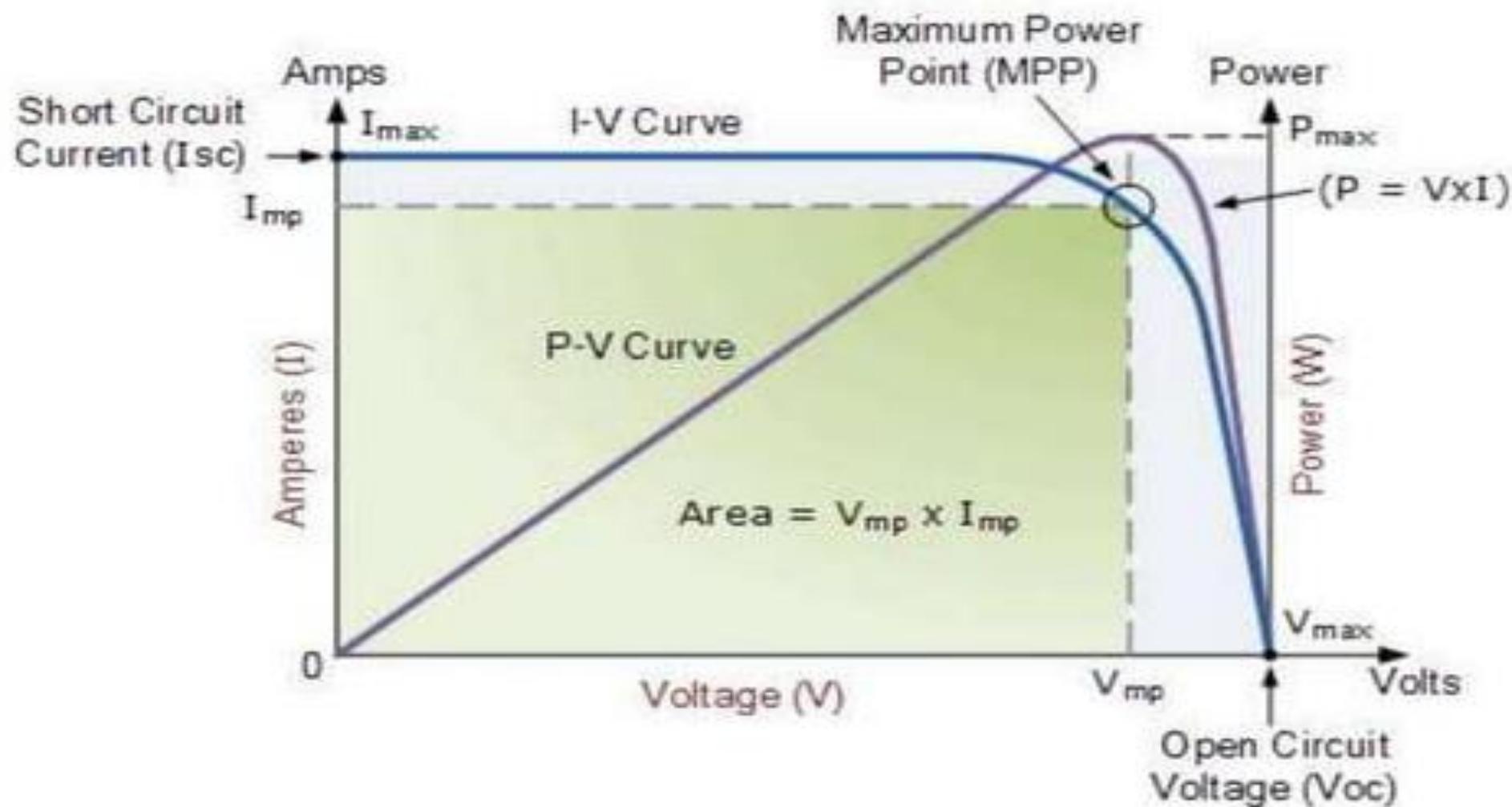
Characteristics of solar cell
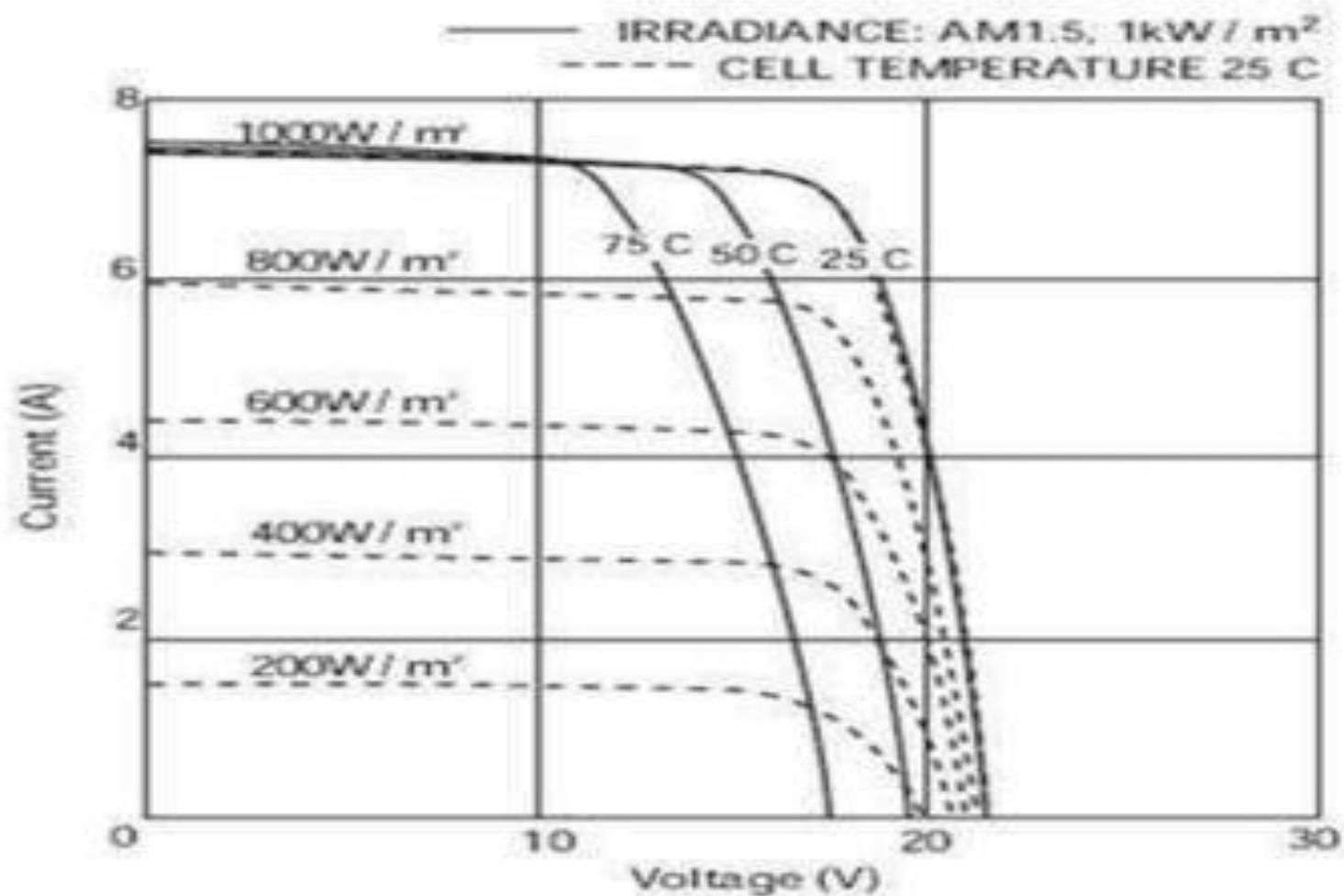
Shading Impacts on I-V curves

- Shading drastically alters solar panel I-V curves, creating multiple peaks (local and global) that confuse traditional MPPTs, causing them to lock onto lower-power local maxima, reducing overall energy yield. This mismatch also creates hot spots, potentially damaging cells. Advanced MPPT algorithms, like PSO(Particle Swarm Optimization) or Grey Wolf Optimizer, use intelligent tracking and shading detection to find the true Global Maximum Power Point (GMPP) and mitigate these effects.
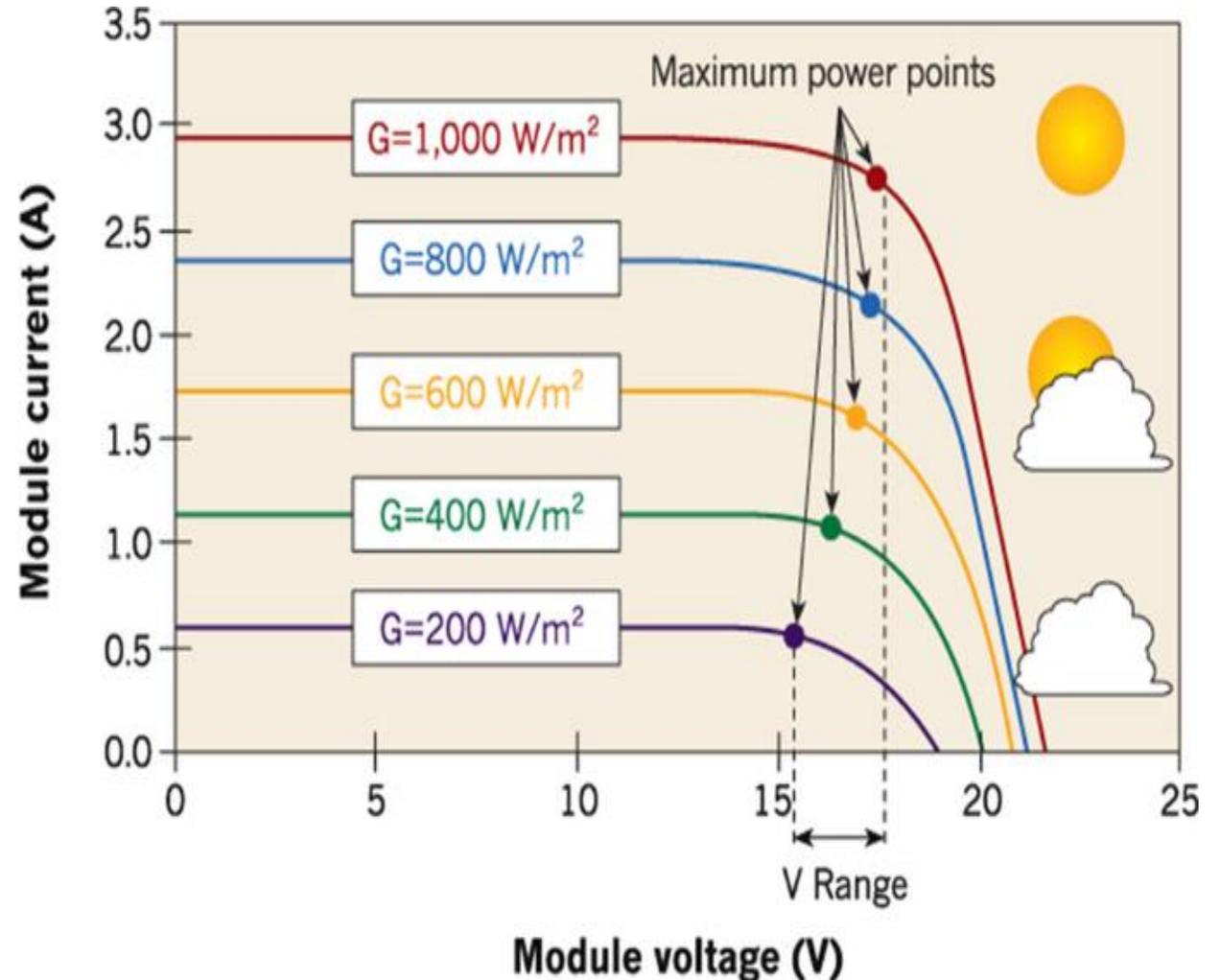
Maximum Power Point Trackers (MPPT)

- Maximum power point refers to the point on an I-V curve where the device produces the most electrical power. Power is a product of voltage and current, and a fundamental principle of solar cells is that you cannot keep increasing voltage without reducing current and vice versa. As a result, there is always a trade-off when attempting to maximize voltage and current simultaneously. This will give you the maximum power point voltage (VMPP) and the maximum power point current (IMPP). The product of these values is the maximum power that can be pulled from the solar device.

$$I_{MPP} \times V_{MPP} = MPP$$
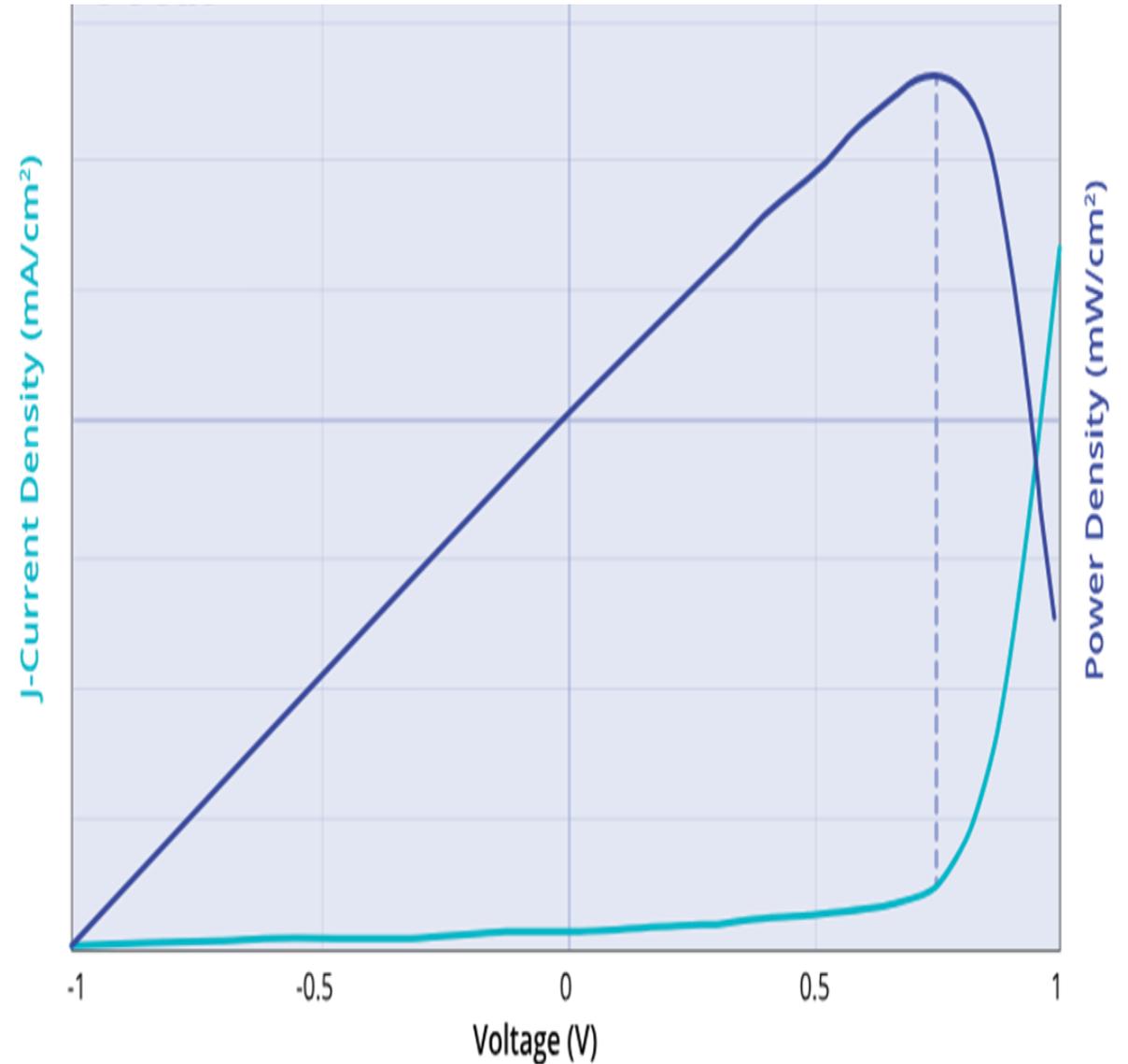
- The location of the maximum power point depends on the shape of the I-V (or J-V) sweep, but it will always be somewhere in the "knee" of the curve.

- In this MPP region, there is a roughly exponential relationship between current and voltage.

- The maximum power point can be found where dI/dV of the IV curve is equal and opposite to the absolute I/V ratio.

- This is the basis of the incremental conductance method of MPPT described later. The maximum power point can be more easily seen on a power density graph, as the peak of the graph.

2 Mark questions:

1. What is meant by renewable energy?
2. Give two examples of non-renewable energy sources.
3. Define SWOT analysis.
4. Mention any two advantages of renewable energy sources.
5. What is global warming?
6. State any two causes of climate change.
7. What is meant by energy transformation by 2050?
8. Mention any two renewable energy resources available in India.
9. What is the solar spectrum?
10. Define extra-terrestrial solar radiation.
11. What is meant by terrestrial radiation?
12. Define solar declination angle.
13. What is hour angle?
14. Mention any two factors affecting solar radiation reaching the earth's surface.
15. What is a solar collector?
16. Mention any two types of solar collectors.
17. What is a solar parabolic trough?
18. What is a solar tower power plant?
19. State any two applications of solar thermal energy.
20. What is a photovoltaic (PV) cell?

10 Mark questions:

1. Explain the fundamentals of renewable energy sources. Discuss their importance in sustainable development and energy security.

2. Classify the different types of energy sources. Clearly distinguish between renewable and non-renewable energy with suitable examples.

3. Define renewable and non-renewable energy sources. Compare them based on availability, environmental impact, cost, and sustainability.

4. Explain SWOT analysis in the context of renewable energy systems. Perform a SWOT analysis for solar energy.

5. Discuss global warming and climate change. Explain the role of conventional energy sources in climate change and how renewable energy mitigates it.

6. Explain the concept of world energy transformation by 2050. Highlight the role of renewable energy in achieving global decarbonization goals.

7. Discuss the prospects of renewable energy in the world. Explain technological, economic, and policy factors influencing its growth.

8. Explain the renewable energy availability in India. Discuss the potential of solar, wind, hydro, biomass, and geothermal energy.

9. Explain the solar spectrum. Discuss its components and significance in solar energy conversion.

10. Describe the propagation of solar radiation from the sun to the earth. Explain attenuation mechanisms in the atmosphere.

11. Explain sun–earth geometry. Discuss solar angles such as declination angle, hour angle, altitude angle, and azimuth angle.

12. Explain solar radiation geometry in detail. Derive expressions for beam, diffuse, and reflected radiation on a horizontal surface.

13. Distinguish between extra-terrestrial radiation and terrestrial radiation. Explain factors affecting terrestrial solar radiation.

14. Explain the working principle and construction of solar collectors. Classify them and discuss their applications.

15. Describe the construction and working of a solar parabolic trough system. Explain its advantages and limitations.

16. Explain the solar tower power plant. Discuss its working principle, components, and performance characteristics.

17. Explain the construction and working of a solar cooker. Discuss different types of solar cookers and their efficiency.

18. Explain the working of a solar water heater system. Discuss its types, advantages, and applications.

19. Describe solar dryers and solar ponds. Explain their working principles and applications in energy storage.

20. Explain the construction and working of a generic PV cell. Discuss PV materials and their characteristics.

Objective type questions:

1. Renewable energy sources are those which are
   A) Exhaustible
   B) Non-replenishable

C) Naturally replenished
D) Costly
Answer: C

2. Which of the following is a non-renewable energy source?
   A) Wind
   B) Solar
   C) Coal
   D) Biomass
   Answer: C

3. SWOT analysis stands for
   A) Strength, Weakness, Opportunity, Threat
   B) System, Work, Output, Time
   C) Solar, Wind, Ocean, Thermal
   D) Supply, Work, Operation, Technology
   Answer: A

4. Global warming is mainly caused by an increase in
   A) Oxygen
   B) Nitrogen
   C) Greenhouse gases
   D) Ozone
   Answer: C

5. Which gas contributes most to global warming?
   A) Oxygen
   B) Carbon dioxide
   C) Nitrogen
   D) Argon
   Answer: B

6. World energy transformation by 2050 mainly aims at
   A) Increasing coal usage
   B) Energy decarbonization
   C) Reducing efficiency
   D) Nuclear dominance
   Answer: B

7. Which renewable energy has the highest potential in India?
   A) Tidal
   B) Geothermal

C) Solar
D) Ocean thermal
Answer: C

8. Biomass energy is derived from
    A) Fossil fuels
    B) Nuclear reactions
    C) Organic matter
    D) Wind motion
    Answer: C

9. The solar spectrum primarily consists of
    A) Gamma rays only
    B) Ultraviolet, visible, and infrared radiation
    C) X-rays only
    D) Microwaves only
    Answer: B

10. Extra-terrestrial radiation is measured
    A) On the earth's surface
    B) Outside the earth's atmosphere
    C) Under water
    D) Inside the sun
    Answer: B

11. The average solar constant value is approximately
    A) 1000 W/m²
    B) 1367 W/m²
    C) 500 W/m²
    D) 2000 W/m²
    Answer: B

12. Solar declination angle varies due to
    A) Earth's rotation
    B) Earth's revolution around the sun
    C) Moon's motion
    D) Atmospheric pressure
    Answer: B

13. Hour angle represents
    A) Seasonal variation
    B) Angular displacement of sun from solar noon

C) Solar altitude
D) Solar azimuth
Answer: B

14. Terrestrial solar radiation is affected by
    A) Atmospheric absorption and scattering
    B) Sun temperature only
    C) Earth's magnetic field
    D) Moon position
    Answer: A

15. A solar collector is used to
    A) Convert solar energy into electrical energy
    B) Collect and transfer solar thermal energy
    C) Store electrical energy
    D) Generate nuclear power
    Answer: B

16. Flat plate collectors are mainly used for
    A) High-temperature applications
    B) Medium-temperature applications
    C) Low-temperature applications
    D) Power generation
    Answer: C

17. Solar parabolic troughs concentrate sunlight using
    A) Flat mirrors
    B) Cylindrical parabolic reflectors
    C) Fresnel lenses
    D) Spherical mirrors
    Answer: B

18. Solar tower systems use
    A) Single reflector
    B) Heliostat field
    C) Flat plate collectors
    D) Solar cells
    Answer: B

19. Solar cooker works mainly on the principle of
    A) Nuclear fusion
    B) Greenhouse effect

C) Electromagnetic induction
D) Thermoelectric effect
Answer: B

20. Solar water heaters commonly use
    A) PV panels
    B) Flat plate or evacuated tube collectors
    C) Wind turbines
    D) Fuel cells
    Answer: B

21. A solar pond is used mainly for
    A) Power storage and generation
    B) Cooking
    C) Lighting
    D) Refrigeration
    Answer: A

22. Solar dryers are mainly used to
    A) Generate electricity
    B) Remove moisture from agricultural products
    C) Heat water
    D) Cool buildings
    Answer: B

23. A photovoltaic cell converts
    A) Thermal energy into electrical energy
    B) Chemical energy into electrical energy
    C) Solar energy into electrical energy
    D) Mechanical energy into electrical energy
    Answer: C

24. The most commonly used PV material is
    A) Germanium
    B) Silicon
    C) Gallium
    D) Selenium
    Answer: B

25. The I-V characteristic of a PV cell is affected by
    A) Temperature only
    B) Insolation only

C) Both temperature and insolation
D) Pressure
Answer: C

26. Increase in temperature of a PV cell causes
    A) Increase in open-circuit voltage
    B) Decrease in open-circuit voltage
    C) Increase in short-circuit current only
    D) No change
    Answer: B

27. Increase in solar insolation results in
    A) Decrease in current
    B) Increase in current
    C) Decrease in voltage
    D) No effect
    Answer: B

28. Shading in a PV array causes
    A) Increase in power output
    B) No change in output
    C) Reduction in power output
    D) Increase in voltage
    Answer: C

29. Maximum Power Point Tracker (MPPT) is used to
    A) Store energy
    B) Increase PV module temperature
    C) Extract maximum power from PV system
    D) Reduce solar radiation
    Answer: C

30. Under Standard Test Conditions (STC), the cell temperature is
    A) 0°C
    B) 25°C
    C) 50°C
    D) 75°C
    Answer: B.   Prepared by

                                                               Dr.V. Maheswari
                                                               Professor-EEE

UNIT-1: ENERGY SCENARIO AND SOLAR ENERGY:

Course Outcomes:

After completion of this unit, students will be able to:

1. **Describe the global energy scenario** and explain the importance of renewable energy resources in sustainable development.

2. **Explain solar radiation principles** and analyze solar geometry and solar spectrum relevant to solar energy applications.

3. **Illustrate the working principles of solar thermal systems** used for heating, drying, and power generation.

4. **Model and analyze photovoltaic systems** using equivalent circuits and interpret the I-V characteristics of PV cells, modules, and arrays.

5. **Evaluate PV system performance** under different operating conditions including temperature variation, solar insolation changes, shading effects, and implement MPPT techniques.

BOOK/NPTEL LINK REFERENCE FOR UNIT -1

1. G N Tiwari, Solar Energy: Fundamentals, Design, Modelling and Applications, Narosa, 2002.

2. Mukund R Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd

3. https://archive.nptel.ac.in/courses/121/106/121106014/

4. https://onlinecourses.nptel.ac.in/noc22_ch27/preview

5. https://www.nptelvideos.com/lecture.php?id=8517https://www.nptelvideos.com/lecture.php?id=8517

ASSIGNMENT TOPICS:

➤ SWOT analysis of Renewable and Non- Renewable Energy

UNIT-2: WIND AND OTHER ENERGY SYSTEMS

Wind Energy: Air, Wind, Global and Local Wind, availability of wind energy in India, wind velocity and power from wind; major problems associated with wind power, Classification of wind energy conversion system (WECS)- Horizontal axis- single, double and multiblade system. Vertical axis- Savonius and darrieus types. Biomass Energy: Introduction; Photosynthesis Process; Biofuels; Biomass Resources; Biomass conversion technologies-fixed dome; Urban waste to energy conversion; Biomass gasification (Downdraft). Tidal Power: fundamental characteristics of tidal power, harnessing tidal energy, advantages, and limitations

Course Objectives:

1. **Understand the fundamentals of wind energy** including air motion, global and local wind patterns, and the availability of wind resources in India.
2. **Explain the principles of wind power generation** and analyze the relationship between wind velocity and power output.
3. **Study different Wind Energy Conversion Systems (WECS)** including horizontal axis and vertical axis wind turbines.
4. **Understand biomass energy systems** including photosynthesis, biomass resources, biofuels, and biomass conversion technologies such as fixed dome plants and gasifiers.
5. **Analyze tidal energy systems** including characteristics of tidal power, methods of harnessing tidal energy, and their advantages and limitations.

UNIT-2: WIND AND OTHER ENERGY SYSTEMS: (9)

- **Wind Energy:** *Air, Wind, Global and Local Wind, availability of wind energy in India, wind velocity and power from wind; major problems associated with wind power, Classification of wind energy conversion system (WECS)- Horizontal axis- single, double and multiblade system. Vertical axis- Savonius and darrieus types.*

- **Biomass Energy:** *Introduction; Photosynthesis Process; Biofuels; Biomass Resources; Biomass conversion technologies-fixed dome; Urban waste to energy conversion; Biomass gasification (Downdraft).*

- **Tidal Power:** *fundamental characteristics of tidal power, harnessing tidal energy, advantages, and limitations.*

Wind Energy-Introduction

- **Air:** A mixture of gases (mostly Nitrogen and Oxygen) that surrounds the Earth. It has mass and exerts pressure, but is generally static in this definition.

- **Wind:** Simply put, wind is air in motion. It is caused by the uneven heating of the Earth's surface by the sun, which creates differences in air pressure. Air always moves from high-pressure areas to low-pressure areas.

- **Global and Local Wind Systems:**
- Winds are categorized based on the scale of the area they affect and their duration.
- Global Winds (Macro-scale)These are large-scale patterns that blow consistently across the entire planet.
- They are driven by the Earth's rotation (Coriolis Effect) and the temperature difference between the Equator and the Poles.

❑**Trade Winds:** Blow from the tropics toward the equator.

❑**Westerlies:** Blow from the west in the middle latitudes.

❑**Polar Easterlies:** Cold winds blowing from the poles.

Local Winds (Micro-scale)

- These are influenced by local geography like mountains, valleys, and proximity to water.
- **Sea Breeze:** During the day, land heats up faster than water, drawing cool air from the sea toward the land.
- **Land Breeze:** At night, land cools faster, pushing air from the land out to the sea.
- **Loo:** A famous local wind in India—a hot, dry summer afternoon wind that blows over the western Indo-Gangetic Plain.

3. Availability of Wind Energy in India

- India has become a global leader in wind energy, currently ranking **4th in the world** for total installed wind power capacity.

Key Geographic Hubs

Wind energy in India is largely concentrated in states with long coastlines or specific mountain passes:

- **Tamil Nadu:** The leader in wind power, home to the Muppandal wind farm (one of the largest onshore wind farms in the world).

- **Gujarat:** Has the highest "potential" due to its massive coastline.

- **Other key states:** Maharashtra, Karnataka, Rajasthan, and Andhra Pradesh.

India is successful:

- **Monsoon Patterns:** The strong seasonal monsoon winds provide a predictable surge in power generation.

- **National Institute of Wind Energy (NIWE):** This body identifies "windy" sites to ensure turbines are placed in the most efficient locations.

- **Offshore Potential:** India is now moving toward **offshore wind farms** (turbines in the ocean) along the coasts of Gujarat and Tamil Nadu, where winds are even stronger and more consistent than on land.

1. Wind Velocity and Power Output

- The most critical thing to understand about wind energy is that the power you get isn't just a 1-to-1 relationship with wind speed. It's actually exponential.

- The Mathematical Relationship

The theoretical power (P) available in the wind is given by the formula:

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

Where:

ρ(rho) is the air density (heavier air = more power).

A is the swept area of the turbine blades (longer blades = more power). v is the wind velocity.

- The "Cubic" Rule Because velocity is cubed (V^3) even a small increase in wind speed leads to a massive jump in power:

- If you **double** the wind speed, you get **8 times** the power ($2^3=8$)

- If you **triple** the wind speed, you get **27 times** the power ($3^3=27$)

Note: Turbines can't capture 100% of this power. According to **Betz's Law**, the maximum theoretical efficiency for any wind turbine is about **59.3%**. Most modern turbines operate at around 35–45% efficiency.

2. Major Problems Associated with Wind Power

A. Intermittency (The "Reliability" Problem)

- Wind is unpredictable. It doesn't always blow when demand for electricity is high (like during a hot summer afternoon).

- This makes it difficult for the power grid to rely solely on wind without expensive battery storage or backup from steady sources like hydro or nuclear.

B. High Initial Capital Costs:

- While the "fuel" is free, building the farm is not.

- **Infrastructure:** Turbines are massive and expensive to transport and install, especially in remote areas or offshore.

- **Grid Connection:** Windy sites are often far from cities. Building long-distance transmission lines to bring that power to people adds significant cost.

C. Environmental & Social Impacts:

Wildlife : Rotating blades can be hazardous to birds and bats. (In India, this is a major concern for the endangered Great Indian Bustard).

Noise Pollution: The "whooshing" sound of the blades and the mechanical hum of the gearbox can be disturbing to people living nearby.

Visual Impact: Some communities oppose wind farms because they "spoil" the natural landscape

D. Technical Maintenance

- **Wear and Tear:** Turbines have many moving parts (gearboxes, bearings) that operate in harsh conditions like salt spray (offshore) or desert sand (Rajasthan).

- **Blade Waste:** Modern blades are made of composite materials (fiberglass/carbon fiber) that are very difficult to recycle. Currently, many old blades end up in landfills.

Solutions & Mitigation

- **Siting:** Carefully placing turbines away from major bird paths and residences.

- **Technology:** Direct-drive turbines, better grid management, energy storage, radar to slow turbines for birds.

- **Policy:** Community benefit sharing, improved permitting, promoting domestic supply chains.

Types of Wind Turbines

' "Windmills" are used to grind grain into flour

° Many "Wind Turbine" names —
  – wind-driven generator
  – wind generator
  —wind turbine
  —wind-turbine generator (WTG)
  - wind energy conversion system (WECS)"

• Wind turbines characterized by turbine blade's axis of rotation
  - Horizontal axis wind turbines (HAWT)
  —Vertical axis wind turbines (VAW

" Groups of wind turbines are located in what is called either a "wind farm" or a "find park"

Typical WECS components
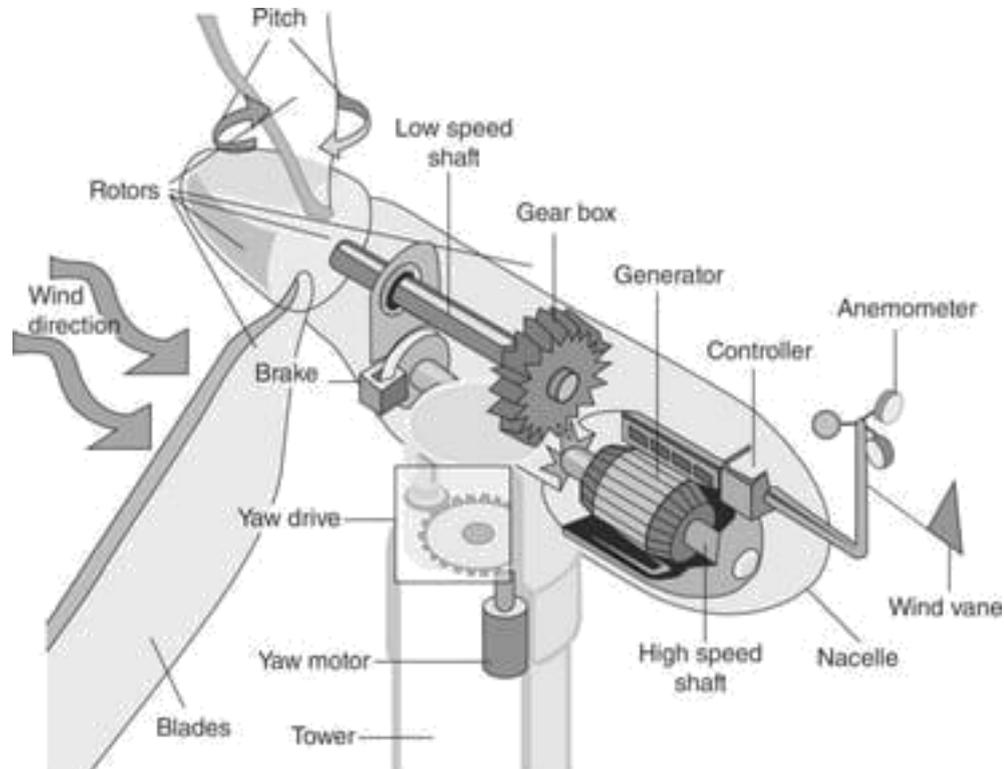
FfGURE 7.5

Turbine Blade —an Air Foil

Lift

Lift

Drag

Lift

Wind

Net resulting across

Relative wind motion

(b)
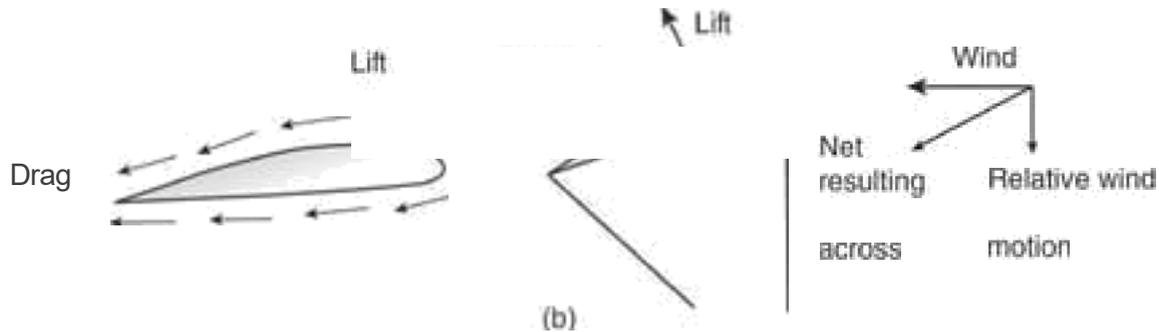
FIGURE 7.z (a) Lift in wing   (b) wind turbine blade forces

Masters, Gilbert M. *Renewable and Efficient Electric Power Systems, 2nd Edition.* Wiley-Blackwell, 21/06/2013.

Lift

Drag

Net wind

Angle of attack

Net

Stall condition
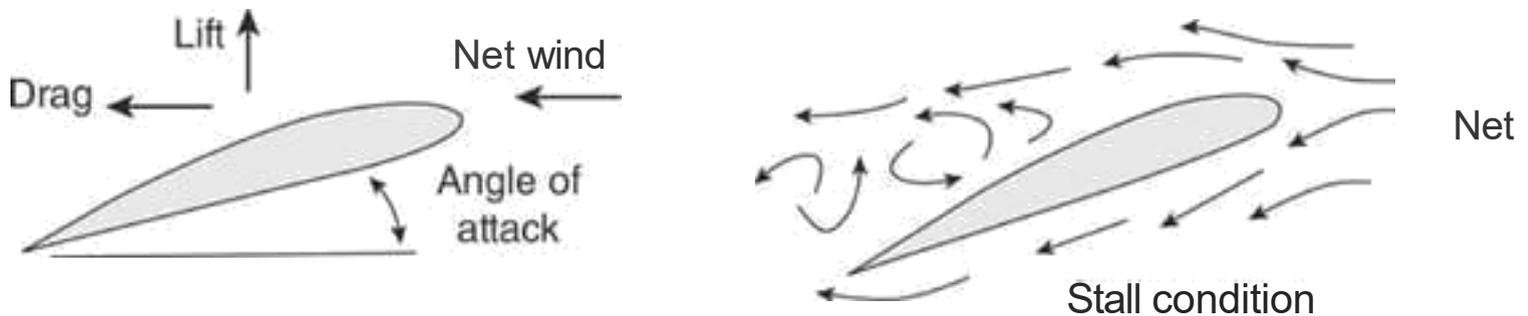
FIGURE 7.8   Increasing the angle of attack can cause a wing to stall

Wind Energy Conveœion Systems

Variable-speed turbines

Fixed-speed turbines

Indirect-drive
(with gearbox)

Direct-drive
(without gearbox)

Squirrel-cage induction
generator (SCIG)

Wound-rotor synchronous
generator (WRSG)

Permanent-magnet synchronous
generator (PMSG)

Squirrel-cage induction
generator (SCIG)

induction
generaxir (DFIO)

Wound-rotor synchronous
generator (WRSG)

Permanent-magnet synchronous
generator (PMSG)

Wound-rotor induction
generator + variable R

No gears
No rotor windings
No brushes
No rotor winding losses
Size & weight reductions

FIGURE 7.9 Sysœm configurations for wind energy systems.

Squirrel-Cage Induction Generator

FIGURE 7.10 Sqvîrrel-Cage Inductian .Generator

Masters, Gilbert M. *Renewable and Efficient Electric Power Systems,*
2nd Edition. Wiley-Blackwell, 21/06/2013.
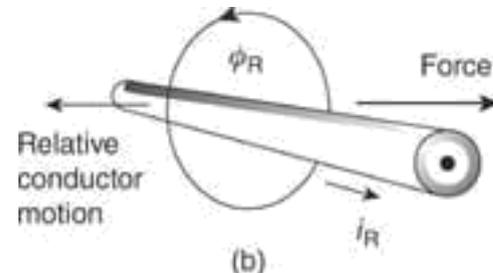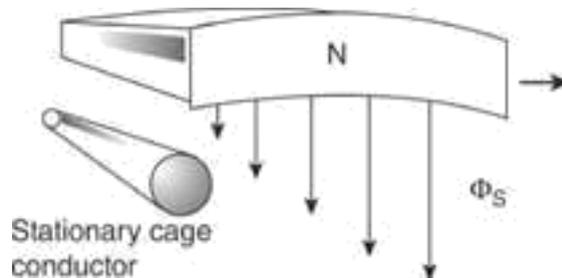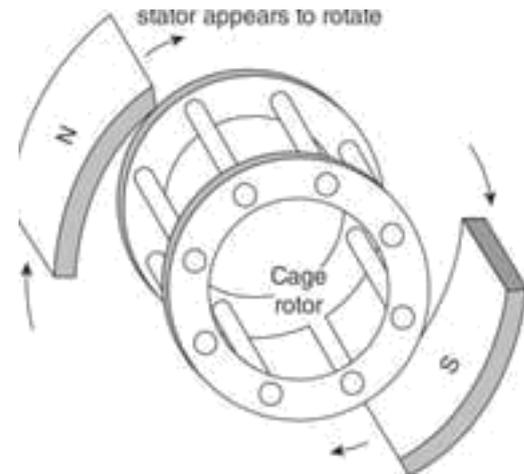
FIGURE 7.11 Cage Corductor Force & Current

Masters, Gilbert M. *Renewable and Efficient Electric Power Systems, 2nd Edition.* Wiley-Blackwell, 21/06/2013.

Doubly-fed Induction Generator
(DFIG)
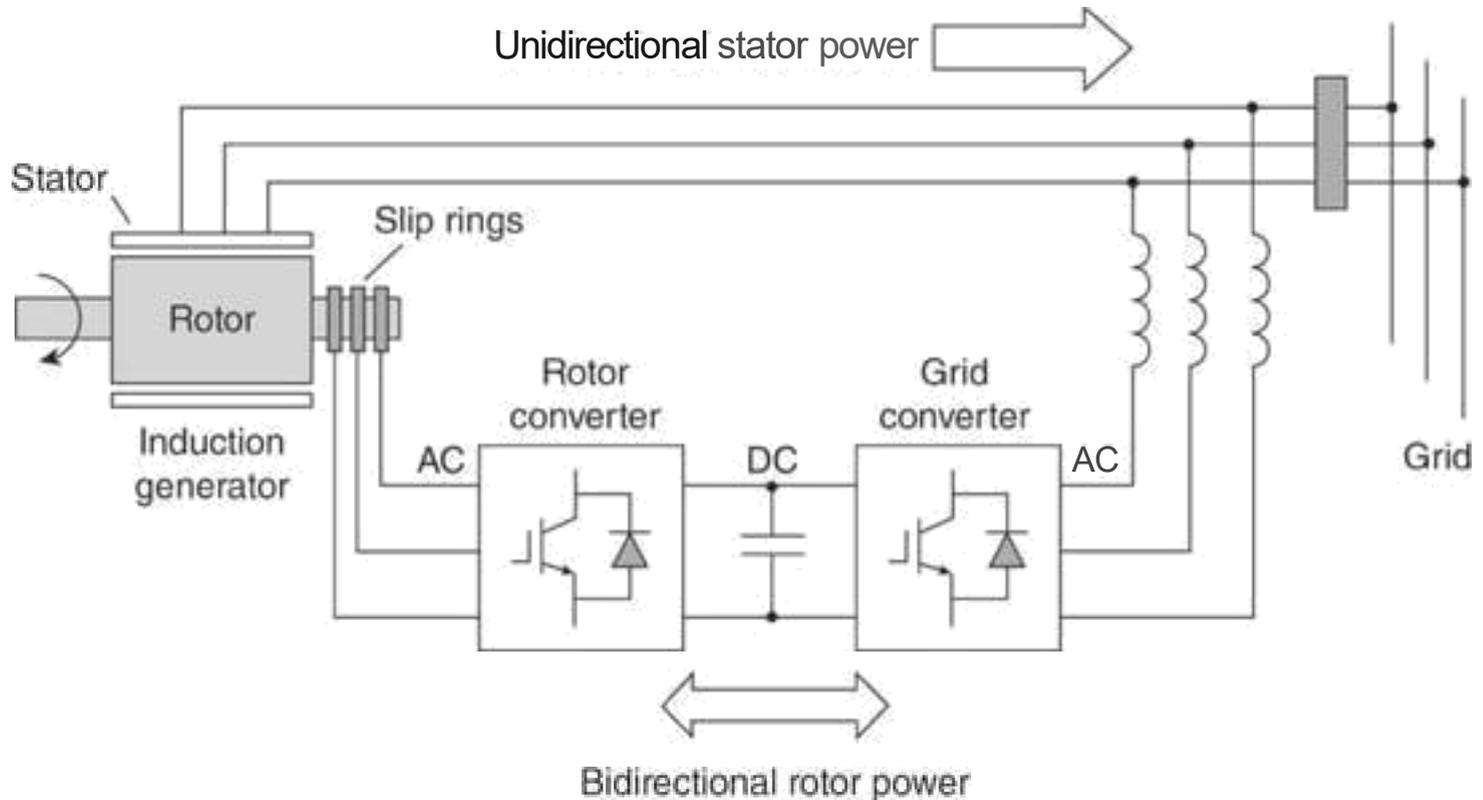
FIGURE 7.12 A wound-rotor, doubly-fed induction generator (DFIG)

Gearless Variable-Speed Synchronous Generator
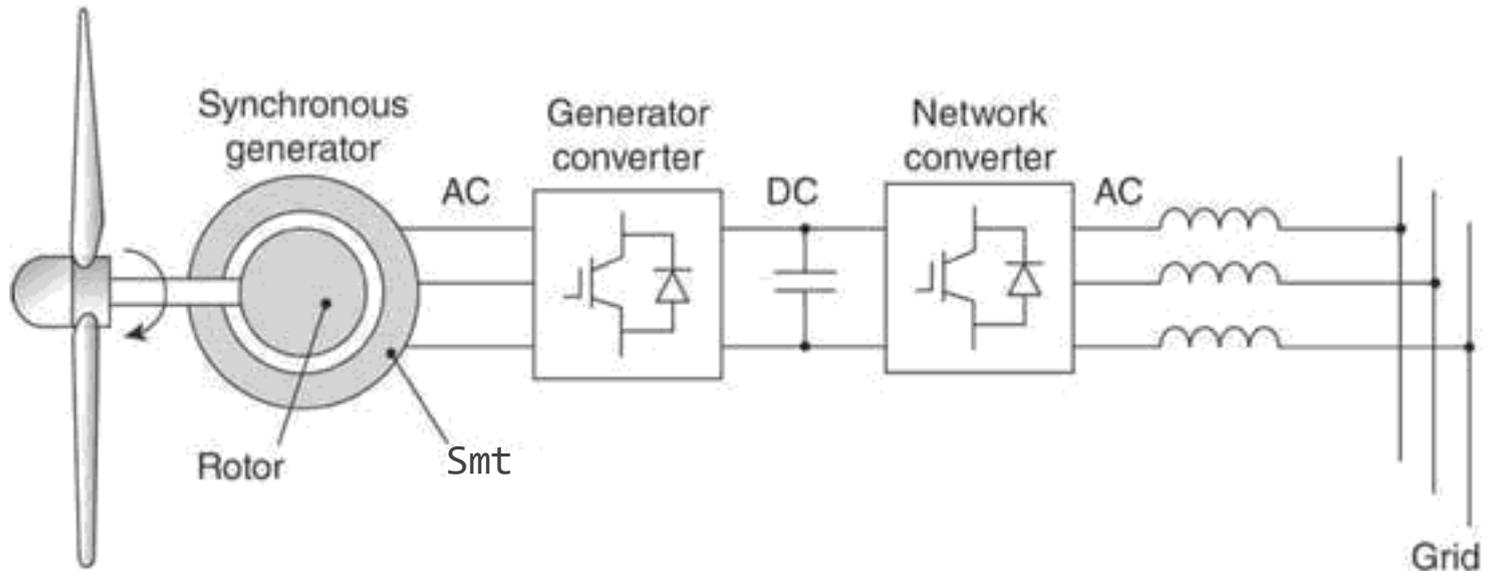
FIGURE 7.13   A gearless variable-speed synchronous generator.

Vertical Axis Wind Turbines

Darrieus VAWT

- ' parrieus rotor - the only vertical axis machine with any commercial success

- Wind flowing by the vertical blades (aerofoils) generates lorce" producing rotation

- No yaw (rotation about vertical axis) control neaded to keep them facing into the wind

- Heavy machinery in the nacelle is located on the ground

- " Blades are closar to ground where wind-speeds are lower
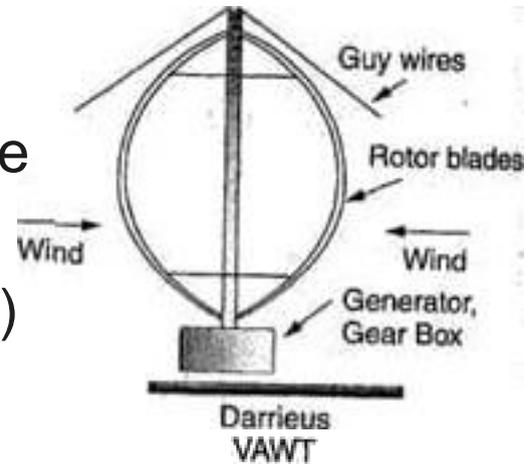
Horizontal Axis Wind Tufines

- "Downwind" HAWT - a turbine with the blades behind (downwind from) the towe No yaw control needed —naturally orients in line with the wind
- Wind's "shadow" behind the vertical axis produces turbulence • vibration ‹ mech stress on the blade and supporting structure
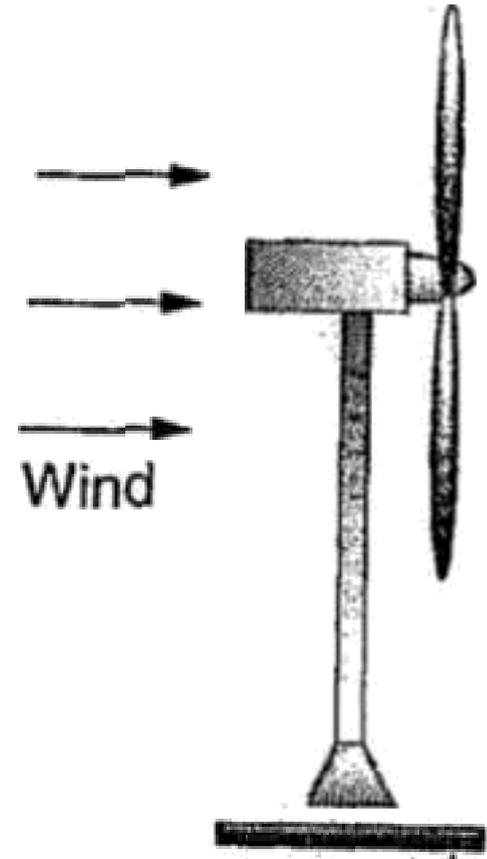
Wind

Upwind" HAWT —blades are in front of (upwind oT) the tower

- Most modern wind turbines are this type

- Blades are "upwind" of the tower

- Require somewhat complex yaw control to keep them facing into the wind

- Operate more smoothly and deliver more power
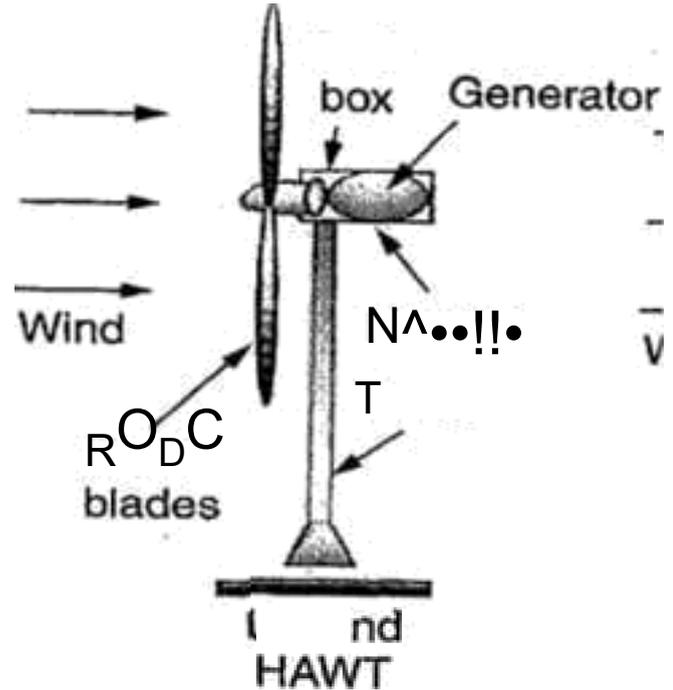
Number of Rotating Blades

- Windmills have multiple blades
  - need to provide high starting torque to overcome weight of the pumping rod
  - must be able to operate at low windspeeds to provide nearly continuous water pumping
  - a larger area of the rotor faces the wind

- Turbines with many blades operate at much lower rotational speeds - as the speed increases, the turbulence caused by one blade impacts the other blades

- Most modern wind turbines have two or three blades

WECS Type A

Soft-starter

Gear

Squirrel Cage Induction Generator
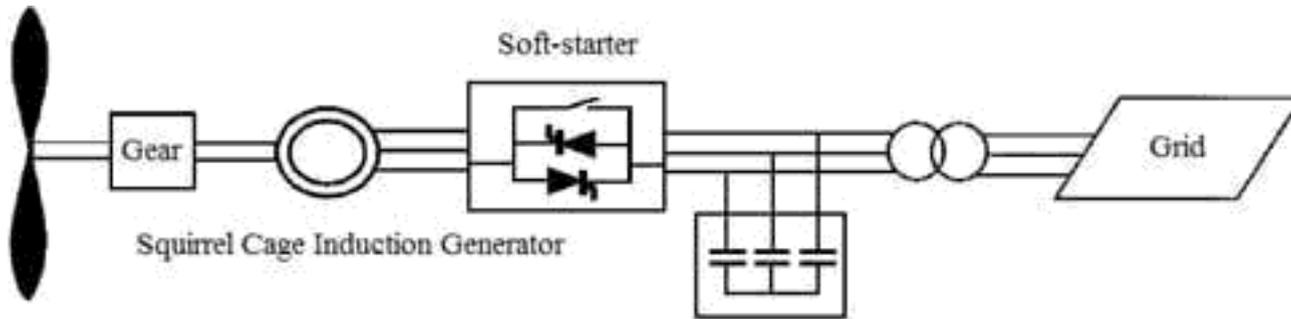
Grid

- Induction generator connected with a fixed-speed wind turbine
- Design requires 2 additional components for grid corir›t›ction:
  - SoR-starter to decrease current transients during startup phase
  - Capacitor back to compensate for reactive power

- Capacitor bank enables the generator can work close to zero value generation and 0 reactive power consumption.

- However, this compensation approach does not provide flexible reactive power control.

WECS Type B
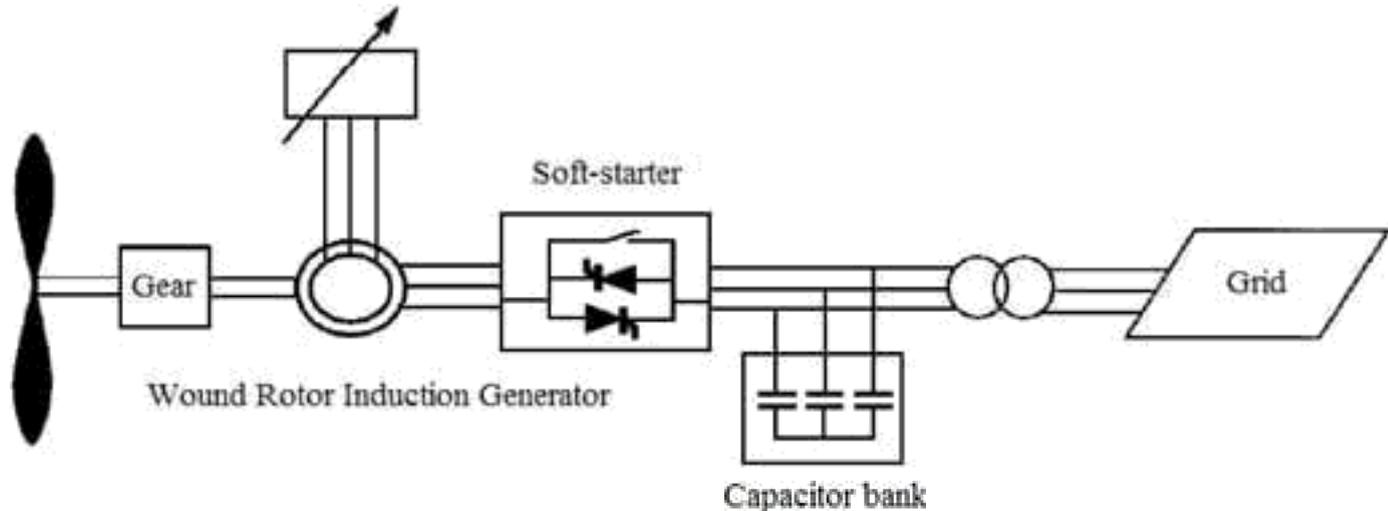
- Type B WECS generator is designed to work with limited variable speed wind turbine
- Variable resistor in the machine rotor, enables controlled-power output
- d pa tor bank and soft starter are analogous to the type A

WfiCSType C

Wound Rotor Induction Generator
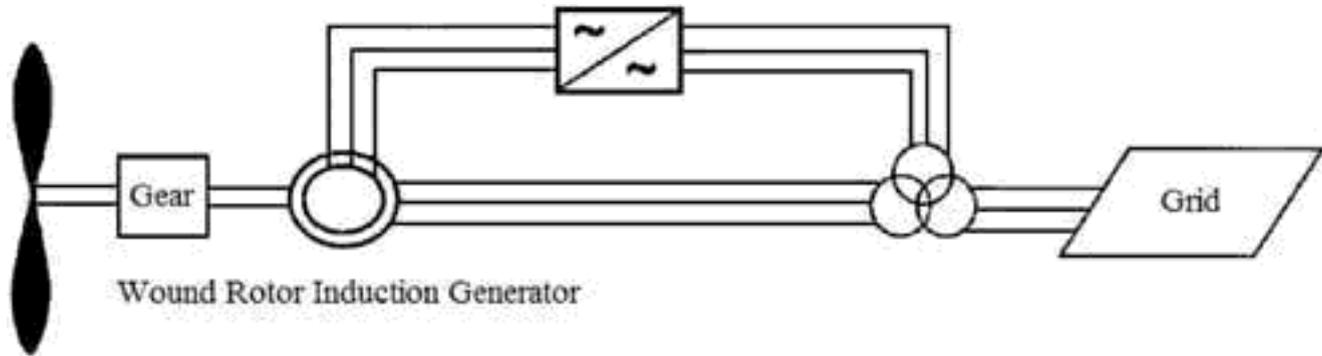
- WfiCS control enabled by fwo MDC converters w/ a connecting capacitor
- Wound rotor Induction generator - known as a doubly féd induction generator:(DFIG)
- "Doubly" as the roter winding is not short-circuited (as In clzssical "singly-fed" induction rttachine); voltage is induced from the rotor-side converter
- 2 operating schemes:constant (1) reactive powar.or (2) voltage
- Most commonly Installad WECS

WECS Type D
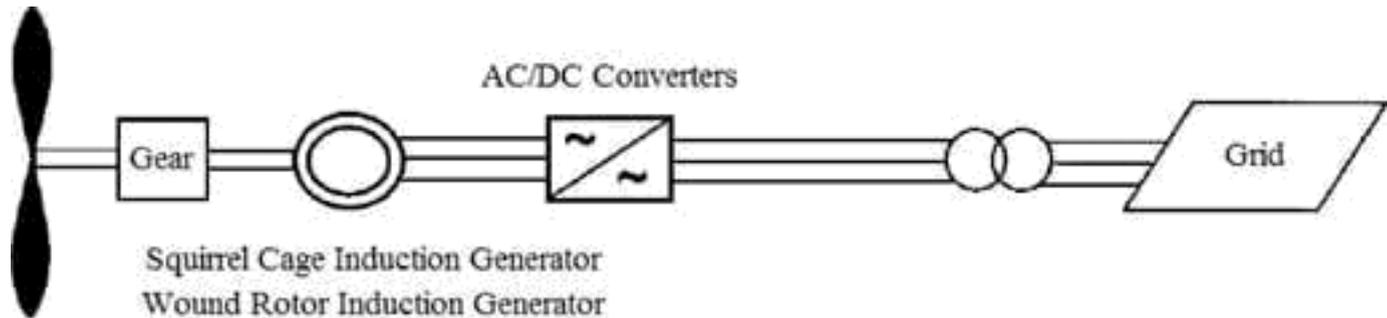
- Type D design includes full-scale frequency converter with different generator types.
- Most common —perrrianerit magnet synchronous generator (PMSG).
- This design enables
  - full active/ reactive power production control
  —high wind energy extractlor›vakie
- Full power control improves power and frequency stability and reduces the short circuit powec
- Most type D designs do not need a.gearbox- a distinct

Darrieus Wind :

An alternate name of Darrieus Wind Turbine is an Eggbeater turbine. This kind of turbine was invented in the year 1931 by Georges Darrieus. A Darrieus machine is a low torque and high-speed device used to generate AC (alternating current). Generally, Darrieus requires physical push so some exterior power source is used to start rotating because the initial torque is extremely low. This machine consists of two blades that are vertically oriented and rotating around a perpendicular shaft.

Wind Turbine

A Darrieus wind turbine is one kind of VAWT. Not like the Savonius type, the Darrieus type is a lift-type VAWT. Instead of gathering the airstream within cups, the turbines will drag around. Darrieus utilizes lift forces which are produced through the airstream hitting aerofoils to make revolution.

Features

The features of the Darrieus wind turbine include the following.

- These turbines are eggbeater shaped which includes high efficiency, but, they are not consistent.

- In order to utilize this turbine, you should have an exterior power source to start them

- This turbine includes two blades so it is the best choice to select instead of selecting a three-blade wind turbine.

- This wind turbine can be supported by using a superstructure that will fix it close to the pinnacle bearing.

A Darrieus wind turbine spins many times than the wind hitting speed. Therefore, a Darrieus wind turbine produces low torque as compared to a Savonius turbine however it turns very fast. So, this turbine rotates very fast to generate electricity instead of water pumping as well as related activities. This turbine generates centrifugal forces which are extremely large & performs on the turbine blades. But the bearings & generator are generally lower as compared to a Savonius.

Darrieus Wind Turbine Design

The design of the Darrieus wind turbine can be done using a number of curved aerofoil blades which are arranged on a rotary framework or shaft. The Darrieus wind turbine is a type of vertical axis wind turbine, used to produce electricity using wind energy. The blade curve of this turbine allows being stressed only in anxiety at high rotary speeds.
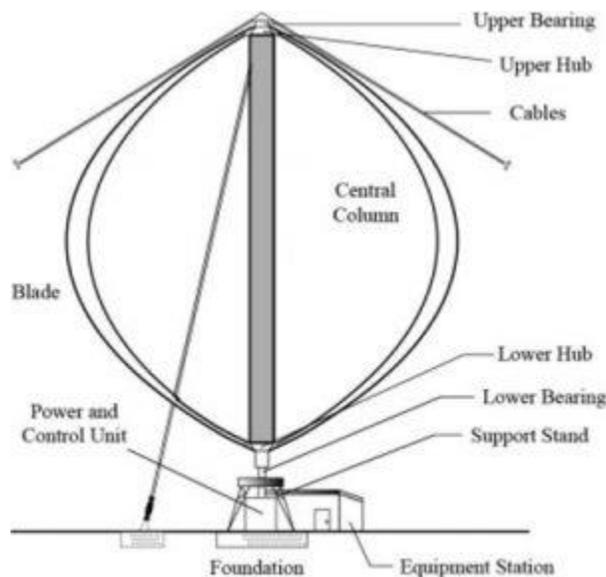
Darrieus Wind Turbine Design

There are numerous closely related wind turbines that utilize straight blades. The Darrieus Wind Turbine Design was patented by a French aeronautical engineer namely Georges Jean Marie Darrieus and filing for the copyright was

done on 1st Oct in 1926. There are many troubles while protecting this turbine from severe wind situations and also in designing it as self-starting.

Darrieus Wind Turbine Working Principle

These turbines are not self-starting but it requires a motor which is small powered to begin the revolution. Once it has sufficient speed then the wind flows across the aerofoils starts to produce torque & the rotor can be driven in the region of the wind. In the Darrieus turbine, two mini Savonius rotors are placed on the shaft to start a revolution. These reduce the Darrieus turbine once it gets going but they make the complete device very simpler as well as easier to keep.

Darrieus Wind Turbine Efficiency

The efficiency of the Darrieus Wind Turbine is less as compared to the horizontal axis wind turbine (HAWT) due to the operational characteristics and design.

Generally, the efficiency of a HAVT (horizontal axis wind turbine) ranges from 40 % to 50 % which means the turbine is capable of converting 40% – 50 % of the KE (kinetic energy) it obtains into real electrical power. Alternatively, the efficiency of a Savonius vertical axis wind turbine ranges from 10 % to 17 %, whereas the Darrieus vertical axis wind turbine achieves 30 % to 40 %. A Savonius wind turbine can generate sufficient power to hold yearly utilization of a usual two-person family.

Darrieus Wind Turbine Power Calculation

The power of wind turbines can be calculated by estimating two values like accessible wind power as well as the wind turbine efficiency. So by multiplying these two values we can get the output power of the turbine.

The sweep area of the wind turbine can be calculated like the following.

To calculate the wind power, we need to find out the swept region of the wind turbine based on the following equations:

For HAWT,

$$A = \pi * L^2$$

For VAWT, A = D * H

From the above equations, 'L' is the blade length

'H' is the turbine's height

'D is the diameter

The available power of wind can be calculated like the following.

If we know the sweep area, we can discover the accessible wind power based on the following formula.

$$Pwind = 0.5 * \rho * v^3 * A$$

From the above equations, 'A' is the sweep area

'ρ' is the density of air

'v' is the wind speed

'Pwind' is the accessible wind power.

The turbine efficiency can be calculated like the following.

$$\mu = (1 - k) * (1 - k_e) * (1 - ke,t) *(1 - kt) * (1 - kw) * C$$

Where,

'kw' is the wake of losses

'k_e' is the electrical losses of the wind turbine

'ke,t' is the electrical losses of transmission to the grid

'kt' is the % of the time out of order because of failure

'μ' is the real efficiency

To find out the power of the wind turbine, simply multiply the efficiency through the available wind power

Poutput = μ * Pwind

The advantages of the Darrieus Wind Turbine :

The rotor shaft of this turbine is vertical. So it is feasible to situate the load similar to a generator otherwise a centrifugal pump at earth level. When the generator is not turning, then the wire toward the load is not bent & no brushes are necessary for huge twisting angles.

- The rotor receives the wind from each direction.

- Easily arranged in the buildings

- The arrangement of the windmill over a building might be bigger as compared to a horizontal-axis windmill.

- Scalability

- Safety for workers

- Very easy to operate, so they don't upset people in housing neighborhoods.

- Portable from one place to another.

- It is allowable wherever taller structures are forbidden.

- Includes low-speed blades so that it reduces the risk to birds & people.

- It works in severe weather through uneven winds as well as mountain conditions.

Disadvantages

- Low efficiency

- It is difficult to start as compared to the Savonius wind turbine

- Self-starting mechanism

- Rotation efficiency is low

- Low efficiency

- Wind speed is less available

- Component wear-down

Applications

- The Darrieus wind turbine is used to produce electricity using wind energy.

- It is also used for water pumping, cooling, or heating.

Savonius wind turbine:

The Savonius wind turbine is a type of vertical-axis wind turbine invented by the finnish engineer sigurd Savonius in the 1920's. It is one of the simplest wind turbine designs. It consists of two to three "scoops" that employ a drag action to convert wind energy into torque to drive a turbine. When looked at from above in cross-section, a two scoop Savonius turbine looks like an S-shape. Due to the curvature of the scoops, the turbine encounters less drag when moving against the wind than with it, and this causes the spin in any wind regardless of facing.

Drag type wind turbines such as the Savonius turbine are less efficient at using the wind's energy than lift-type wind turbines, which are the ones commonly used in wind farms.

A Savonius is a drag type turbine, they are commonly used in cases of high reliability in many things such as ventilation and anemometers. Because they are a drag type turbine they are less efficiency than the common HAWT. Savonius are excellent in areas of turbulent wind and self-starting. The schematic diagram of savonius wind turbine as shown in fig.5.10.

Fig. 5.10 Schematic Structure of Vertical Axis Wind Turbines (Savonius wind turbine)
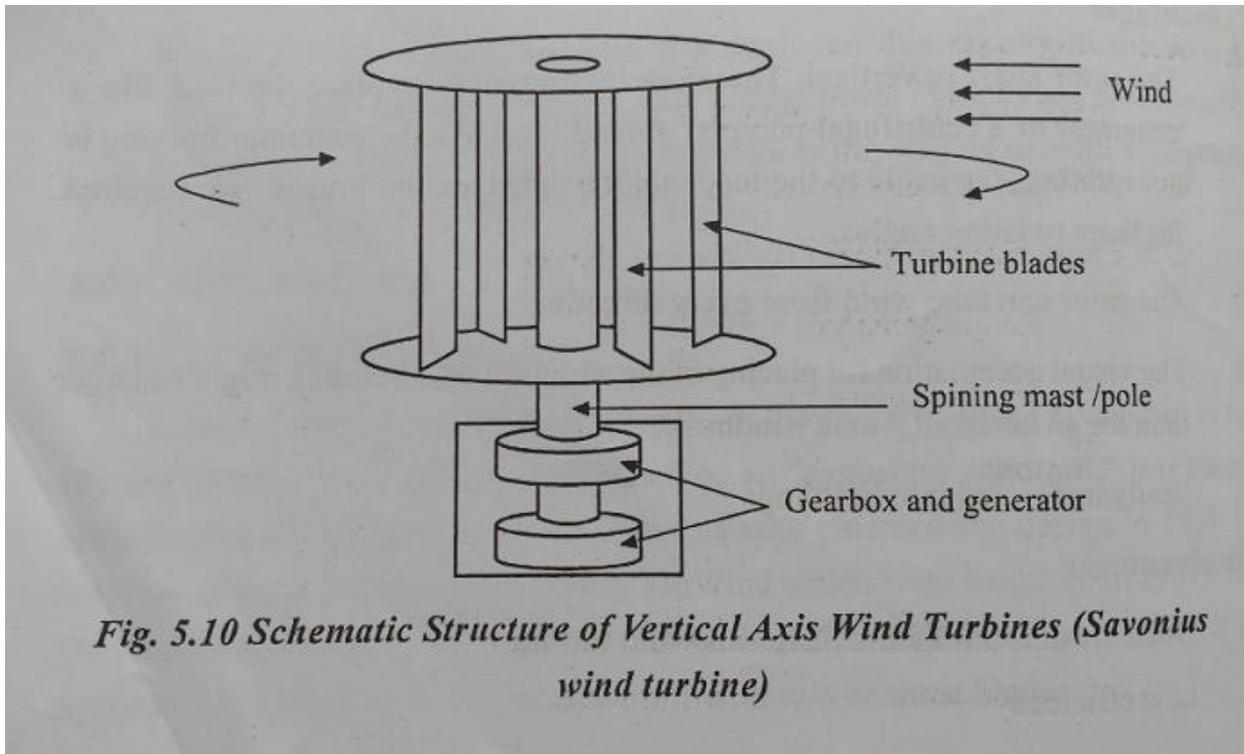
Savonius Wind Turbine Power Output:
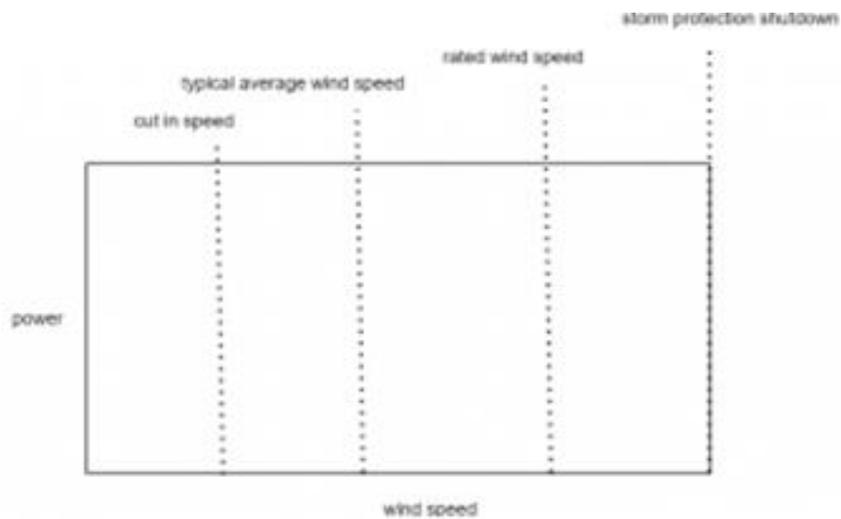
The curve which is plotted for power output shows the wind turbine's efficiency at various speed levels. The plot represents the power output in relation to the wind speed and this provides a detailed thought regarding the lesser and higher levels of a wind turbine.

As per Betz's principle, the high range of power that is received by the rotor is

$$Pmax = (16/27) (1/2) . \rho. d. h. v3$$

Where 'ρ' corresponds to the density of the air

'd' and 'h' corresponds to the height and diameter of the rotor

'v' corresponds to the speed of the wind

Whereas in the practical scenarios, the received power is only half which is given by

$$Pmax = 0.18 \text{ kg/m-3 d. h. v3}$$

Power output defines the higher power level which can be extricated from the airflow. Due to the mass and momentum conservation, there will be no complete energy extraction from the wind. With Betz's law, it was demonstrated that the higher amount of kinetic energy that was received from the wind should not go beyond 60%.

Advantages

(1) Having a vertical axis, the Savonius turbine continues to work effectively even if the wind changes direction.

(2) Because the Savonius design works well even at low wind speeds, there's no need for a tower or other expensive structure to hold it in place, greatly reducing the initial setup cost.

(3) The device is quiet, easy to build, and relatively small.

(4) Because the turbine is close to the ground, maintenance is easy.

Disadvantages

The scoop system used to capture the wind's energy is half as efficient as a conventional turbine, resulting in less power generation.

Biomass Energy

- Introduction
- Biomass Resources
- Bio Fuel
- Bio Gas
- Producer Gas
- Liquid Fuel (Ethanol)
- Biomass Conversion Techniques
- Biomass Casification
- Biogas Technology and Biogas Plants
- Ethanol from Biomass and Bio Diesel

Biomass refers to solid carbonaceous material derived from plants and animals. These include residues of agriculture and forestry, animal waste and discarded material from food processing plants

- Biomass being organic matter from terrestrial and marine vegetation, renews naturally in a short span of time, thus, classified as a renewable source of energy

It is a derivative of solar energy as plants grow by the process of photosynthesis by absorbing CO_2 from the atmosphere

Biomass does not add CO_2 to the atmosphere as it absorbs the same amount of carbon in growing the plants as it releases when consumed as fuel

It is a superior fuel as the energy produced from biomass is carbon cycle neutral'

B IO   ass   continued....

Biomass fuel is used in over 90% of rural households and in about 15% urban dwellings

Agriculture products rich in starch and sugar like wheat, maize, sugarcane can be fermented to produce ethanol {C_2H,OH)

Methanol (CH_3OH) is also produced by distillation of biomass that contains cellulose like wood ano biogases

Both these alcohols can be used to fuel vehicles and can be mixed with diesel to make biodiesel

Biomass resources for energy production are widely available in forest areas, rural farms, urban refuse and organic waste from agro- industries. Biomass classification is illustrated in the next slide

India produces over 550 million tones of agricultural and agro-industrial residues every year. Similarly, 290 million cattle population produces about 438 million tones of dung annually
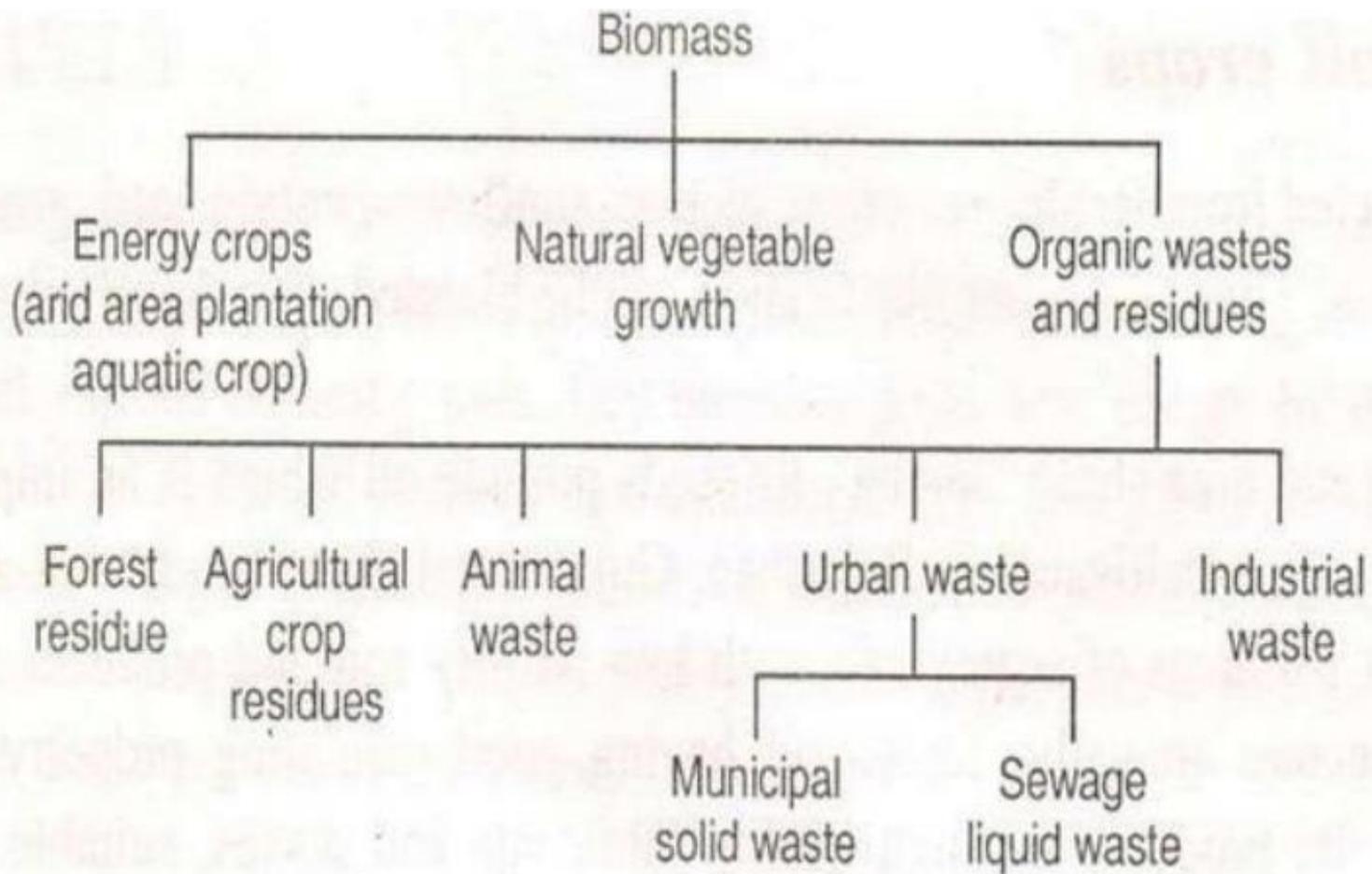
Biomass classification.

Biomass Resources

Forests

Agricultural crop residues (rice husk, wheat straw, corn cobs, cotton sticks, sugarcane biogases, groundnut shell, coconut shell etc)

Energy crops (fast growing plants)

Vegetable oil crops (rapeseed, sunflower, cotton seed, palm, groundnut, coconut etc)

Aquatic crop (water plants)

Animal waste

Urban waste

- Industrial waste

Cont.,

1. Forests:
   - Forests,are rich source of timber,fuel wood,charcoal and raw materials for paper mills and other industries
   - Forest also provide foliage and logging residues.
   - An important characteristics of forest residue is its calorific value ,which is 4399 to 4977 kcal/kg for softwood foliage and 3888 to 5219 kcal/kg for hardwood species.

2.Agricultural crop residues:

- Rice husk,wheat straw,com cobs,cotton sticks,
- Sugarcane bagasse,groundnut,coconut shells.
- These are converted into briquettes or pellets for use as clean fuel.
- These are called "biofuels" which are high efficiency solid fuels

Cont.,

3.Energy Crops:

a   Energy farming refers to the cultivation of fast growing plants which supply wood,biornass that can be converted in to gaseous and liquid fuels like biogas,vegetable oil and alcohol.

- Energy farming promoted by MNRE in nine different regions namely
  Garhwal(UP)
  Gwalpahar(Haryana)
  Udaipur(Rajastan)
  Shantiniketan(West bengal)
  Maduari(Tami lnadu)
  Calicut (f‹eraa)
  Raipur(C hattisgarh)
  Bhuvaneswar(Orissa)

Cont.,

- "kubabul" trees grow well on saline and rocky soils ,provides wood of high calorific value 4500kcal/kg

Cont.,

4.Vegetable oil Crops:

- extracted from sunflower,cotton seeds,groundnut, rapeseed, palm and cocunut oil.

rapeseed is the third largest source of vegetable oil in th wort

- Jajoba-seed provide oil
- rajastan,gujarat,orissa
- used as transformer oil
- high insulating property
  » raw material for paint and varnishes

Cont.,

5. Aquatic crop:
- constitute algae,water hyacinth,sea wood.

6.Animal waste:
- with combustible property   is a rich source of fuel
- dung cake-for cooking in rural and semi urban areas.
- raw matenal for bio gas plant

7.Urban waste:
- two types-MSW and Liquid waste from domestic sewage
- Sewage is processed to produce Bio gas

Cont.,

8. Industrial waste:
- Pulp and paper industry effulent
- Starch and glucose industry waste
- Palm oil industry waste
- Distillary waste and Tanneries waste

Tannery-is a place where leather is made.
Distillary waste-unwanted liquid waste during alcohol production

Biofuels

Charcoal (smokeless dry solid fuel with high energy density)

Briquetting (densification of loose biomass into a high density solid fuei)

Vegetable oil (rapeseed, palm, coconut and cotton seed oil)

Biogas (can be produced by digestion of plant, animal and human waste)

Producer gas {mixture of a few gases- obtained by partial combustion of wood or any cellulose organic material of plant origin)

Liouid fuel {ethanol − inflammable colorless biofuel − produced by fermentation of any feedstock which contains sugar or starch and even cellulose material)

Advantages of Biomass Energy

It is a renewable source

Energy storage is an inbuilt feature of it

It is an indigenous source requiring little or no foreign exchange

The pollutant emissions from the combustion of biomass are usually lower than those from fossil fuels

Commercial use of biomass may avoid the problems of waste disposal in urban centers

Use of biogas plants [eads to improved sanitatiOD änd better hygienic conditions

It is available in all the seasons

The nitrogen rich slurry and sludge from a biogas plant improves the fertility of the soil

The forestry and agricultural industries associated with biomass provide substantial economic development opportunities in the rural areas

Disadvantages of Biomass Energy

It is dispersed and land intensive

It is of low energy density

- It is labour intensive

The cost of collecting large quantities of biomass is significant

- It is not suitable for varying loads

It is not feasible to set up biomass power plants in all locations

Biomass Conversion Technologies

- Densifcation
- Direct combustion and incineration
- Thermo-chemical conversion
- Bio-chemical conversion

Densification :

4 In this process bulky biomass is reduced to a better volume - to -wait ratio by compressing in a die at a high temperature and pressure.

4 The biomass pressed into briquettes or pellets (either to transport and store) can be used as clean fuel in domestic chulhas, bakeries and hotels.

Cont.,

Direct Combustion:

This is the main process adopted for utilizing biomass energy. It is burnt to produce heat utilized for cooking, space heating, industrial processes and for electricity generation.

Tnis utilization method is very inefficient with heat transfer losses of 30 – 90 % of the original energy contained in the biomass. The problem is addressed through the use of more efficient cook-stove for burning solid fuels

Incineration:

It is the process of burning completely the solid masses to ashes by hign temperature oxidation.

Cont.,

Incineration (Cont.,):

Although the terms combustion and incineration are synonymous, yet the combustion process is applicable to all fuels (i.e., solid, liquids, and gases): incineration is a special process which is used for incinerating municipal solid waste to reduce the volume of sOlid refuse (90 per cent) and to produce heat steam and electricity.

Pyrolysis:

Wood, dung, vegetable waste can be dried and burnt to provide heat or converted into low calorific value by pyrolysis.

In the pyrolysis process, the organic material is converted to gases, solids and liquids by heating to 500 to 900 degree celcius in the absence of oxygen.

Cont.,

Thermo-Chemical Conversion:

It is a process to decompose biomass with various combinations of temperatures and pressures.

Thermo-Chemical conversion in two forms

i) Gasification:

It is the process of heating the biomass with limited oxygen to produce low heating value or by reacting !t with steam and oxygen at high pressure and temperature to produce medium heating value gas.

ii) Liquification:

Biomas can be liqiufied through fast or flash pyrolysis called pyrolytiC Oil which is dark brown liquid of low viscosity and a mixture of hydrocarbons.

Biomass can also be liquified by methanol sysnthesis.

Cont.,

Bio-Chemical Conversion:

In biochemical conversion there are two principal conversion process

(i) Anaerobic Digestion:

This process involves micrObial digestion of biomass and is done in tne absence of oxygen.

The process and end products depend upon the micro-organisms cultivated under culture conditions.

This process generates mostly methane (CH_4) and CO_2 gas with small impurities such as hydrogen sulphide.

Aerobic Decomposition : is done in the presence Oi oxygen and it produces CO_2 , NHS and some other gases in small quantities and large quantity of heat. The final by product of this process can be used as fertilizer.

Cont.,

Bio-Chemical Conversion (Cont.,)

(ii) FermentatiOD:

In this process of decomposition of organic matter by micro-organisms especially bacter a and yeasts.

- It is well establish and widely used technology for conversion of grains and sugar crops into ethanol (ethyl alcohol).

Ethanol can be blended with gasoline (petrol) to produce gasohol (90% petrol and 10%ethanol). Processes have been developed to produce various fuels from various types of fermentations.

Working of a Downdraft Gasifier (Downdraft Method)
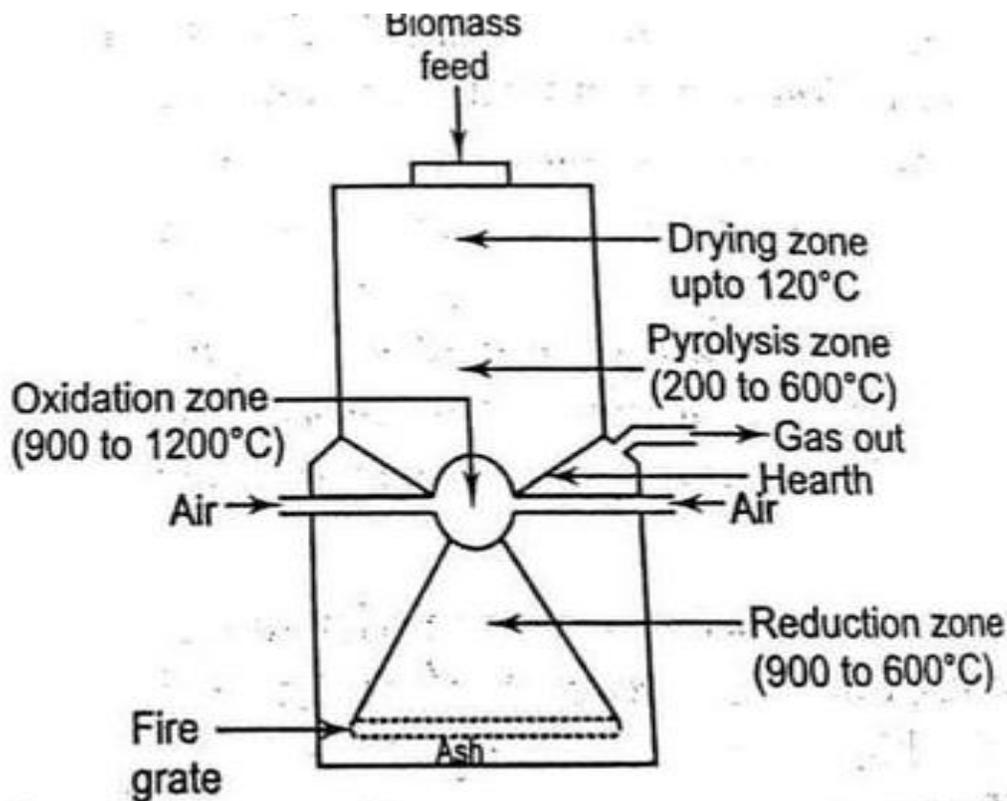
Fig. . Downdraft gasifier.

The **downdraft gasifier** is a biomass gasification system in which **both the biomass and the produced gases move downward** through the reactor. It is widely used because it produces **low-tar producer gas**, suitable for engines and power generation.

1. Feeding and Drying Zone (Up to ~120 °C)

- Biomass (wood, agricultural residue, etc.) is fed from the **top** of the gasifier.
- As it moves downward, it encounters hot rising gases.

- **Moisture is removed** from the biomass by evaporation.
- No chemical reaction occurs here—only **drying**.

2. Pyrolysis Zone (≈ 200–600 °C)

- The dried biomass enters the pyrolysis (devolatilization) zone.
- Due to high temperature and absence of oxygen:
    - Biomass decomposes into **char, tar, volatile gases, and vapors**.
- This stage produces hydrocarbons and tar vapors.

3. Oxidation (Combustion) Zone (≈ 900–1200 °C)

- **Air is introduced** through side nozzles (tuyeres).
- Partial combustion of biomass and char takes place.
- Main reactions:
    - $C + O_2 \rightarrow CO_2$
    - $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
- This zone generates **high heat**, which is essential for the gasification reactions below.
- Tar vapors formed earlier pass through this **high-temperature zone**, where they are **cracked**, resulting in low-tar gas.

4. Reduction Zone (≈ 600–900 °C)

- Hot combustion products (CO_2 and H_2O) react with hot char.
- Main gasification reactions:
    - $C + CO_2 \rightarrow 2CO$

- $C + H_2O \rightarrow CO + H_2$
- $CO + H_2O \rightleftharpoons CO_2 + H_2$

- These reactions produce **producer gas**, mainly containing:

  - Carbon monoxide (CO)

  - Hydrogen (H_2)

  - Small amounts of methane (CH_4)

  - Nitrogen (N_2)

5. Ash Zone and Gas Exit

- Remaining **ash collects on the grate** at the bottom.

- Producer gas flows **downward**, exits near the bottom, and is sent for cooling and cleaning before use.

- Ash is periodically removed.

Features of Downdraft Gasifier

- Low tar content in producer gas

- Suitable for **IC engines and small power plants**

- Simple construction and operation

- Requires relatively **dry and uniform biomass**

Advantages

- Clean gas with minimal tar

- High gas quality

- Efficient for decentralized energy systems

Limitations

- Sensitive to fuel moisture

- Not suitable for very fine or high-ash biomass

Tidal power

Index

Definition of tidal power

It's the energy that makes use of tides to generate electricity.

These power plants are in an experimental stage and their level of production is still very low.

Methods of generating tidal energy

- Tidal barrage

› Tidal stream generator (TSG)

- Dynamic tidal power (DTP)

- Tidal lagoon

Diagram of a tidal barrage
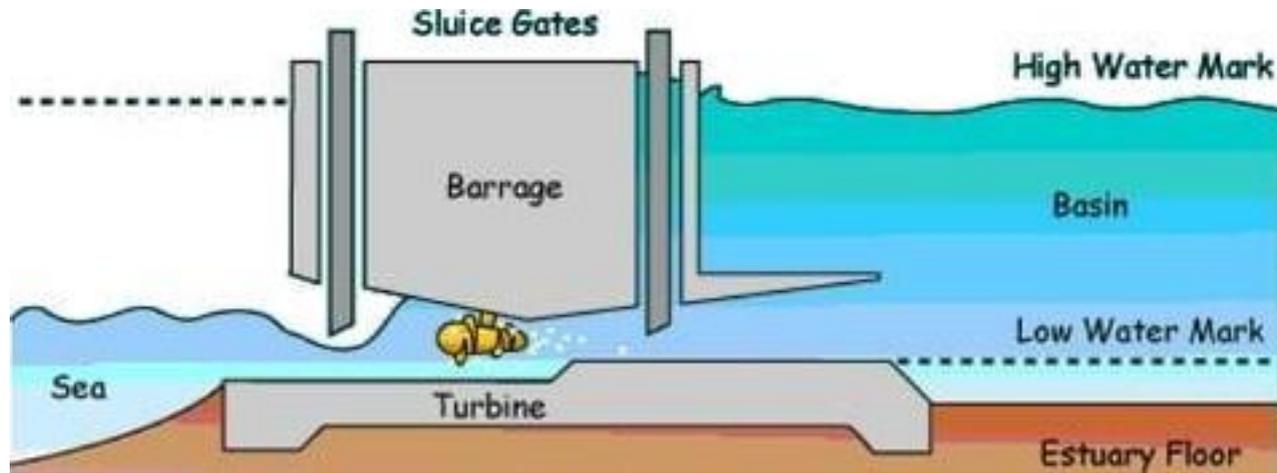
How does a tidal barrage operate?

A tidal barrage uses the potential energy produced by the difference in height between high tides and low tides.

TIDE COMING IN

Advantages and disadvantages of tidal barrages

Advantages:
- They don't produce any waste or grsanhouse gases.
- Tides are predictable.
- The energy that they produce is renewable.

Disadvantages:
- The high cost of the infrastructure.
- Global shortage of viable sites.
- Environmental issues.
- Tidak barrages only produce energy for about 10 hours a day.

Diagram of a tidal stream generator
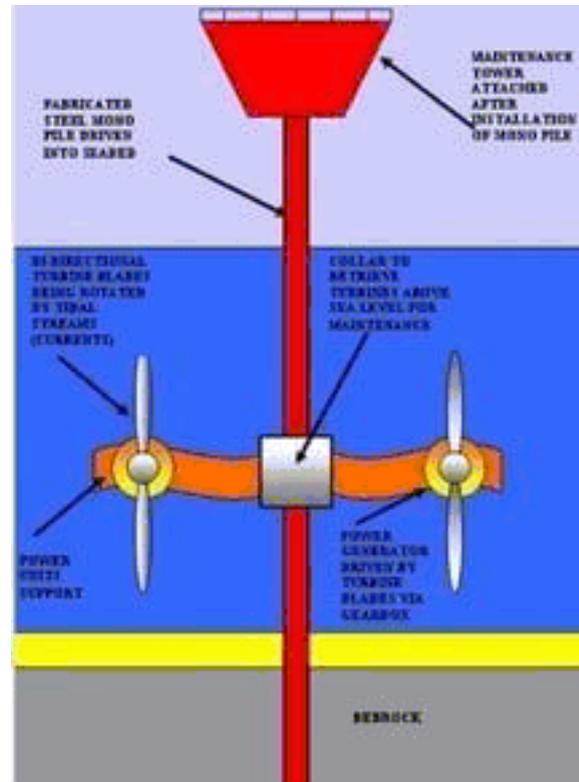
How does a tidal stream generator operate?

Tidal stream generators make use of the kinetic energy of the water which comes up and down with the tide by moving the turbines.
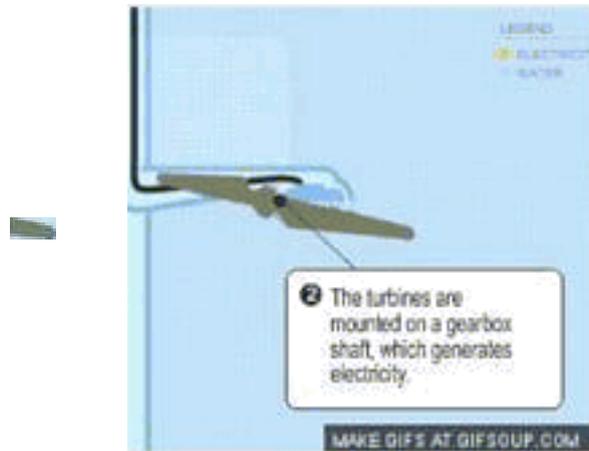
Advantages and disadvantages of tidal stream generators

Advantages:

- They are low-cost compared with tidal barrages.

- They have a smaller ecological impact than tidal barrages.

- They don't produce any waste or greenhouse gases.

- Tides are predictable.

- The ensrgy that they produce is renewable.

Disadvantages:
- Grid connection.

- The pipes can be dangerous for animals and humans.

Dynamic tidal power

DTP is an untried but promising technology hat would exploit an interaction between potential and kinetic energies in tidal flows.

It means that very long dams (3&50 km long) would be built from the coast straight out into the sea Dr ocean.

DTP advantages:
- No areas are enclosed.
- It doesn't produce any waste or greenhouse gases.
- Tides are predictable.
- It's a renewable source of energy.

DTP disadvantages:
- It's very expensive.
- Global shortage of viable sites.

High Tide
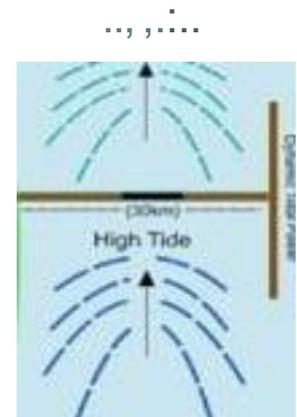
Tidal lagoon
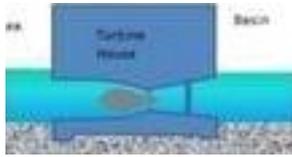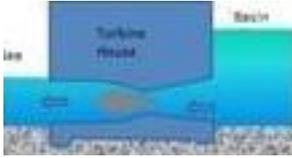
A newer tidal energy design option is to construct circular retaining walls embedded with turbines that can capture the potential energy of tides.

The reservoirs created are similar to those of tidal barrages.

Advantages:
- It doesn't produce any waste or greenhouse gases.
- Tides are predic&ble.
- Renewable resource.

Disadvantages:
- It's more expensive than tidal barrages.

Production in Europe

The production of tidal energy in Europe is so low that it isn't usually represented in graphics or it appears under the category of "others".
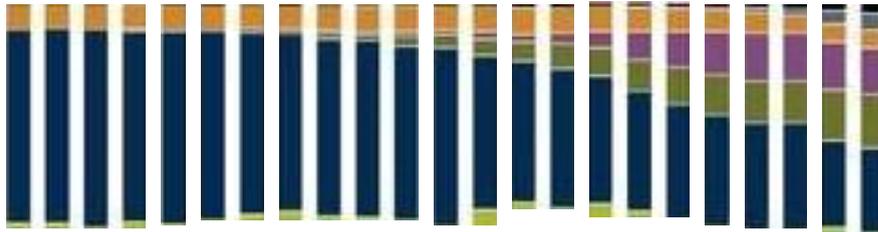
Use of tidal energy in Spain

In Spain it's used on a trial basis in Mutriku (Gipuzkoa) and on the shores of Santoña (Cantabria).

Use of tidal energy in Europe

The biggest tidal energy power station in Europe is located on the mouth of River Ranch in France. It has been operational since 1967, with a power of 240MW, covering the energetic needs of 10,000 homes in the French region of Britanny.

This energy is frequentiy used in the UK too.

Use of tidal energy worldwide

The biggest tidal energy plant in the world is in south Korea, the new Sihwa Lake Tidal Power Station, with 254MW.

Tidal energy is used in other countries like Japan, China, Australia, Canada or New Zealand.

Tidal Power Generation:

As tidal power generation is relatively new, there are not a lot of tidal energy companies out there developing investing in this technology yet. However, there are several tidal power plants in use and more is coming. Some of these are solely for research and experimental purposes, but the number of commercial tidal energy power plants is increasing.

La Rance tidal power station was the first large large-scale tide energy project and was opened already in 1966. It lays in the water-rich river Rance in the north-western France. This is a tidal power plant with a total installed capacity of 240 MW capacity generated from 24 turbines. Annual production of electricity is about. 0.6 TWh (600 GWh), which means that the average effect of day throughout the year is 68 MW. La Rance is a form of what we call a tidal barrage power plant.

High Tide

Dam

Sea

Tidal Basin

Turbine generator

Low Tide

Dam

Low Tide

Sea

Tidal Basin

Turbine generator

ELECTRICAL PAT

T.G. : TURBINE GENERATOR

HIGH TIDE

SEA

T.G.

TIDAL BASIN

LOW TIDE

SEA

T.G.
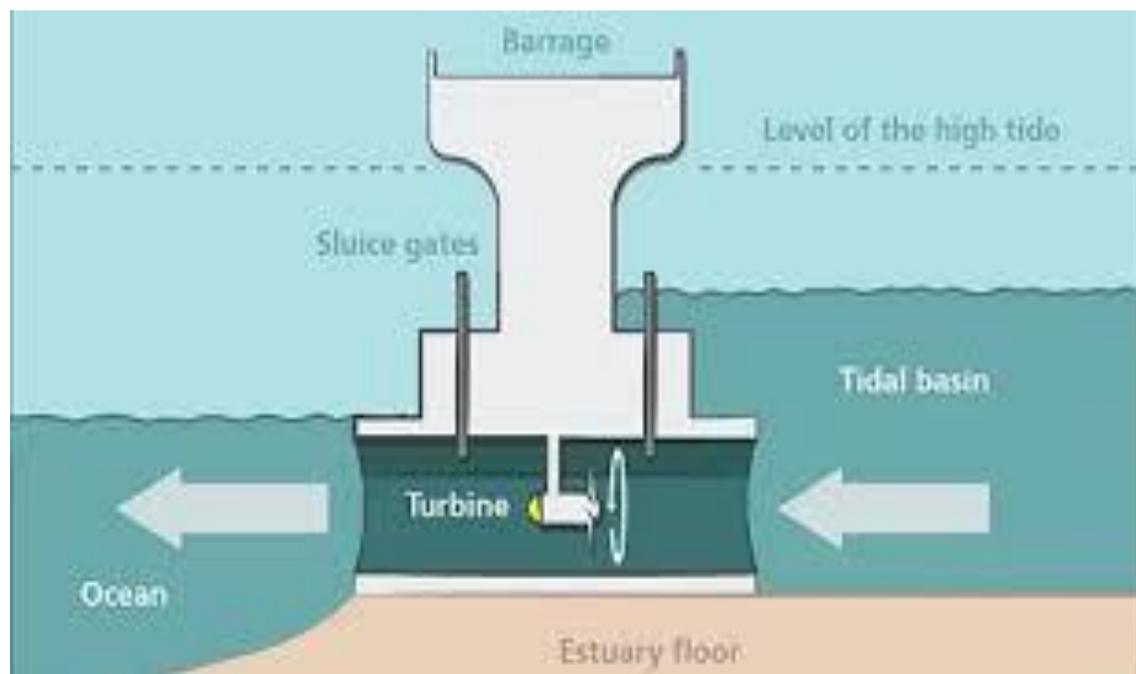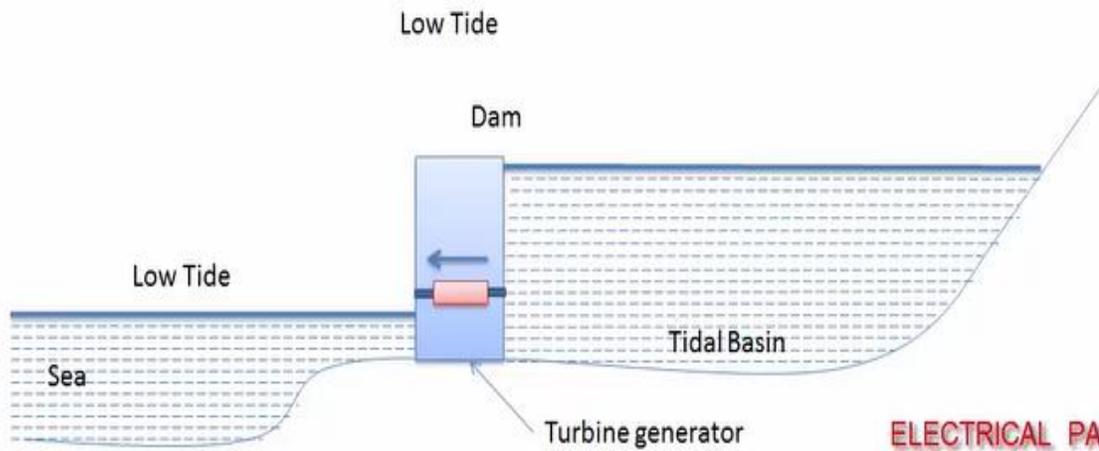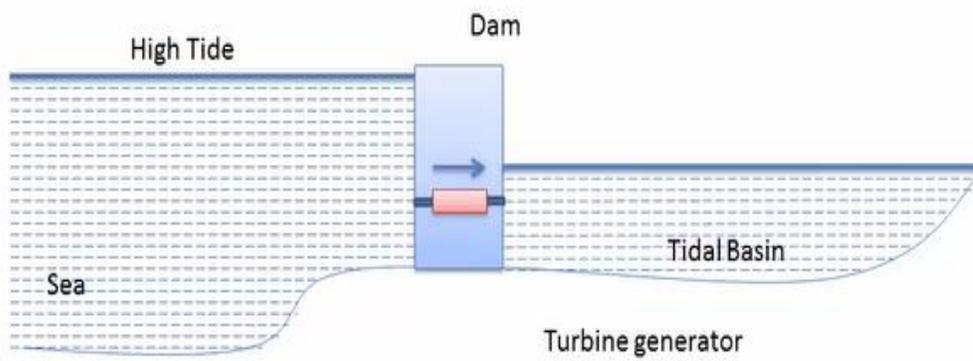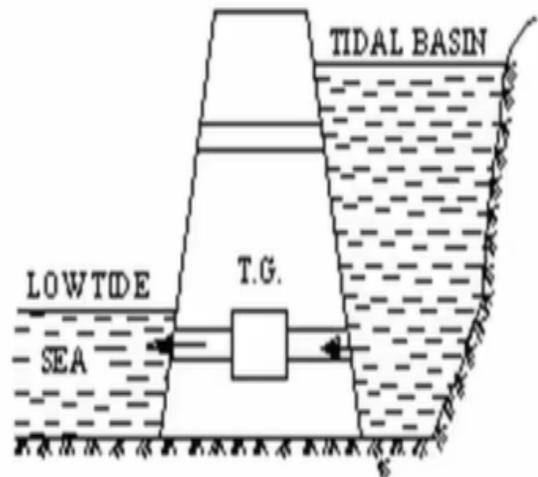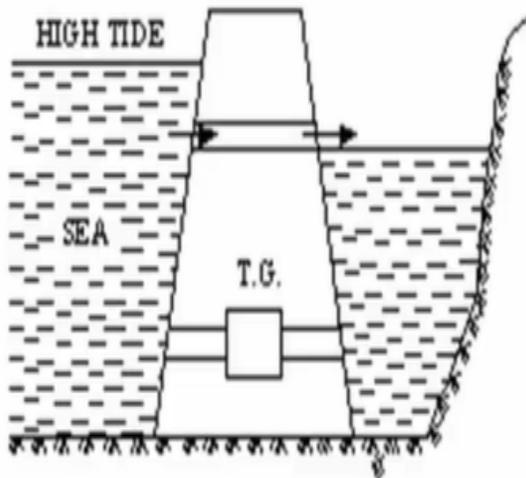
PART -A

1. Define wind energy.

2. What is the role of air movement in wind formation?

3. What are global winds?

4. Distinguish between global wind and local wind.

5. Mention any two regions in India with high wind energy potential.

6. Define wind velocity.

7. Write the expression for power available in wind.

8. What is meant by wind power density?

9. List any two problems associated with wind power.

10. What is a Wind Energy Conversion System (WECS)?

11. Define biomass energy.

12. Explain the photosynthesis process briefly.

13. What are biofuels? Give one example.

14. List any two biomass resources.

15. What is a fixed dome biogas plant?

16. Define urban waste-to-energy conversion.

17. What is biomass gasification?

18. What is a downdraft gasifier?

19. Mention any two advantages of biomass energy.

20. Mention two applications of biomass gasification.

21. Define tidal power.

22. What are the fundamental characteristics of tidal power?

23. What is meant by harnessing tidal energy?

24. Mention any two advantages of tidal power.

25. State any two limitations of tidal power generation.

PART -B

1. Explain air movement and wind formation in detail.

2. Describe global and local winds and explain their significance in wind energy generation.

3. Discuss the availability of wind energy in India.

4. Derive the expression for power available in wind and explain the effect of wind velocity.

5. Explain the major problems associated with wind power generation.

6. Classify Wind Energy Conversion Systems (WECS) with neat diagrams.

7. Explain the construction and working of a horizontal axis single-blade wind turbine.

8. Describe horizontal axis double-blade and multi-blade wind turbine systems?

9. Explain the construction and working of Savonius wind turbine with advantages and disadvantages.

10. Explain the construction and working of Darrieus wind turbine with advantages and disadvantages.

11. Explain biomass energy and its importance in renewable power generation.

12. Describe the photosynthesis process and its role in biomass energy.

13. Explain different types of biofuels and their applications.

14. Discuss various biomass resources available for energy production.

15. Explain the construction and working of a fixed dome biogas plant with neat sketch.

16. Describe urban waste-to-energy conversion methods.

17. Explain the principle and process of biomass gasification.

18. Describe the construction and working of a downdraft biomass gasifier.

19. Discuss the advantages and limitations of biomass energy systems.

20. Explain the **fundamental characteristics of tidal power** in detail.

21. Describe the **methods of harnessing tidal energy** with neat diagrams.

22. Discuss the **advantages and limitations of tidal power generation**.

Objective-Type Questions (MCQs)

1. Wind energy is derived from
   A) Solar radiation
   B) Atmospheric pressure differences
   C) Earth's rotation
   D) Ocean currents
   Ans: B

2. Global winds are mainly caused by
   A) Earthquake activity
   B) Uneven heating of Earth
   C) Ocean tides
   D) Magnetic field
   Ans: B

3. Wind power is proportional to
   A) Wind velocity
   B) Square of wind velocity

C) Cube of wind velocity

D) Inverse of velocity

Ans: C

4. Which state has the highest wind power potential in India?

A) Kerala

B) Tamil Nadu

C) Bihar

D) Assam

Ans: B

5. WECS stands for

A) Wind Energy Control System

B) Wind Energy Conversion System

C) Wind Electrical Control System

D) Wind Energy Current System

Ans: B

6. Horizontal axis wind turbines rotate about

A) Vertical axis

B) Inclined axis

C) Horizontal axis

D) Circular axis

Ans: C

7. Savonius turbine works on

A) Lift principle

B) Drag principle

C) Centrifugal force

D) Magnetic force

Ans: B

8. Darrieus turbine works on

A) Drag principle

B) Lift principle

C) Gravity

D) Pressure difference

Ans: B

9. Multi-blade turbines are mainly used for

A) Power generation

B) Water pumping

C) Lighting

D) Heating

Ans: B

10. Major disadvantage of wind power is

A) Pollution

B) High fuel cost

C) Intermittent nature

D) Noise-free operation

Ans: C

11. Biomass energy is a form of

A) Fossil fuel

B) Nuclear energy

C) Renewable energy

D) Electrical energy

Ans: C

12. Photosynthesis occurs in

A) Roots

B) Stem

C) Chlorophyll

D) Xylem

Ans: C

13. Main product of photosynthesis is

A) CO_2

B) Oxygen

C) Glucose

D) Nitrogen

Ans: C

14. Example of biofuel is

A) Petrol

B) Diesel

C) Biogas

D) Coal

Ans: C

15. Fixed dome biogas plant is made of

A) Steel

B) Plastic

C) Masonry

D) Aluminium

Ans: C

16. Biomass gasification converts solid fuel into

A) Liquid fuel

B) Producer gas

C) Steam

D) Electricity

Ans: B

17. Downdraft gasifier produces gas with

A) High tar content

B) Low tar content

C) No carbon monoxide

D) No hydrogen

Ans: B

18. Urban waste-to-energy helps in

A) Pollution increase

B) Waste accumulation

C) Waste management

D) Fossil fuel use

Ans: C

19. Major advantage of biomass energy is

    A) High pollution

    B) Non-renewable

    C) Carbon neutrality

    D) High cost

    Ans: C

20. Biomass resource includes

    A) Uranium

    B) Coal

    C) Agricultural waste

    D) Natural gas

    Ans: C

21. Tidal energy is caused due to

    A) Wind action

    B) Solar radiation

    C) Gravitational pull of moon

    D) Earthquake

    Ans: C

22. Tidal power is a

    A) Continuous source

    B) Seasonal source

    C) Predictable source

    D) Unreliable source

    Ans: C

23. Tidal power plant requires

    A) High wind speed

B) High tidal range

C) High temperature

D) Fossil fuel

Ans: B

24. Tidal energy is harnessed using

    A) Barrages

    B) Boilers

    C) Turbines only

    D) Solar panels

    Ans: A

25. Major advantage of tidal energy is

    A) High pollution

    B) Predictability

    C) High fuel cost

    D) Intermittency

    Ans: B

26. Tidal power plants are usually located in

    A) Mountains

    B) Deserts

    C) Coastal regions

    D) Forests

    Ans: C

27. One limitation of tidal power is

    A) Air pollution

    B) High initial cost

    C) Fuel shortage

    D) Carbon emission

    Ans: B

28. Tidal power depends on

    A) Weather conditions

B) Ocean currents only

C) Lunar cycle

D) Solar panels

Ans: C

29.Energy obtained from tides is

A) Thermal

B) Mechanical

C) Nuclear

D) Chemical

Ans: B

30.Tidal power is best suited for

A) Inland areas

B) River basins

C) Coastal areas with high tidal range

D) Dry regions

Ans: C

UNIT-3: ENERGY STORAGE AND GREEN ENERGY

Course Outcomes:

After completing this unit, students will be able to:

1. **Explain different energy storage technologies** and evaluate the performance of stationary battery systems.

2. **Analyze battery parameters** such as storage capacity, coulomb efficiency, and determine appropriate battery sizing for energy systems.

3. **Describe the working principles of supercapacitors** and compare them with conventional battery storage systems.

4. **Explain the operation and thermodynamic principles of fuel cells**, including Gibbs free energy, entropy, and efficiency.

5. **Evaluate hydrogen energy systems** including hydrogen production, storage, applications, and associated challenges.

Book/NPTEL link Reference:

1. G. D. Rai, Non-Conventional Sources of Energy, Khanna Publisher, 2004
2. G N Tiwari, Solar Energy: Fundamentals, Design, Modelling and Applications, Narosa, 2002.
3. Mukund R Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd
4. https://archive.nptel.ac.in/courses/121/106/121106014/
5. https://onlinecourses.nptel.ac.in/noc22_ch27/preview
6. https://www.nptelvideos.com/lecture.php?id=8517https://www.nptelvideos.com/lecture.php?id=8517

ASSIGNMENT TOPICS:

➢ Case Study: Availability of Wind Energy Resources in India

UNIT-3: ENERGY STORAGE AND GREEN ENERGY:

Energy Storage: Stationary Battery Storage – Basics of Lead-Acid batteries, Battery Storage Capacity, Coulomb efficiency instead of energy efficiency, Battery Sizing. Different Battery storage technologies and comparison of their performance. Introduction to Super capacitors. Green Energy: Historical Development, Basic Operation of a Fuel Cell, Fuel Cell Thermodynamics, Entropy and the theoretical efficiency of Fuel Cells, Gibbs Free Energy and Fuel Cell efficiency, Electrical output of an Ideal Cell, Electrical Characteristics of Real Fuel Cells, Types of Fuel Cells, H2: Operating principles, Zero energy Concepts. Benefits of hydrogen energy, hydrogen production technologies (electrolysis method only), hydrogen energy storage, applications of hydrogen energy, problem associated with hydrogen energy.

Course Objectives:

1. Understand the importance of energy storage systems and study the fundamentals of stationary battery storage such as lead–acid batteries, storage capacity, and coulomb efficiency.

2. Explain battery sizing methods and compare different battery storage technologies used in renewable energy applications.

3. Introduce advanced energy storage devices such as supercapacitors and analyze their characteristics and applications.

4. Study the fundamentals of green energy technologies, particularly fuel cells, including their operation, thermodynamics, and efficiency.

5. Understand hydrogen energy systems, including hydrogen production through electrolysis, hydrogen storage methods, applications, and challenges.

Stationary battery storage:

Stationary battery storage systems are fixed, rechargeable energy storage units, often using lithium-ion (specifically LFP), lead, or flow batteries, that store excess electricity for later, on-demand use. They are essential for stabilizing power grids, integrating renewable energy (solar/wind), and providing backup power, ranging in size from residential units to large-scale, utility-grade installations.

Functionality:

System Components: A typical unit consists of battery racks, an inverter, an electronic control system, and a thermal management system.

Operation: They charge during periods of high production (or low demand) and discharge when needed, acting as a buffer to balance grid volatility.

Installation: Designed for fixed locations, they do not require, nor are they designed for, mobility.

Core Applications:

Grid Services: Providing frequency response, voltage control, and peak shaving.

Renewable Integration: Storing excess energy from solar or wind, reducing curtailment.

Backup Power: Providing resilience and security for critical infrastructure and residential homes.

EV Charging: Powering fast-charging infrastructure for electric vehicles.

Market and Technology Trends

Growth: The sector is experiencing rapid expansion, with nearly 60% year-on-year growth since 2021, driven by renewable energy adoption and declining costs.

Chemistries: While lithium-ion is dominant, Lithium Iron Phosphate (LFP) makes up 80–85% of European stationary projects due to safety and cost.

Future Outlook: By 2040, stationary storage could account for 30–50% of total

lithium-ion battery demand.

Safety: The increasing deployment has led to enhanced focus on safety standards to manage thermal runaway risks.

Benefits

Sustainability: Enables a higher penetration of renewable energy.

Reliability: Enhances grid stability and reduces the need for expensive, traditional power plant upgrades.

Independence: Promotes energy independence for users.

Lead Acid Battery:

Working of Lead Acid Battery | Lead Acid Secondary Storage Battery:
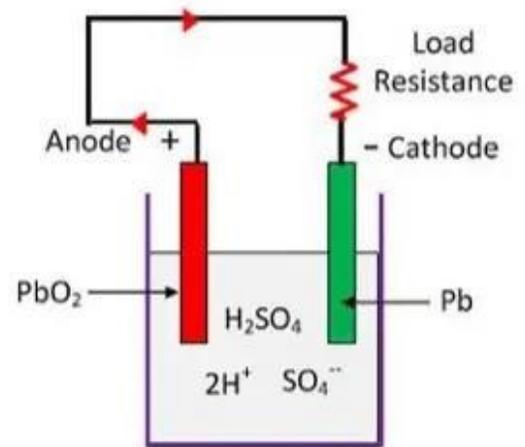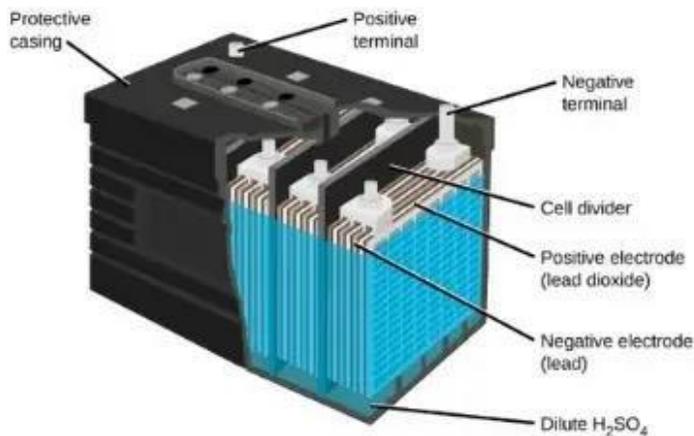
- **Lead Acid Battery Defined**: A lead acid battery is defined as a rechargeable storage device where electrical energy is transformed into chemical energy during charging, and vice versa during discharging.

- **Materials and Composition**: Essential materials include lead peroxide and sponge lead, used in the positive and negative plates respectively, submerged in dilute sulfuric acid.

- **Working of Lead Acid Battery**: The battery operates by converting stored chemical energy into electrical energy through a series of electron exchanges between its lead plates during discharge.

- **Chemical Changes**: Key reactions involve hydrogen and sulfate ions interacting with lead plates to form lead sulfate, dictating the flow of electrons and hence current through the battery.

- **Charging Process**: Recharging the battery reverses the chemical reactions, converting lead sulfate back into lead peroxide and pure lead, thus restoring and enhancing battery capacity.

Working of Lead Acid Battery

A storage or secondary battery stores electrical energy as chemical energy, which is then converted back into electrical energy as needed. Charging a battery involves converting electrical energy into chemical energy using an external electrical source. Conversely, discharging a battery converts this stored chemical energy back into electrical energy to power external loads. During charging of battery, current is passed through it which causes some chemical changes inside the battery. These chemical changes absorb energy during their formation.

When connected to an external load, the battery's chemical changes reverse, releasing the stored e n e r g y a s electrical power for the load. Now we will try to understand the principle **working of lead acid battery** and for that we will first discuss about **lead acid battery** which is very commonly used as storage battery or secondary battery.

Materials used for Lead Acid Storage Battery Cells

The main active materials required to construct a lead acid battery are

1. Lead peroxide (PbO_2).
2. Sponge lead (Pb)
3. Dilute sulfuric acid (H_2SO_4).

Lead Peroxide (PbO_2)

The positive plate is made of lead peroxide. This is dark brown, hard and brittle substance.

Sponge Lead (Pb)

The negative plate is made of pure lead in soft sponge condition.

Dilute Sulfuric Acid (H_2SO_4)

Dilute sulfuric acid used for lead acid battery has a ratio of water : acid = 3:1.

The **lead acid storage battery** is formed by dipping lead peroxide plate and sponge lead plate in dilute sulfuric acid. A load is connected externally between these plates. In diluted sulfuric acid the molecules of the acid split into positive hydrogen ions (H^+) and negative sulfate ions (SO_4^{--}). The hydrogen ions when reach at PbO_2 plate, they receive electrons from it and become hydrogen atom which again attack PbO_2 and form PbO and H_2O (water). This PbO reacts with H_2SO_4 and forms $PbSO_4$ and H_2O (water).

$$PbO_2 + 2H \rightarrow PbO + H_2O$$

$$\frac{PbO + H_2SO_4 \rightarrow PbSO_4 + H_2O}{PbO_2 + H_2SO_4 + 2H \rightarrow PbSO_4 + 2H_2O}$$
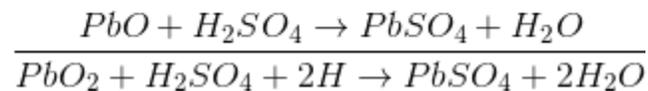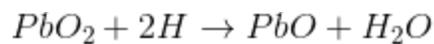
SO_4^{--} ions are moving freely in the solution so some of them will reach to pure Pb plate where they give their extra electrons and become radical SO_4. As the radical SO_4 cannot exist alone it will attack Pb and will form $PbSO_4$. As $H+$ ions accept electrons from the PbO_2 plate and SO_4^{--} ions donate electrons to the Pb plate, an electron imbalance occurs. This imbalance drives a current through the external load between the plates to balance the electrons, a process known as the discharging of the lead acid battery.

The lead sulfate ($PbSO_4$) is whitish in color. During discharging,

1. Both of the plates are covered with $PbSO_4$.

2. Specific gravity of sulfuric acid solution falls due to formation of water during reaction at PbO_2 plate.

3. As a result, the rate of reaction falls which implies the potential difference between the plates decreases during discharging process.

Now we will disconnect the load and connect $PbSO_4$ covered with PbO_2 plate with positive terminal of an external DC source and PbO_2 covered with Pb plate with negative terminal of that DC source.

During discharging, the density of sulfuric acid falls but there still sulfuric acid exists in the solution. This sulfuric acid also remains as H^+ and SO_4^{--} ions in the solution.

Hydrogen ions (cation) being positively charged, move to the electrode (cathode) connected with negative terminal of the DC source. Here each H^+ ion takes one electron from that and becomes hydrogen atom. These hydrogen atoms then attack $PbSO_4$ and form lead and sulfuric acid.

$$PbSO_4 + 2H \rightarrow H_2SO_4 + Pb$$
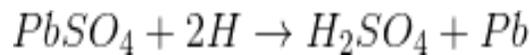
SO_4^{--} ions (anions) move towards the electrode (anode) connected with positive terminal of DC source where they will give up their extra electrons and become radical SO_4. This radical SO_4 cannot exist alone hence reacts with $PbSO_4$ of anode and forms lead peroxide (PbO_2) and sulfuric acid (H_2SO_4).

$$PbSO_4 + 2H_2 + SO_4 \rightarrow PbO_2 + 2H_2SO_4$$
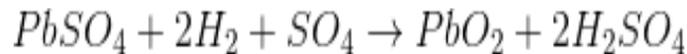
Hence by charging the lead acid storage battery cell,

1. Lead sulfate anode gets converted into lead peroxide.

2. Lead sulfate of cathode is converted to pure lead.

3. Terminal; potential of the cell increases.

4. Specific gravity of sulfuric acid increases.

Battery Storage Capacity:
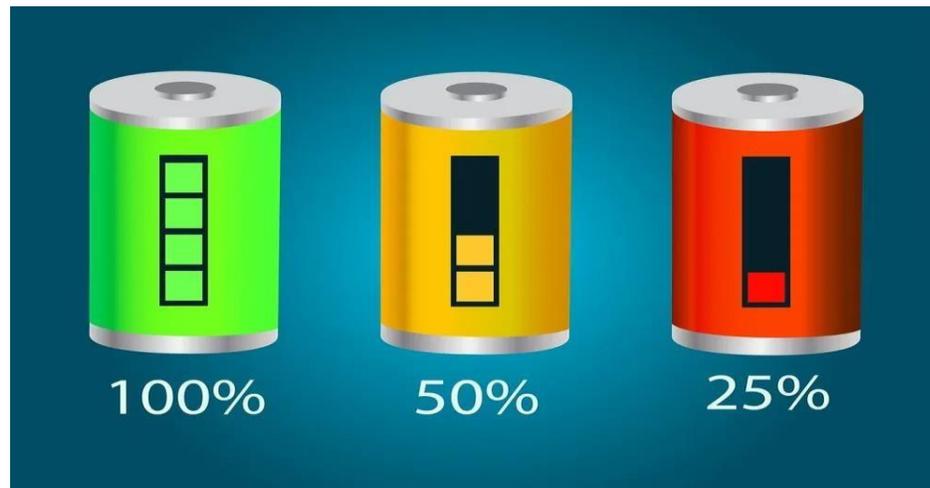
Battery storage capacity refers to the total amount of **energy that a battery can store and discharge.**

It's usually measured in **kilowatt-hours (kWh)** for larger systems, like those used in homes or businesses, or **amp-hours (Ah)** for smaller systems, like those found in electronics or electric vehicles.

The higher the storage capacity, the more energy the battery can hold.

In practical terms, a battery with a higher storage capacity will last longer between charges and can provide more power when needed.

Think of it like a water tank. The tank's capacity tells you how much water it can hold.

Similarly, a battery's storage capacity tells you how much energy it can store and supply to power devices, appliances, or even entire homes.

Why Battery Storage Capacity important:

- ➢ Understanding battery storage capacity is crucial for making informed decisions, whether you're choosing a battery for a solar energy system, an electric vehicle, or any other application.
- ➢ The more storage capacity you have, the longer your battery can power things without needing to be recharged.

➢ For example, a home solar system paired with a battery storage solution allows you to store energy generated during the day for use at night.
➢ If your battery has high storage capacity, you can use more of the solar energy you've captured, reducing reliance on the grid.
➢ Battery storage capacity also plays a significant role in reducing energy costs. In places with peak energy pricing, having a larger storage capacity allows you to use stored energy when electricity prices are high, thus saving money on your electricity bill.

Factors That Affect Battery Storage Capacity

Several factors influence a battery's storage capacity, and understanding these factors is important for selecting the right battery for your needs. Some of the main elements include:

Battery Chemistry

Different battery chemistries offer varying energy densities, which affect storage capacity.

For example, **lithium-ion batteries typically have a higher energy density than lead-acid batteries,** meaning they can store more energy in a smaller space. This is why lithium-ion batteries are commonly used in electric vehicles and renewable energy systems.

Size of the Battery

Larger batteries naturally have a higher storage capacity because they have more room for energy. However, size isn't the only factor—battery design and chemistry also come into play.

Voltage and Current

Voltage refers to the electrical potential, while current is the flow of electricity. The combination of voltage and current determines how much energy a battery can store and how efficiently it can discharge.

State of Charge (SOC)

The SOC indicates how much energy remains in a battery. A fully charged battery has a SOC of 100%, while a completely depleted battery has a SOC of 0%. As the SOC changes, so does the available energy for use.

Efficiency of the Battery

Not all the energy stored in a battery can be used. Battery efficiency accounts for losses that occur during charging and discharging. A highly efficient battery will have less energy loss, allowing it to deliver more usable power.

How to Calculate Battery Storage Capacity

To understand how much energy a battery can hold, it's essential to look at its capacity, which is typically expressed in either kWh or Ah. Here's a simple breakdown:

Amp-Hours (Ah)

Amp-hours are the most common unit of measurement for small batteries, such as those used in electronics or electric vehicles.

If a battery is rated for 10 Ah, this means it can supply 10 amps of current for one hour. To calculate the total capacity, you multiply the voltage by the amp-hour rating:

$$Capacity\ (Wh) = Voltage\ (V) \times AmpHours\ (Ah)$$

For example, a 12V battery with a 10Ah rating would have a capacity of:

$$Capacity = 12V \times 10Ah = 120Wh$$

Kilowatt-Hours (kWh)

Larger systems, like those used in homes or businesses, typically use kWh to measure capacity. One kWh is equal to 1,000 watt-hours (Wh).

So, for a home energy system that uses a 10kWh battery, it can supply 10,000 watt-hours of energy. A battery with a 10kWh capacity can power a 1,000-watt device for 10 hours (if it operates at full efficiency).

Different Uses of Battery Storage Capacity

Battery storage capacity plays a role in various applications, from personal devices to large-scale energy storage. Here's how battery capacity impacts different industries and use cases:

Home Solar Energy Systems

If you're using a solar panel system, the battery storage capacity is key to how much of the energy you generate can be used during the night or cloudy days. A larger storage capacity means you can store more energy for later use, reducing your reliance on the grid and saving on electricity bills.

Electric Vehicles (EVs)

The range of an electric vehicle is directly related to its battery capacity. A car with a larger battery storage capacity can travel farther on a single charge, which is a major consideration for potential EV buyers. As battery technology advances, manufacturers are focusing on increasing storage capacity to improve vehicle range and reduce charging frequency.

Off-Grid Living

For those who live off the grid, battery storage capacity is a lifeline. It determines how much energy you can store from sources like solar panels or wind turbines, allowing you to live independently without a connection to the local power grid. In off-grid systems, maximizing storage capacity ensures you have enough energy during periods of low sunlight or wind.

Industrial Applications

Industrial systems, like those used for backup power or in data centers, require high-capacity batteries to ensure reliable power during blackouts or emergencies. The larger the battery capacity, the longer it can provide backup power to critical systems.

How Battery Storage Capacity Affects Your Energy Needs

When deciding on the right battery storage capacity for your needs, consider your energy consumption patterns.

For instance:

Daily Usage: Calculate your average daily energy usage in kilowatt-hours (kWh). This helps determine the size of the battery required to meet your needs. For example, if your household uses 20 kWh of energy daily, you'll need a battery system capable of storing at least this much energy for optimal performance.

Peak Load: This refers to the maximum energy your system requires at any given moment. A larger storage capacity can help meet peak demands more effectively.

Battery Life: Larger batteries may have a longer life because they aren't stressed as much as smaller batteries. By choosing a battery with the right capacity for your needs, you can extend its lifespan and get better value for your investment.

Factors to Consider When Choosing Battery Storage Capacity

When selecting a battery for your home or business, there are several factors to consider beyond just storage capacity:

Budget

Bigger batteries come with a higher upfront cost. It's important to balance your energy needs with your budget, ensuring you invest in a system that meets your needs without going overboard.

Space Availability

Larger capacity batteries typically require more space. If you have limited room, you may need to consider more compact options or plan for battery placement accordingly.

Efficiency and Reliability

It's not just about storage capacity; efficiency also matters. A highly efficient battery will store and release energy more effectively, saving you money in the long run.

Maintenance Requirements

Some batteries require more maintenance than others. Lithium-ion batteries, for instance, tend to have lower maintenance needs compared to older lead-acid models.

Coulomb Efficiency Instead of Energy Efficiency:

In battery systems, efficiency indicates how effectively the battery stores and delivers electrical energy.

Two types of efficiencies are commonly used:

1. Coulomb Efficiency (Charge Efficiency)
2. Energy Efficiency

Although both are important, Coulomb efficiency is preferred for battery analysis, sizing, and health monitoring.

Coulomb Efficiency:

Coulomb efficiency is defined as the ratio of charge delivered during discharge to the charge supplied during charging.

Mathematical Expression,

$$\eta_c = \frac{Discharge\ \ Capacity(Ah)}{Charge\ Capacity(Ah)} \text{ x } 100\%$$

- Charge is measured in Ampere-hour (Ah)
- Depends only on current and time
- Independent of voltage

Coulomb efficiency indicates:

- How reversible the battery chemical reactions are

- The charge is lost due to:

  - Side reactions- Side reactions are **extra reactions that take place unintentionally**, reducing efficiency and performance.

- o Self-discharge

- o Electrolyte decomposition- Occurs because of,

  - Voltage exceeds safe limits
  - Temperature is high
  - Overcharging occurs
  - Side reactions take place

Energy Efficiency

Energy efficiency is defined as the ratio of energy obtained during discharge to the energy supplied during charging.

Mathematical Expression

$$\eta\ E = \frac{Discharge\ Capacity(wh)}{Charge\ Capacity(wh)} \text{x } 100\%$$

- Energy = Voltage × Current × Time
- Depends on both charge and voltage
- Always lower than Coulomb efficiency in practical batteries

Variation in Batteries:

In real batteries:

- Charging voltage is **higher**

- Discharging voltage is **lower**

This is due to:

- Internal resistance

- Activation polarization

- Concentration polarization

Coulomb Efficiency is Preferred because,

- Battery capacity is rated in Ah
- Load demand is current-based
- Directly measures charge loss

Battery Efficiency

The energy supplied to a battery when charging at voltage v_s, current I_C, and time Δt_{ic} is

$$E_C = v_C I_C \Delta t_C$$

If the battery is discharged at voltage v and current I for time Δt, the energy delivered is

$$E = vI\Delta t$$

Energy efficiency is the ratio of the energy returned to the charging energy supplied.

$$\varepsilon = \frac{E}{E_C} = \left(\frac{v}{v_C}\right)\left(\frac{I\Delta t}{I_C \Delta_c t_C}\right)$$

The second term on the right-hand side $\left(\frac{I\Delta t}{I_C \Delta_c t_C}\right)$ is the ratio of Ah delivered by the battery to the Ah provided to the battery during charging. This ratio is the Coulomb efficiency.

$$\varepsilon_C = \frac{I\Delta t}{I_C \Delta_c t_C})$$

The voltage efficiency is

$$\varepsilon_v = \frac{v}{v_C}$$

Thus, the energy efficiency is

$$\varepsilon = \varepsilon_v \times \varepsilon_C$$

Coulomb Efficiency vs Energy Efficiency

Coulomb Efficiency (η_C):

Ratio of charge extracted during discharge to charge supplied during charging.

$$\eta_c = \frac{\text{Ah discharged}}{\text{Ah charged}} \times 100$$

Why Coulomb efficiency is preferred:

- Batteries store **charge**, not directly energy

- Energy efficiency includes voltage losses

- Coulomb efficiency directly reflects electrochemical reversibility

Typical lead–acid Coulomb efficiency: **85–95%**

Battery sizing:

Battery sizing is balancing the power requirement of a given system and coming up with a battery that meets the client's requirements.

Sizing determines the number of kilowatt-hours stored in a particular battery. It is an important action that gives a product lifetime.

Undersized batteries reduce the shelf life of an electrical product.

To size a battery, gather the following information:

- load that will be supported by the battery to be designed

- minimal voltage the battery should handle

- backup time

IEEE Sizing Calculations

Our calculations are based on the IEEE-provided standards for the sizing of both nickel-cadmium and lead-acid station application batteries. This is a directive to all users that the calculation here may not be used to design any other battery type unless you refer to the guides provided by the manufacturers of the other types.

The following should guide you during the sizing process:

Collect the total loads that will be supported by the battery. This step will help the designer determine the total load the battery should supply.

Develop a load profile. The load profile is determined using the autonomy method, and IEEE standards give the guidelines for the autonomy, discharge, or backup times.

Select the type of battery to design. Choose the type of battery, for example, lead-acid and follow IEEE-provided guidance on characteristics of charging and discharging; essentials on cell orientations; the threshold for ambient temperature; cell life; ventilation and maintenance requirements; other physical properties such as battery terminals and weight.

Using the manufacturer's datasheet, determine the battery cell characteristics, including cell temperature; cell floating voltage; end of discharge voltage (EODV, which in most batteries ranges between 1.75 V to 1.8 V per cell if the discharge time is more than one hour and 1.66 V if the discharge time is less than 15 minutes); AH battery cell capacity; electrolyte density in the case of lead-acid batteries.

Choose battery cells that can be linked in series method. For lead acid of a particular size, the list below shows the number of cells that can fit in them.

RATED VOLTAGE (V)	CELLS
6	3
12	6
24	12
48	24
120	60

Table Showing Different Battery Voltage Ratings and The Number of Cells Required for The Lead Acid Battery.

I would not advise designers to always stick to the list above because they can perform calculations and determine the required number of cells to match a specific load. The formulas here will guide designers in determining the number of cells required, which should not go below or above this limit:

$$N_{max} = \frac{V_{dc}(1 + V_{load,max})}{V_{charging}}$$

$$N_{min} = \frac{V_{dc}(1 - V_{load,min})}{V_{EODV}}$$

Where

N_{max} = Maximum number of cells needed per battery

N_{min} = Minimum number of cells needed per battery

V_{dc} = Nominal voltage of the battery

$V_{charging}$ = Cell's charging voltage

$V_{load,\ max}$ = Maximum battery load tolerance computed in %

$V_{load,\ min}$ = Minimum battery load tolerance computed in %

V_{EODV} = End-of-discharge battery cell voltage

When choosing the number of cells between the two limits, always choose the average number of cells between the two limits for the best outcome.

Calculating Battery Capacity in Ampere-Hour

This can be computed by use of the following equation

$$C_{min} = \frac{E_{de}(k_{af}k_{tcf}k_{crt})}{V_{dc}k_{mdod}k_{se}}$$

Where

C_{min} = Minimum battery desired capacity

E_{de} = Total required energy over the backup time (VAH)

k_{tcf} = Temperature correction factor

k_{af} = The aging factor of the battery

k_{crt} = Battery capacity rating factor

k_{se} = System efficiency in percentage

k_{mdod} = Maximum discharge depth

V_{dc} = Nominal battery voltage

Make sure to choose the battery capacity which is more than the calculated minimum above.

Different Battery storage technologies and comparison of their performance:

Battery Energy Storage System:

➢ A battery energy storage system is a technology that stores electrical energy in rechargeable batteries for later use.

➢ These systems help balance supply and demand, improve grid reliability, and integrate renewable energy sources like solar and wind. BESS can range in size from small residential units to large-scale grid storage solutions used by utilities and industrial facilities.

➢ By storing excess energy when demand is low and discharging it when demand is high, BESS enhances energy efficiency, reduces reliance on fossil fuels, and provides backup power in case of outages.

➢ The choice of battery chemistry, such as lithium-ion, lead-acid, sodium-sulfur, or flow batteries, depends on factors like cost, lifespan, energy density, and application requirements.

Battery Chemistries and Their Characteristics

The performance, safety, and longevity of a battery energy storage system largely depend on its battery chemistry. Different chemistries offer unique advantages and trade-offs in terms of cost, energy density, cycle life, and fire risk, making it essential to select the right type for each application.

Battery Type	Fire Risk	Energy Density	Cost	Cycle Life	Environmental Impact	Charge/Discharge Speed
Lithium ion (Li-ion)	High	High	High	3,000-10,000 cycles	Moderate (mining impact)	Fast
Lead-Acid	Low	Low	Low	500-2,000 cycles	High (lead contamination)	Slow
Sodium-Based	Medium	Medium	Medium	3,000-5,000 cycles	Moderate (corrosion risk)	Medium

Battery Type	Fire Risk	Energy Density	Cost	Cycle Life	Environmental Impact	Charge/Discharge Speed
Flow Batteries	Low	Low	Medium	10,000+ cycles	Low	Slow
Nickel-Based	Medium	Medium	Medium	2,000-5,000 cycles	High (toxic metals)	Medium
Hydrogen Fuel Cells	Low	High	Very High	Unlimited (depends on fuel)	Low (emission-free)	Slow
Zinc-Air	Low	Medium	Low	500-2,000 cycles	Low	Slow
Supercapacitors	Low	Low	Medium	1,000,000+ cycles	Low (no toxic waste)	Utra-Fast
Solid-State	Low	High	Very High	10,000+ cycles	Low	Fast

Lithium-Ion Batteries (Li-ion)

Lithium-ion batteries are the dominant choice for modern Battery Energy Storage Systems due to their high energy density, efficiency, and long cycle life. They are widely used in grid storage, renewable energy integration, electric vehicles (EVs), and data center backup power.

The technology includes various chemistries, such as lithium iron phosphate (LFP) and nickel manganese cobalt (NMC), each offering different performance characteristics.

Pros:

High Energy Density: Stores more energy in a compact form, making it ideal for space-constrained applications.

Long Cycle Life: Can last thousands of charge-discharge cycles, reducing replacement costs over time.

High Efficiency: Round-trip efficiency often exceeds 90%, meaning minimal energy is lost during charge and discharge.

Fast Charging & Discharging: Suitable for applications that require rapid energy deployment, such as frequency regulation and grid balancing.

Low Maintenance: Unlike lead-acid batteries, Li-ion systems require minimal maintenance and have no memory effect.

Cons:

Fire Risk & Thermal Runaway: If improperly managed, Li-ion batteries can overheat and experience thermal runaway, leading to safety concerns. Advanced cooling and battery management systems (BMS) are necessary for safe operation.

Higher Cost: While prices have declined, Li-ion batteries remain more expensive than lead-acid alternatives.

Raw Material Constraints: Uses materials like lithium, cobalt, and nickel, which are subject to supply chain risks and geopolitical concerns.

Degradation Over Time: Capacity gradually declines with repeated charge-discharge cycles, especially in high-temperature environments.

End-of-Life Challenges: Recycling and disposal remain complex due to the battery's chemistry and the need for specialized recycling processes.

Common Lithium-Ion Battery Subtypes

Lithium Iron Phosphate (LFP)

Known for its safety, long lifespan, and thermal stability, LFP batteries are widely used in stationary energy storage and commercial BESS applications. They do not contain cobalt, making them more sustainable and cost-stable, but they have lower energy density than NMC.

Nickel Manganese Cobalt (NMC)

Offers higher energy density, making it ideal for space-constrained applications like electric vehicles and high-performance BESS. However, it is more expensive, has a shorter lifespan than LFP, and requires careful thermal management to prevent overheating.

Lead-Acid Batteries (PbA)

Lead-acid batteries are one of the oldest and most widely used energy storage technologies, valued for their low cost and reliability. They are commonly found in uninterruptible power supplies (UPS), telecommunications backup, and industrial applications where affordability and ease of maintenance are priorities.

Pros:

Low Cost: One of the most affordable battery chemistries, making it an accessible option for backup power.

Proven and Reliable: A mature technology with a long history of dependable performance in various industries.

High Surge Power: Capable of delivering high current for short durations, which is beneficial for backup power applications.

Cons:

Short Cycle Life: Typically lasts only a few hundred to a few thousand charge cycles, limiting long-term viability.

Heavy and Bulky: The high weight and large size make lead-acid batteries less practical for applications requiring space efficiency.

Limited Depth of Discharge (DoD): Frequent deep discharges significantly shorten the battery's lifespan.

Environmental Concerns: Contains toxic lead and sulfuric acid, requiring proper recycling and disposal to mitigate environmental impact.

Sodium-Based Batteries

Sodium-based batteries are a promising alternative to lithium-ion for energy storage, offering lower costs, improved safety, and greater sustainability by using abundant sodium instead of scarce materials like lithium and cobalt. The two main types are

Sodium-Ion (Na-ion) Batteries, which function similarly to lithium-ion but at a lower cost, making them ideal for grid storage and backup power, and Sodium-Sulfur (NaS) Batteries, which operate at high temperatures and are well-suited for long-duration utility-scale energy storage.

Pros:

Lower Cost: Uses abundant sodium instead of expensive lithium, nickel, or cobalt.

Enhanced Safety: Lower risk of thermal runaway compared to lithium-ion.

Sustainability: No reliance on rare or geopolitically sensitive materials.

Good Cycle Life: Sodium-sulfur batteries, in particular, have long operational lifespans.

Cons:

Lower Energy Density: Requires more space than lithium-ion for the same energy capacity.

High Operating Temperatures (NaS): Sodium-sulfur batteries need insulation and careful thermal management.

Still Developing: Sodium-ion technology is not yet as commercially mature or widely available as lithium-ion.

Flow Batteries

Flow batteries are a scalable and long-duration energy storage solution that store energy in liquid electrolytes housed in external tanks. Unlike conventional batteries, where energy is stored in solid electrodes, flow batteries allow for independent scaling of power and energy capacity by adjusting the size of the electrolyte tanks. This makes them ideal for grid storage, renewable energy integration, and large-scale backup power.

Pros:

Long Cycle Life: Can last for tens of thousands of cycles without significant degradation.

Scalability: Energy storage capacity can be expanded by increasing electrolyte volume.

Non-Flammable: Uses liquid electrolytes, reducing fire risks compared to lithium-ion.

Deep Discharge Capability: Can discharge fully without damaging battery life.

Cons:

Lower Energy Density: Requires large tanks, making it impractical for space-constrained applications.

High Initial Cost: Expensive upfront due to complex system components.

Lower Efficiency: Typically has lower round-trip efficiency compared to lithium-ion batteries.

Nickel-Based Batteries

Nickel-based batteries, including Nickel-Cadmium (NiCd) and Nickel-Metal Hydride (NiMH), have been widely used in energy storage and industrial applications due to their durability, reliability, and ability to operate in extreme temperatures. While less common in large-scale BESS today, they still play a role in certain applications requiring high power output and long lifespan.

Pros:

Durability: Resistant to extreme temperatures and harsh environments.

Long Cycle Life: Can withstand thousands of charge/discharge cycles with minimal degradation.

High Discharge Rate: Provides strong power output when needed.

Cons:

Toxic Materials (NiCd): Cadmium is hazardous and requires careful disposal.

Lower Energy Density: Bulkier than lithium-ion, making it less efficient for high-capacity storage.

High Cost (NiMH): More expensive than some alternatives without significant performance advantages.

Supercapacitor

Supercapacitor is an electrochemical capacitor that has high energy density and better performance efficiency as compared to the common capacitor, the reason why it has the prefix 'super 'attached to it. It stores and releases energy by reversible desorption and adsorption of ions at the electrode-electrolyte interface.

Conventional capacitors have low energy density with wider cell voltage and higher specific power. On the other hand, supercapacitors have high capacitance over a lower limit of cell voltage.

Let us understand the structure of the supercapacitor:
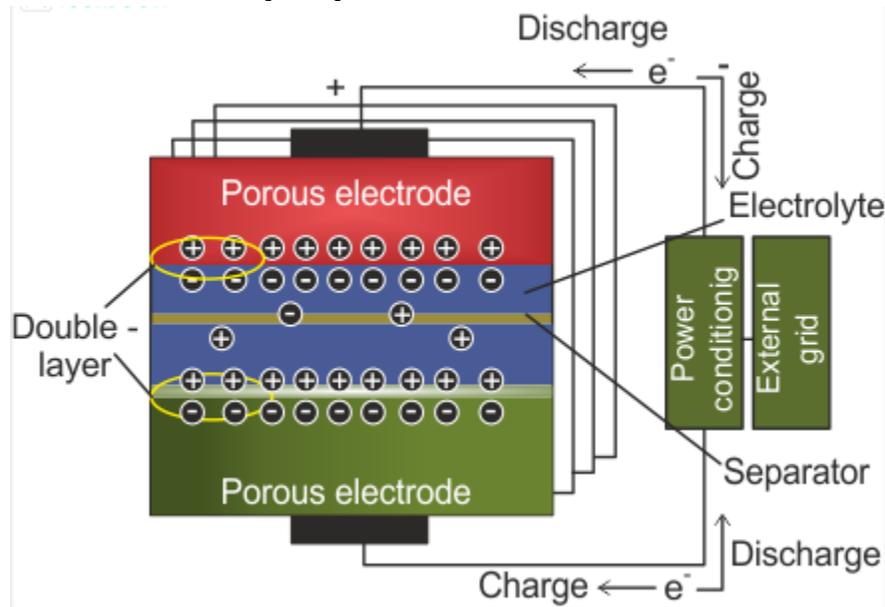
Supercapacitors are made up of two electrodes, an electrolyte and a porous membrane separator. This specific structure of supercapacitors makes them have the features of conventional capacitors as well as electrochemical batteries.

Nanomaterial-based supercapacitors are used to increase the electrode surface area so as to achieve high performance and enhanced capacitance.

Let us now move to learn more about the types and properties of supercapacitors.

Types of Supercapacitors

Supercapacitors are also referred to as gold capacitors, power capacitors, ultracapacitors or super condensers.

On the basis of their charge storage mechanism, these are classified into three types:

1. Electrostatic double-layer capacitors

2. Pseudo capacitors

3. Hybrid capacitors

Electrostatic Double-Layer Capacitor (EDLC)

This type of capacitor works on the charge storage mechanism where a charge is physically stored on the surface of the electrodes without causing any irreversible chemical reactions via the formation of an electrical double layer. Usually, carbon-based electrodes are used in supercapacitors which are separated by a dielectric

substance that acts as an insulator and possesses electrical properties that eventually affect the performance of the supercapacitor.

Charges are electrostatically stored in supercapacitors. An electric field is generated at each electrolyte as soon as the voltage is applied across the terminals which leads to the polarisation of the electrolyte. As a result of which ions diffuse through the dielectric to the porous electrodes of opposite charges. In such a way, the formation of an electric double layer takes place at each electrode. This results in the increased surface area of each electrode and decreased distance between the electrodes.
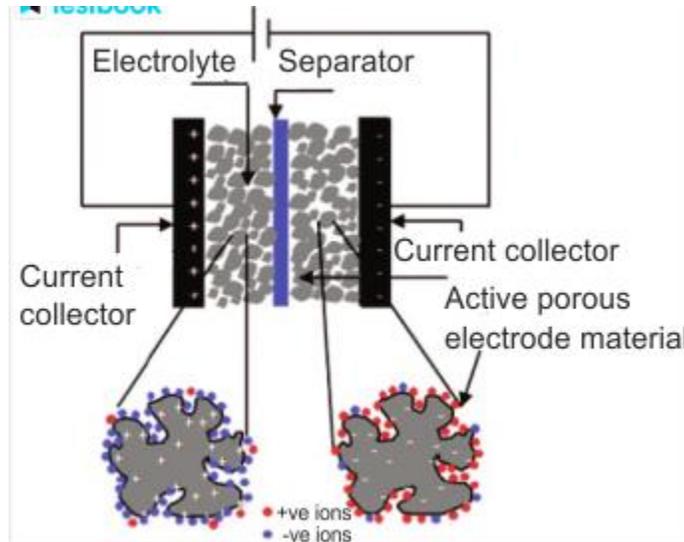
Pseudo Capacitors

Pseudo-capacitors are also called faradaic supercapacitors. These devices use electrodes made up of redox-active materials such as metal oxides and conducting polymers (polyanilines, polypyrroles, and polythiophenes). These electrodes store charge through reversible faradaic reaction mechanisms, near the electrode or at the electrode surface where charges are transferred across the metal-electrolyte interface.

Pseudocapacitance with specifically adsorbed ions
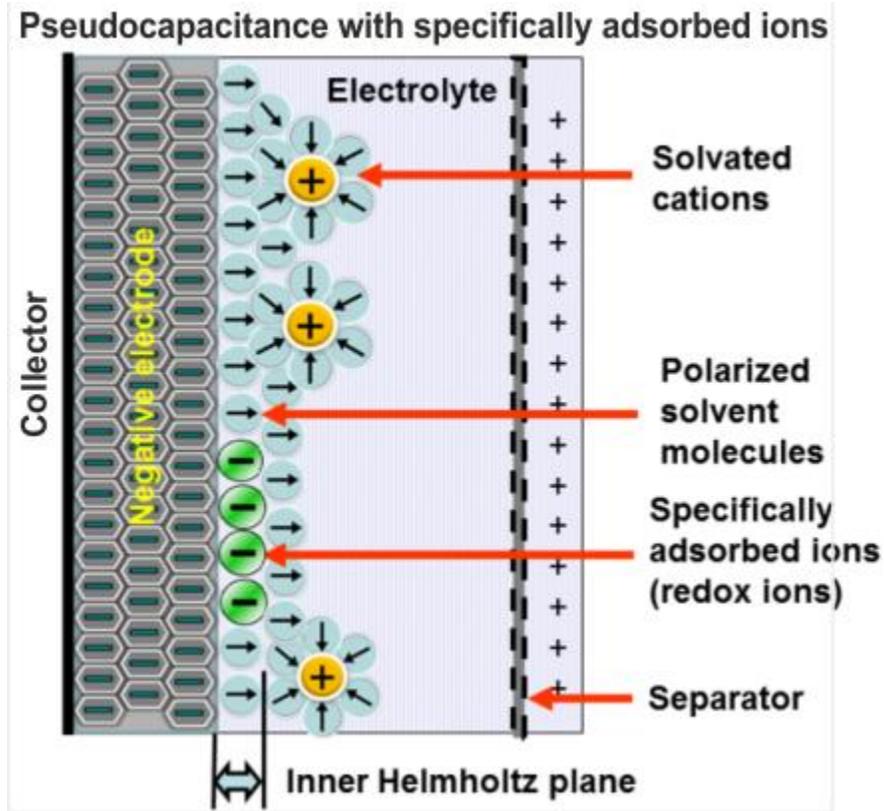
Hybrid Capacitors

These capacitors have adopted both the mechanisms of EDLC and pseudo capacitors. Hybrid capacitors are composed of electrodes with different characteristics based on chemical as well as electrical mechanisms. As a result, one electrode exhibits electrostatic capacitance and the other provides electrochemical capacitance. The advantage includes higher operating voltage (3.8 V maximum), increased capacitance and energy density.
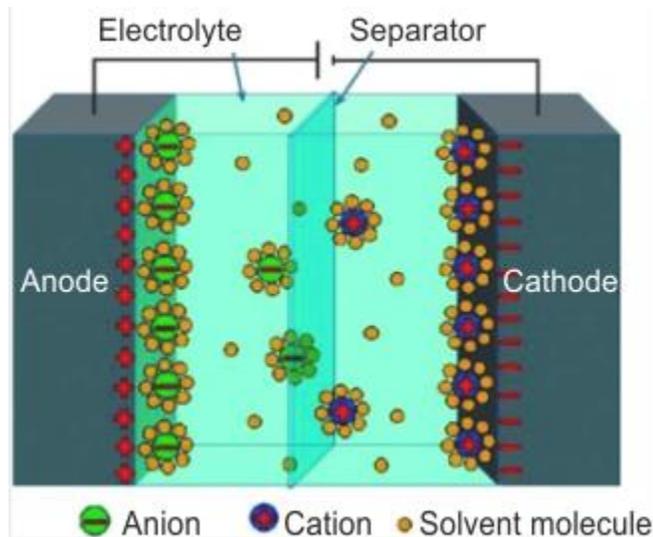
Properties of Supercapacitors

Some properties of supercapacitors are listed in the points below:

- o Supercapacitors have a long cycling time, with a high cycle efficiency (84-97%) and this is considered to be one of the most important features of supercapacitors.

- o Supercapacitors have capacitance ranging from 1mF to >10kF

- Supercapacitors have a high energy density of up to 10 Wh/kg

- There is less potential for pollution in supercapacitors as no heavy metals are used in their development.

- The charge/discharge time of supercapacitors ranges from milliseconds to a few seconds.

- Supercapacitors come up with the property of a longer service life of about 10-15 years

- As supercapacitors have higher capacitance with lower voltage limits, they are preferred over batteries and conventional capacitors.

Hydrogen Fuel Cells

Hydrogen fuel cells are an emerging energy storage and power generation technology that convert hydrogen into electricity through an electrochemical reaction, producing only water and heat as byproducts. Unlike traditional batteries, fuel cells do not store

energy directly but generate electricity on demand, making them suitable for long-duration backup power, grid support, and remote energy applications.

Pros:

High Energy Density: Capable of storing large amounts of energy for extended use.

Zero Emissions: Produces only water as a byproduct, making it environmentally friendly.

Long Duration Storage: Can store energy for weeks or months, unlike conventional batteries.

Cons:

High Infrastructure Costs: Requires specialized storage, transportation, and refueling systems.

Lower Efficiency: Energy conversion losses make it less efficient than direct battery storage.

Hydrogen Production Challenges: Most hydrogen today is derived from fossil fuels, limiting sustainability unless sourced from renewables.

Zinc-Air Batteries

Zinc-air batteries use oxygen from the air as a reactant, combining it with zinc to generate electricity. This design makes them lightweight, cost-effective, and energy-dense, making them an attractive option for long-duration energy storage and renewable energy integration. While traditionally used in hearing aids and small electronics, advancements in zinc-air technology are positioning them for large-scale

BESS applications.

Pros:

Low Cost: Uses abundant zinc, making it cheaper than lithium-ion.

High Energy Density: Provides more energy storage per unit weight than many traditional batteries.

Non-Toxic & Environmentally Friendly: Does not rely on hazardous materials like lead or lithium.

Cons:

Limited Rechargeability: Traditional zinc-air batteries are not fully rechargeable, though new developments are improving this.

Lower Power Output: Not ideal for applications requiring rapid discharge.

Air Management Requirements: Sensitive to humidity and air quality, affecting performance.

Supercapacitors

Supercapacitors, also known as ultracapacitors, store energy through electrostatic charge rather than chemical reactions like traditional batteries. This allows them to charge and discharge extremely quickly, making them ideal for applications requiring rapid power delivery and short-term energy storage. While they are not typically used as primary energy storage in BESS, they are often combined with batteries to enhance performance, efficiency, and lifespan.

Pros:

Ultra-Fast Charging & Discharging: Can deliver high power almost instantly.

Extremely Long Cycle Life: Can withstand millions of charge-discharge cycles without significant degradation.

High Efficiency: Minimal energy loss during charge and discharge.

Cons:

Low Energy Density: Cannot store as much energy as lithium-ion or other battery chemistries.

Short Duration Storage: Best suited for seconds to minutes, not long-term energy storage.

Higher Cost per kWh: More expensive than traditional batteries for large-scale energy

storage.

Solid-State Batteries

Solid-state batteries replace the liquid electrolyte found in traditional lithium-ion batteries with a solid electrolyte, improving safety, energy density, and lifespan. This next-generation technology is being developed for electric vehicles (EVs), consumer electronics, and eventually large-scale energy storage applications. While not yet widely used in BESS, solid-state batteries hold promise for higher efficiency and enhanced thermal stability.

Pros:

Higher Energy Density: Can store more energy in a smaller footprint than conventional lithium-ion batteries.

Improved Safety: Eliminates flammable liquid electrolytes, reducing fire risk and thermal runaway.

Longer Lifespan: Less degradation over time, leading to more charge cycles and lower replacement costs.

Cons:

High Cost: Expensive materials and complex manufacturing processes limit commercial adoption.

Scalability Challenges: Large-scale production for BESS is still in early development.

Limited Availability: Most solid-state batteries are still in research or early prototype stages.

Factors to Consider When Choosing BESS Battery Chemistry Type

Selecting the right battery chemistry for a battery energy storage system depends on several key factors, each influencing the system's performance, safety, and cost-effectiveness.

1. Storage Capacity

The total amount of energy a battery can store is crucial for determining how long it can supply power. Applications requiring extended energy discharge, such as grid storage or microgrids, may favor high-capacity chemistries like lithium-ion (LFP/NMC) or flow batteries.

2. Power Output

Some applications need batteries capable of delivering high bursts of power in short

durations, such as frequency regulation and backup power. Lithium-ion (NMC) and lead-acid batteries are often chosen for their ability to handle high power demands, while flow batteries are better suited for steady, long-duration discharge.

3. Operating Conditions

Temperature and environmental factors impact battery performance and lifespan. LFP batteries are more thermally stable and perform well in high-temperature environments, while sodium-sulfur (NaS) batteries operate at high temperatures and require insulation. Cold climates may require additional heating or management systems for certain chemistries.

4. Cycle Life

The number of charge and discharge cycles a battery can undergo before its capacity significantly degrades affects long-term costs and maintenance. LFP and flow batteries typically offer longer cycle life than NMC or lead-acid batteries, making them more suitable for applications requiring frequent cycling.

5. Cost

Initial capital costs and long-term operational expenses vary by chemistry. Lead-acid and sodium-sulfur batteries have lower upfront costs but may require more frequent replacements. Lithium-ion batteries, particularly LFP, offer a balance between cost, longevity, and performance, while flow batteries can have high initial costs but lower lifetime costs due to their extended cycle life.

Battery Types: Efficiency vs. Cost in BESS
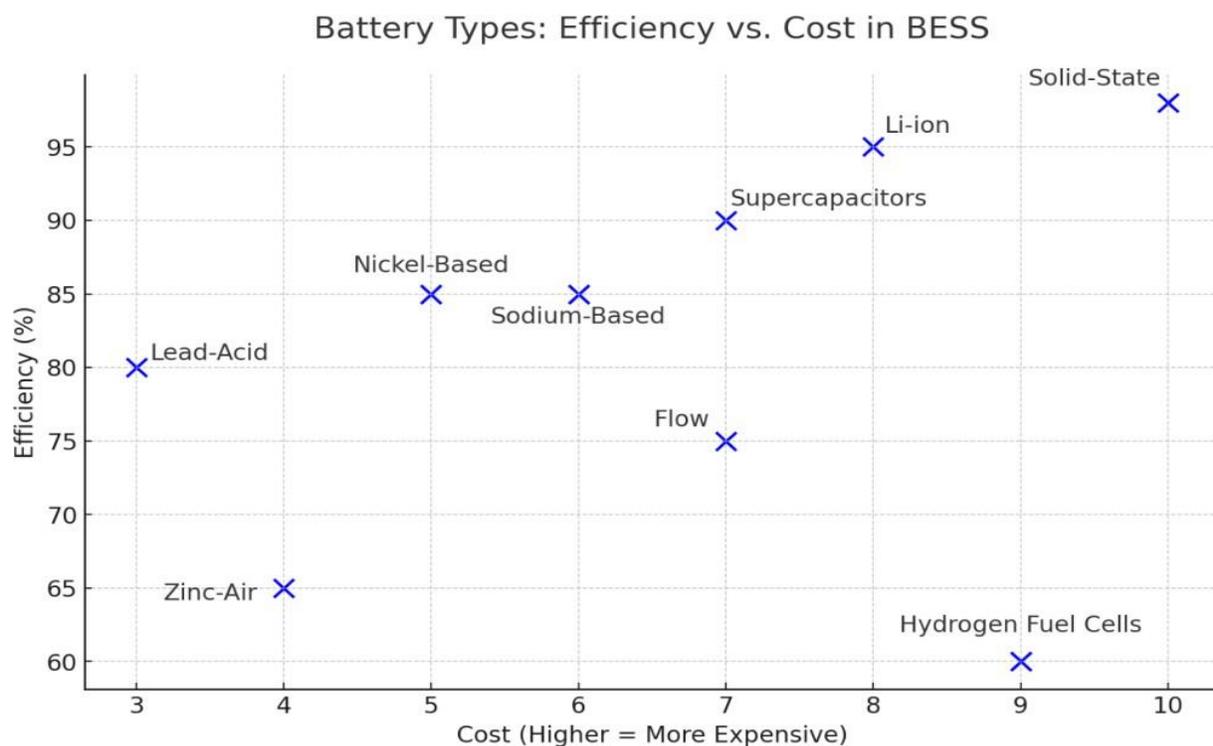
Historical Development of Green Energy

1. Introduction

Green Energy refers to energy derived from renewable, environmentally sustainable sources that produce minimal greenhouse gas emissions. These include:

- Solar Energy

- Wind Energy

- Hydropower

- Biomass Energy

- Geothermal Energy

- Ocean Energy

Green energy development has evolved through **technological innovation, energy crises, environmental policy, and economic transitions**.

1. Ancient Foundations (Pre-1800s)
Long before electricity, civilizations harnessed natural energy:

Wind: Used as early as 5000 BC to sail boats on the Nile. Windmills for grinding grain and pumping water were used in Persia and China by 200–600 AD.

Solar: Greeks and Romans used "burning mirrors" (concentrated sunlight) to light torches as early as 300 BC.

Hydropower: Waterwheels were used by Greeks and Romans to grind grain.

Geothermal: Used for bathing and heating in the Paleolithic(Old Stone Age (c. 3.3 million years ago – 10,000 BCE)) era and by Romans.

2. Scientific Revolution & Early Technology (1800s–1950s)

The 19th century brought the understanding of physics principles required for modern green energy.

Solar: Edmond Becquerel discovered the photovoltaic effect in 1839. Augustin Mouchot developed a solar-powered engine in the 1860s.

Wind: The first wind turbines for electricity generation were developed in the late 1880s by James Blyth in Scotland and Charles Brush in the US.

Hydropower: The first hydroelectric power plant began operation in Wisconsin, USA, in 1882.

Geothermal: The first commercial, dry steam geothermal power plant was constructed in Italy in 1913.

3. The 1970s Energy Crisis & Resurgence

Following a decline in renewable interest due to cheap fossil fuels during the Industrial Revolution, the 1970s oil crisis served as a major turning point.

Wind: The crisis spurred development, leading to the "Danish concept" of three-blade wind turbines in the late 1970s.

Solar: In 1954, Bell Labs created the first practical silicon photovoltaic cell, but the 1970s oil crisis truly accelerated research into commercial applications.

Policy: Governments started investing heavily in research and development to achieve energy independence.

4. Modern Era: Mainstreaming (1990s–Present)

The late 20th and 21st centuries saw rapid scaling driven by climate change concerns and falling costs.

Offshore Wind: The world's first offshore wind farm was installed in Denmark in 1991.

Policy Support: Germany's "100,000 Roofs" programme (1999) and Renewable Energy Sources Act (2000) introduced feed-in tariffs that revolutionized the solar market.

Growth: From 2000–2022, renewable energy capacity grew more than 4-fold, from 754 GW to 3,372 GW.

Cost Reductions: Solar PV module costs fell by 85% over the decade leading to 2024.

Current Status: As of early 2025, clean electricity surpassed 40% of global generation for the first time.

Source: BP Statistical Review of World Energy June 2016
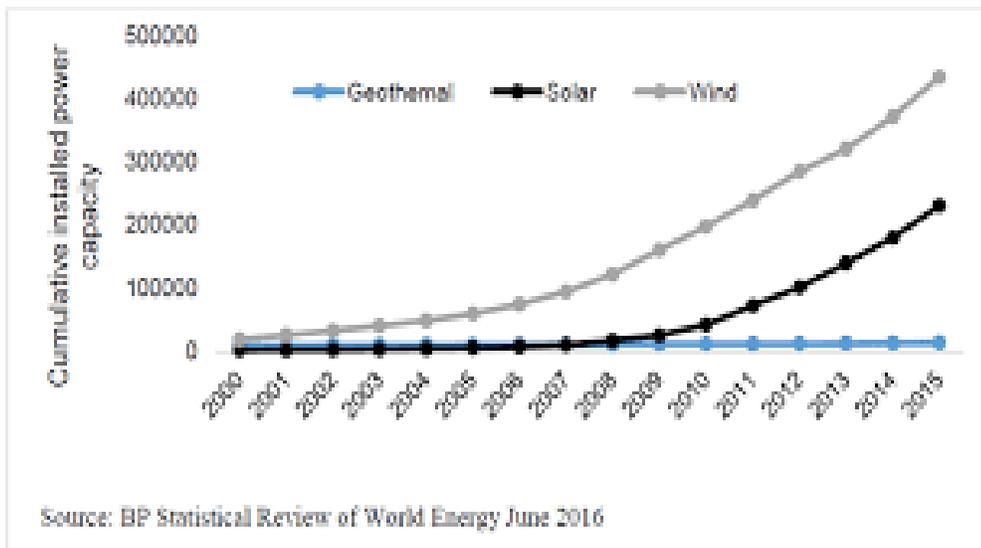
Figure-4. Historical trend of renewable energy sources

2. Evolutionary Phases of Green Energy

I. Pre-Industrial Renewable Era (Before 1800)

Dominant Energy Sources

- Biomass (wood combustion)
- Windmills
- Water wheels

- Animal power –

Types of Work Done Using Animal Power

Application	Type of Mechanical Work
Ploughing	Linear traction
Transportation (carts)	Pulling force
Water lifting	Rotational motion
Grain milling	Rotary shaft work
Oil extraction	Circular torque

Example:

Large-scale windmill usage in **Netherlands** for drainage and grain milling.

Technical Characteristics

- Purely mechanical conversion

- No electrical generation

- Localized energy usage

- Zero grid dependency

- ❖ Energy conversion efficiency was low, but sustainability was inherently high.

II. Birth of Renewable Electricity (1800–1900)

Scientific Breakthroughs

1. Photovoltaic Effect (1839)

Discovered by **Edmond Becquerel**

Principle:
When light strikes certain materials, electrical current is produced.

2. First Hydroelectric Power Plant (1882)

Established in **Appleton**

Hydropower Working Diagram

Power Equation P=ρgQHη

Where:

- **ρ**= Density of water

- **(Q)** = Flow rate

- **(H)** = Head

- **Hη**= Efficiency

3. Early Wind Turbines

Wind electricity development in **Denmark**

Key Engineering Advancement

Transition from:

Mechanical Energy → Electromechanical Energy Conversion

III. Fossil Fuel Dominance (1900–1970)

Characteristics

- Coal-based thermal power plants dominate
- Oil expansion
- Centralized grid systems developed
- Renewable research stagnates

Limitations Identified
- Air pollution
- Carbon emissions
- Finite fuel reserves

IV. Energy Crisis and Renewable Revival (1970s)

Trigger Event:

1973 Oil Crisis (OPEC embargo) - The **OPEC embargo** refers to the 1973 oil export ban imposed by the **Organization of the Petroleum Exporting Countries (OPEC)** on certain Western nations.

It is also called the **1973 Oil Crisis**.

V. Environmental Policy Era (1990–2010)

Climate Awareness

1. UN Framework Convention (1992)

Led by **United Nations**

2. Kyoto Protocol - The Kyoto Protocol is an international climate agreement adopted in 1997 in Kyoto, Japan, under the framework of the United Nations.

It legally required developed countries to reduce greenhouse gas (GHG) emission

Period	Technology Level	Grid Integration	Policy Support	Renewable Sha
Pre-1800	Mechanical	No	None	High
1800–1900	Early Electrical	Local	Minimal	Moderate
1900–1970	Thermal Dominanc	Centralized	Low	Low
1970–1990	Research Stage	Limited	Moderate	Growing
1990–2010	Commercial Stage	Grid-connected	Strong	Significant
2010–Prese	Smart & Digital	High	Global	Rapid Growth

Fuel Cell Working Principle and Schematic Diagram:

Fuel Cell Working Principle explains that it is an electrochemical device that converts chemical energy of a conventional fuel directly into low voltage D.C. electrical energy. It is then described as a primary battery in which fuel and oxidizer are stored external to the battery and fed to it when needed.

A schematic diagram of fuel cell is shown in Fig.4.57. The fuel gas is diffused through the anode and is oxidized, thus releases electrons to the external circuit. The oxidizer is diffused through the cathode and is reduced by the electrons coming from the anode through the external circuit.
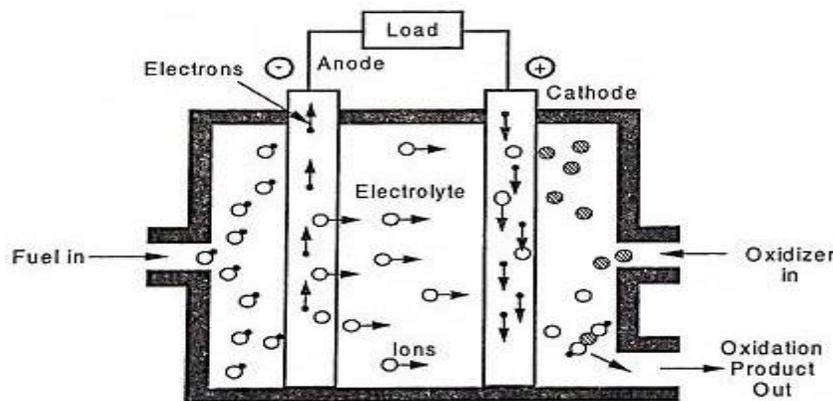
Fig:4.57 Fuel Cell

The fuel cell keeps permitting the fuel molecule to mix with the oxidizer molecules, and allow the transfer of electron by a metallic path that contains a load.

Hydrogen-oxygen fuel cell:

This fuel cell uses hydrogen as fuel and oxygen as an oxidiser. A typical hydrogen-oxygen fuel cell is shown in the Fig.4.58.
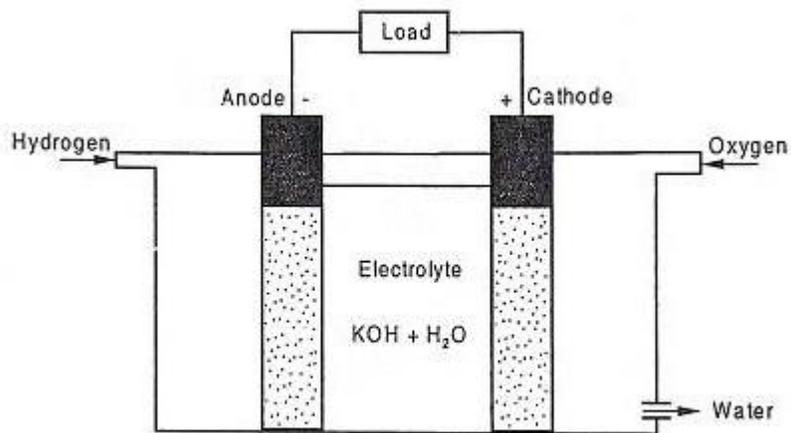
Fig:4.58 Hydrogen - Oxygen Fuel Cell

There are three chambers separated by two porous electrodes, the anode and cathode. The middle chamber between the two electrodes is filled with electrolyte (strong solution of potassium hydroxide). The electrodes surfaces are chemically treated to repel the electrolyte in order to restrict the flow of potassium hydroxide to the outer chambers.

The gases diffuse through the electrodes by undergoing the following reaction.

At Anode: $2H_2 \longrightarrow 4H^+ + 4e^-$

At Cathode: $4H^+ + 4e^- + O_2 \longrightarrow 2 H_2O$

Overall cell reaction: $2H_2 + O_2 \longrightarrow 2H_2O$
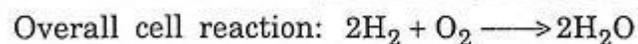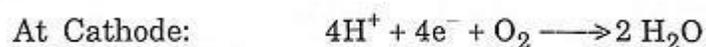
When the temperature is high, the electrolyte material acts as a sieve(mesh) and the hydrogen ions migrates through the material. An electrical load is connected between the anode and the cathode.

The chemical reaction in the cathode, the energy representing the enthalpy (the sum of its internal energy and the product of its pressure) of combustion of fuel is released and a part of it is available for conversion into electrical energy.

The water formed is drawn off from the side.

Advantages of fuel cells:

1. Conversion efficiency is high.

2. Easy and simple construction.

3. Require very little attention and maintenance.

4. High power to weight ratio.

5. Fuel cell does not make any noise.

6. Less space required.

7. Quick operation.

8. Can be installed at the use point.

Disadvantage of fuel cell:

1. It is very costly.

2. Short service life.

3. Low voltage output.

4. Proper attention is needed while selection of materials.

Application of fuel cell:

There are numerous applications of fuel cell because of its compact size and easy to handle nature. Some of the main areas of applications are

1. Domestic use

2. Automotive vehicle

3. Central power station

Fuel Cell:

Fuel cells convert chemical energy directly into electrical energy.

• Difference with batteries: fuel cells require a fuel to flow in order to produce electricity.

• Heat is produced from chemical reaction and not from combustion.

Types of fuel cells:

Proton exchange membrane (PEMFC).

Direct Methanol fuel cell (DMFC)

Alkaline fuel cell (AFC).

Phosphoric acid fuel cell (PAFC) (*)

Molten-carbonate fuel cell (MCFC) (*)

Solid-oxide fuel cell (SOFC) (*)

Suitable for microgrids.

Fuel cells operation

The hydrogen atom's electron and proton are separated at the anode. Only the protons can go through the membrane (thus, the name proton exchange membrane fuel cell).

$$H_2 \rightarrow 2H^+ + 2e^-$$

$$1/2O_2 + 2H^+ + 2e^- \rightarrow 1H_2O$$

$$O_2 + 2H_2 \rightarrow 2H_2O \qquad (E_r = 1.23\ V)$$
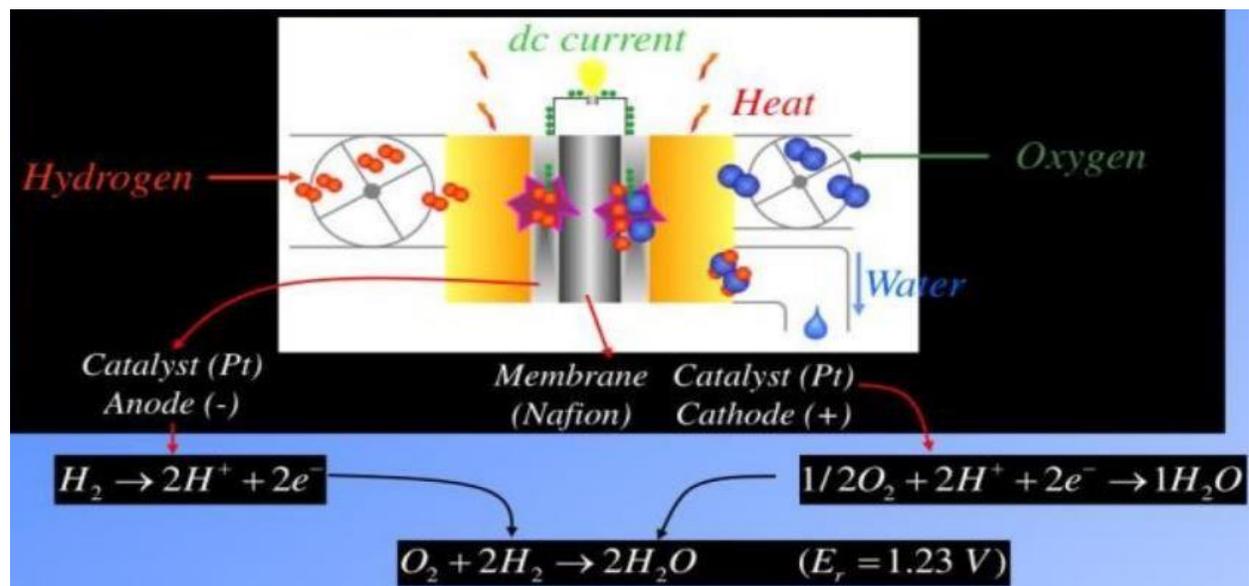
The first law of thermodynamics:

The energy of a system is conserved

$$\delta Q - \delta W = dE$$

In conservational fields, potential functions change depend only on initial and final values. Hence,

$$Q - W = \Delta E$$

For a closed system (control mass system), such as a piston

$$\Delta E = \Delta U + \Delta K + \Delta P$$

(The total energy change equals the sum of the change in internal energy, the change in kinetic energy, and the change in potential energy)

For an open system with mass flow across its boundaries (control volume), such as a steam turbine

$$\Delta E = \Delta U + \Delta K + \Delta P + \Delta(pV)$$

pV represents the work to keep the fluid flowing (p is pressure and V is volume). Hence, if a magnitude called enthalpy H is defined as,

$$H = U + pV$$

Then, $$\Delta H = \Delta E - \Delta K - \Delta P$$

If we use the 1st law of thermodynamics for a stationary control volume (i.e. the kinetic and potential energies are constant in time, then

$$\Delta H = Q - W$$

Thus, the enthalpy is the difference between the heat and the work involved in a system such as the one defined immediately above.

If the change in enthalpy is negative, heat is liberated and the reaction occurs spontaneously (contrary to endothermic reactions that requires to apply heat in order for the reaction to occur).

In the anode: $H, 2H^+ + 2e^-$, $\Delta H = 0$ kJ

In the cathode: $1/2O_2 + 2H^+ + 2e^- \rightarrow 1H_2O$, $\Delta H = -285.8$ KJ

Hence, in a PEMFC, 285 kJ/mol are converted into heat (Q) and electricity (W).

Entropy: it is a property that indicates the disorder of a system or how much reversible is a process. This last definition relates entropy to energy "quality".

In a reversible isothermal process involving a heat transfer (Q_{rev}) at a temperature (T_o) the entropy is defined as

$$\Delta S = \frac{Qrev}{To}$$

In all processes involving energy conversion or interactions AS is nonnegative. 4S is zero only in reversible processes.

For any process then

$$\Delta S \geq \frac{Q}{T}$$

The "=" in the above relationship will give us the minimum amount of heat

Q_{min} required in a process.

From the enthalpy definition a fuel cell can be considered as a system like the following one
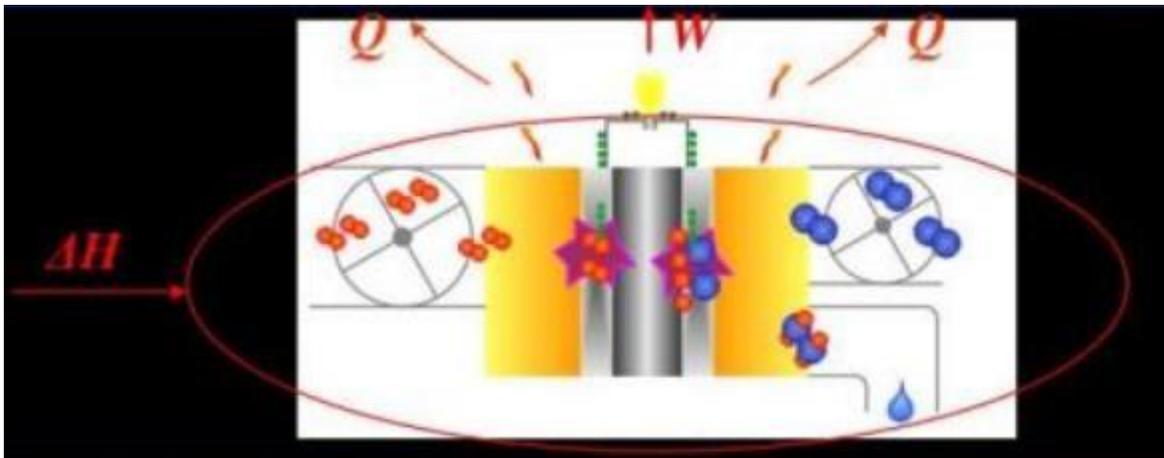
The maximum possible efficiency for a fuel cell is, then

$$\eta_{max} = \frac{W}{\Delta H} = 1 - \frac{Qmin}{\Delta H}$$

An alternative derivation involves using "Gibbs Free Energy"

The definition of entropy relates with the 2nd Law of Thermodynamics. One of its interpretations is that it is impossible to convert all the energy related with irreversible processes, such as heat or chemical energy, into work.

Hence, it is possible to define a magnitude with units of energy called Gibbs Free Energy that represents the reversible part of the energy involved in the process.

Hence, for fuel cells, the electrical work represents the Gibbs Free Energy and the maximum possible energy conversion efficiency is

$$\eta_{max} = \frac{\Delta G}{\Delta H}$$

In the anode: $H, 2H^+ + 2e^-$, $\Delta G = 0$ kJ

In the cathode: $1/2O_2 + 2H^+ + 2e^- \rightarrow 1H_2O$, $\Delta G = -237.2$ KJ

ΔH equals 285 kJ/mol.

$$\eta_{max} = \frac{\Delta G}{\Delta H} = \frac{237.2}{285} = 0.83$$

The Gibbs Free Energy can also be used to calculate the output voltage of an ideal fuel cell. Since the Gibbs Free Energy equals the electrical work, and the electrical work equals the product of the charge and voltage, then

$$W = \Delta G = -2FE_o$$

where F is the Faraday constant (charge on one mole of electrons) the factor of two represents the fact that two electrons per mole are involved in the chemical reaction.

Thus,

$$E_0 = \Delta G/-2F$$

and since F = 96,485 C/mole and AG = -237.2 kJ/mole, then

$$\textbf{Eo} = \frac{\textbf{(}-\textbf{237200)}}{\textbf{(2)(96485)}} = \textbf{1.299} = \textbf{1.23 V}$$

E is also denoted by E, the reversible voltage.

Hydrogen Fuel Cell:

A hydrogen fuel cell uses the chemical energy of hydrogen to produce electricity. It is a clean form of energy with electricity, heat and water being the only products and by-products. Fuel cells offer a variety of applications, from transportation to emergency back-up power, and can power systems as large as a power plant or as small as a laptop.

Working of Hydrogen Fuel Cell:
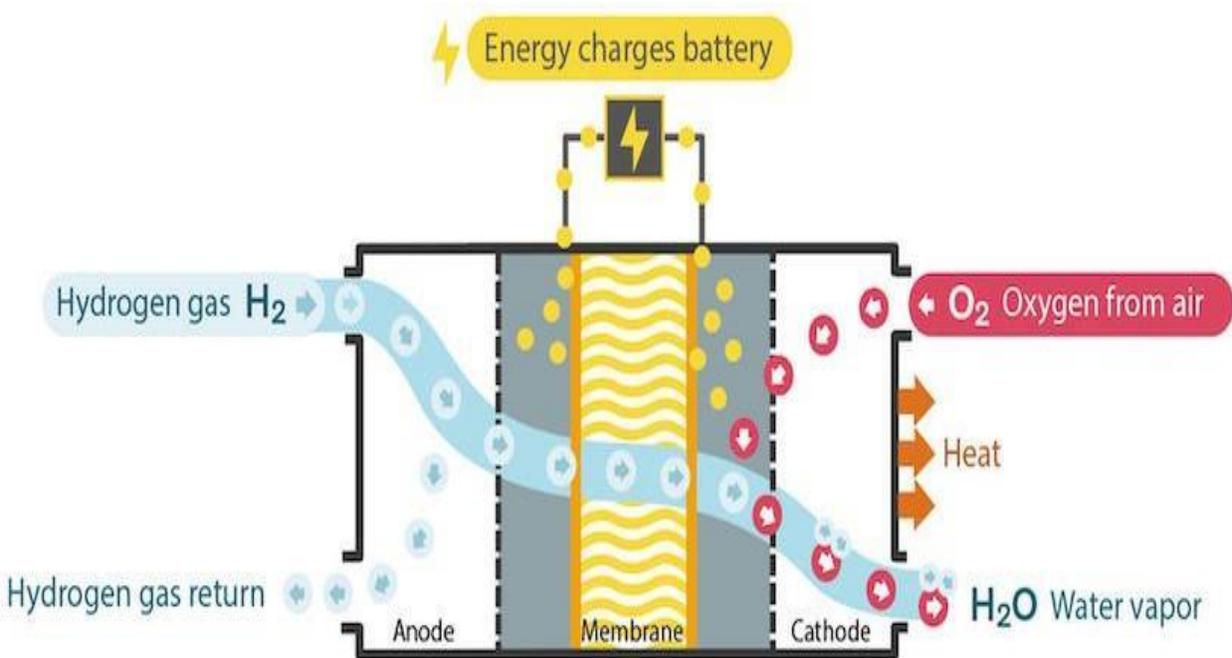
- ➢ Hydrogen atoms enter the fuel cell at the anode, while oxygen is fed to the cathode.
- ➢ The fuel cell consists of a membrane coated with a catalyst. When the hydrogen molecules hit the catalyst, they're split into hydrogen ions and electrons.
- ➢ The membrane lets positively charged hydrogen ions pass through, but not the negatively charged electrons, which instead flow through an electric circuit where the electric current is generated.
- ➢ At the cathode side, the hydrogen ions, electrons and the oxygen in the air combine to produce heat
- ➢ In order to produce enough electricity to be able to propel a vehicle, a complete fuel cell system consists of several hundred membranes stacked together.
- ➢ The fuel cell system is adequate for normal use, but whenever extra power is needed, it's provided by a battery on the machine. When the fuel cells produce more power than the machine currently needs, the excess energy can be used to charge the battery. The battery is also charged by regenerative braking.
- ➢ A control unit balances the dynamics between the fuel cells and the battery to optimize the use of energy.
- ➢ So in principle, a fuel cell works much like a battery, except that it generates its own electricity from the hydrogen onboard rather than being charged from an external source. Fuel cells also won't run down or need recharging as long as the

fuel source (hydrogen) is supplied. Again, this means they can deliver longer driving ranges, and therefore are more feasible for long-haul transportation and for powering heavier construction equipment.

➢ An added benefit of hydrogen fuel cell technology is that, without an internal combustion engine, hydrogen-powered machines will be comparable to the low noise levels of electric machines.

The process by which a fuel cell works can be summarized as follows:

1. Hydrogen atoms enter at the anode, while oxygen is fed to the cathode

2. The hydrogen atoms are separated into protons and electrons at the anode

3. The now positively charged protons pass through the membrane (or electrolyte) to the cathode, with the negatively charged electrons take a different route as they are forced through a circuit to generate electricity

4. After passing through the circuit and the membrane accordingly, the electrons and protons meet at the cathode where they combine with oxygen to produce heat and water as by-products.

Single fuel cells do not generate a large amount of electricity, so they are arranged into stacks to create enough power for their intended purpose, whether that is powering a small digital device or a power plant.

Fuel cells work like batteries but, unlike batteries, they will not run down or need recharging and can continue to produce electricity while the fuel source (in this case, hydrogen) is supplied.

Being comprised of an anode, cathode and an electrolyte membrane, there are no moving parts in a fuel cell, making them silent in operation and highly reliable.

Advantages

- Durability
- Energy Security
- Fuel Flexibility
- High Efficiencies

- Low / Zero Emissions

- Quiet Operation

- Reliability

- Scalability

The challenges associated with fuel cells include:

Disadvantages:

The cost of fuel cells can be high given the use of platinum as one of the largest component materials. There is work underway to find non-platinum catalyst approaches

Applications of Hydrogen Energy:

Hydrogen energy applications span transportation, industry, and power generation, acting as a clean fuel source that emits only water. Key uses include powering fuel cell electric vehicles (cars, buses, trucks), industrial processes like ammonia production and oil refining, renewable energy storage, and manufacturing (steel, glass).

Applications

- **Transportation Fuel Cell Electric Vehicles (FCEVs):** Hydrogen is used to power fuel cell electric vehicles (FCEVs), including cars, buses, trains, and heavy-duty trucks, offering longer ranges and faster refuelling than battery electric vehicles.

- **Industrial Processes and Feedstock:**

  - **Ammonia Production:** A major industrial use involves combining hydrogen with nitrogen to produce ammonia for fertilizers and chemicals.

  - **Petroleum Refining:** Hydrogen is used to desulfurize fuels, lower their sulfur content, and process crude oil.

  - **Metal Processing:** Hydrogen is utilized in welding, annealing, and reducing iron ore in steel manufacturing to replace fossil fuels.

- **Power Generation and Storage:**

  - **Energy Storage:** Hydrogen serves as a storage medium for excess electricity generated from renewable sources like wind and solar.

  - **Electricity Production:** Fuel cells can provide electricity in stationary applications, such as power plants or for off-grid and backup power.

- **Heating and Emerging Uses:**

  - **Heating Systems:** Hydrogen is being integrated into heating systems for buildings and industrial applications.

  - **Aerospace:** Hydrogen is used as a propellant for rockets and in fuel cells for spacecraft.

  - **Material Handling:** Fuel cells power forklifts and other equipment in large warehouses.

Hydrogen, especially green hydrogen produced from renewables, is critical for achieving energy security and reducing carbon emissions across these sectors

Problem associated with hydrogen energy:

Hydrogen energy faces major challenges, primarily high production costs (especially for green hydrogen), low energy density requiring specialized, high-pressure, or cryogenic storage, and significant safety risks due to its high flammability and potential to cause metal embrittlement. Additionally, the infrastructure for transport is lacking, and production is often energy-intensive.

Problems:

High Production and Storage Costs: Green hydrogen (produced via electrolysis) is currently much more expensive than fossil fuel-based "grey" hydrogen.

Energy Inefficiency: The entire process, from electrolysis to end-use (e.g., fuel cells), is energy-intensive, with significant energy losses (around 50% or more).

Storage and Transportation Difficulties: Hydrogen has a very low volumetric energy density, requiring it to be stored at either extremely high pressures (350–700 bar) or cryogenic temperatures (-252.8^oC), increasing costs and technical complexity.

Material Compatibility (Embrittlement): Hydrogen causes material degradation, leading to leaks and safety risks in pipelines and storage tanks.

Safety and Environmental Risks: Hydrogen is highly flammable, burns with a nearly invisible flame, and can cause explosions. Furthermore, 96% of hydrogen is currently produced from fossil fuels, contributing to carbon emissions.

Water Intensity: Producing green hydrogen requires significant amounts of purified water for electrolysis, which can strain local water supplies.

Infrastructure Limitations: Lack of extensive, specialized infrastructure for transportation and distribution hampers widespread adoption

Two-Mark Questions (Short Answer)

1. Define **stationary battery storage**.
2. What is a **lead–acid battery**?
3. State the **basic components of a lead–acid battery**.
4. Define **battery storage capacity**.
5. What is **Coulomb efficiency** of a battery?
6. Write the expression for **Coulomb efficiency**.
7. What is meant by **battery sizing**?
8. List any **two battery storage technologies**.
9. What is a **supercapacitor**?
10. Mention **two advantages of supercapacitors**.
11. Define a **fuel cell**.
12. What is meant by **hydrogen energy**?
13. Write the **overall reaction in a hydrogen fuel cell**.
14. Define **Gibbs Free Energy**.
15. What is **entropy**?
16. What is the **theoretical efficiency of a fuel cell**?
17. What is meant by the **electrolysis method of hydrogen production**?
18. List any **two methods of hydrogen storage**.
19. Mention **two applications of hydrogen energy**.
20. State **two problems associated with hydrogen energy**.

1. Explain the construction and working principle of lead–acid batteries used for stationary energy storage.
2. Discuss the concept of battery storage capacity and explain Coulomb efficiency with suitable equations.
3. Explain the procedure for battery sizing in energy storage applications.
4. Describe the different battery storage technologies and compare their performance characteristics.
5. Write short notes on supercapacitors, their construction, advantages, and applications.
6. Explain the historical development and basic operation of fuel cells with a neat diagram.
7. Discuss the thermodynamics of fuel cells, including entropy and theoretical efficiency.
8. Explain the relationship between Gibbs free energy and fuel cell efficiency.
9. Discuss the types of fuel cells and their operating principles.
10. Explain the hydrogen energy system, including electrolysis production method, storage methods, applications, benefits, and challenges.

Objective Type Questions:

1. A lead–acid battery uses which electrolyte?
A) Sulfuric acid
B) Hydrochloric acid
C) Nitric acid
D) Distilled water

Answer: A

1. The positive plate of a lead–acid battery is made of
A) Lead peroxide
B) Pure lead
C) Carbon
D) Zinc

Answer: A

2. The negative plate of a lead–acid battery is made of
A) Lead dioxide
B) Spongy lead
C) Zinc
D) Copper

Answer: B

3. The nominal voltage of a lead–acid cell is approximately
A) 1 V
B) 1.5 V
C) 2 V
D) 3 V

Answer: C

4. Battery capacity is usually expressed in
A) Volt
B) Ampere-hour
C) Watt
D) Joule

Answer: B

5. Coulomb efficiency refers to
A) Voltage efficiency
B) Charge efficiency
C) Power efficiency
D) Thermal efficiency

Answer: B

6. Coulomb efficiency is defined as
A) Output charge / Input charge
B) Input charge / Output charge
C) Energy output / Energy input
D) Voltage output / Voltage input

Answer: A

7. Battery sizing is done to determine
A) Battery color
B) Required storage capacity
C) Battery shape
D) Battery weight

Answer: B

8. Which battery has higher energy density than lead–acid?
A) Lithium-ion
B) Nickel-cadmium
C) Nickel-metal hydride
D) All of the above

Answer: D

9. Supercapacitors store energy through
A) Chemical reactions
B) Electrostatic charge
C) Nuclear reaction
D) Magnetic field

Answer: B

10. Supercapacitors have
A) Low power density
B) High power density
C) Low life cycle
D) Low efficiency

Answer: B

11. One major advantage of supercapacitors is
A) Long cycle life
B) Low efficiency
C) High pollution
D) Low reliability

Answer: A

12. Fuel cells convert chemical energy into
A) Heat energy
B) Electrical energy
C) Mechanical energy
D) Nuclear energy

Answer: B

13. The most commonly used fuel in fuel cells is
A) Methane
B) Hydrogen
C) Coal
D) Petrol

Answer: B

14. The by-product of hydrogen fuel cells is
A) CO_2
B) Water
C) Methane
D) Nitrogen

Answer: B

15. The electrode where oxidation occurs is
A) Cathode
B) Anode
C) Electrolyte
D) Separator

Answer: B

16. Reduction occurs at the
A) Anode
B) Cathode
C) Electrolyte
D) Membrane

Answer: B

18 The maximum electrical work obtainable from a fuel cell is given by
A) Enthalpy
B) Gibbs free energy
C) Entropy
D) Internal energy

Answer: B

19 The theoretical efficiency of a fuel cell is
A) $\Delta H / \Delta G$
B) $\Delta G / \Delta H$
C) $\Delta G + \Delta H$
D) $\Delta H - \Delta G$

Answer: B

20 Entropy represents
A) Energy storage
B) Degree of disorder
C) Electrical current
D) Voltage

Answer: B

21 Hydrogen production by electrolysis involves splitting
A) Air
B) Water
C) Oil
D) Coal

Answer: B

22 Electrolysis produces
A) Hydrogen and oxygen
B) Hydrogen and nitrogen
C) Oxygen and nitrogen
D) Carbon dioxide

Answer: A

23 Hydrogen energy is considered
A) Fossil energy
B) Renewable and clean energy
C) Nuclear energy
D) Thermal energy

Answer: B

24 Hydrogen has
A) High energy content per unit mass
B) Low energy content
C) Zero energy content
D) Medium energy content

Answer: A

25 Hydrogen storage in compressed cylinders is an example of
A) Physical storage
B) Chemical storage
C) Biological storage
D) Thermal storage

Answer: A

26 Hydrogen can also be stored in
A) Metal hydrides
B) Fuel tanks
C) Cylinders
D) All of the above

Answer: D

27 One advantage of hydrogen energy is
A) Zero carbon emission
B) High pollution
C) Limited use
D) Low efficiency

Answer: A

28 One major problem with hydrogen energy is
A) Easy storage
B) Difficult storage and transport
C) High pollution
D) Low efficiency

Answer: B

29 Hydrogen fuel cells are used in
A) Spacecraft
B) Automobiles
C) Power generation
D) All of the above

Answer: D

30 Zero energy concept refers to
A) No energy production
B) Efficient use of energy with minimal external input
C) Fossil fuel usage
D) Thermal power plant

Answer: B

31 The fuel supplied to the **anode** is
A) Oxygen
B) Hydrogen
C) Nitrogen
D) Carbon dioxide

Answer: B

32 The gas supplied to the **cathode** is
A) Hydrogen
B) Oxygen

C) Nitrogen
D) Carbon monoxide

Answer: B

33 Which type of fuel cell uses **phosphoric acid electrolyte**?
A) PAFC
B) PEMFC
C) SOFC
D) MCFC

Answer: A

34 Which fuel cell operates at **very high temperature (~1000°C)**?
A) PEMFC
B) SOFC
C) AFC
D) PAFC

Answer: B

35 Fuel cells produce electricity by
A) Combustion
B) Electrochemical reaction
C) Magnetic induction
D) Mechanical motion

Answer: B

36 The overall reaction in hydrogen fuel cell is
A) $H_2 + O_2 \rightarrow H_2O$
B) $H_2 + CO_2 \rightarrow H_2O$
C) $H_2 + N_2 \rightarrow NH_3$
D) $H_2 + CH_4 \rightarrow CO_2$

Answer: A

37 Hydrogen is considered a
A) Secondary energy carrier
B) Primary fuel
C) Fossil fuel
D) Nuclear fuel

Answer: A

38 The efficiency of fuel cells is generally
A) Very low
B) Moderate
C) High
D) Zero

Answer: C

39 Hydrogen fuel cells are environmentally friendly because
A) They produce water as by-product
B) They produce CO_2
C) They produce smoke
D) They produce ash

Answer: A

40 Supercapacitors are mainly used for
A) Long-term energy storage
B) High power short-duration storage
C) Fuel production
D) Nuclear storage.

UNIT-3: ENERGY STORAGE AND GREEN ENERGY:

Course Outcomes:

After completing this unit, students will be able to:

1. **Explain different energy storage technologies** and evaluate the performance of stationary battery systems.

2. **Analyze battery parameters** such as storage capacity, coulomb efficiency, and determine appropriate battery sizing for energy systems.

3. **Describe the working principles of supercapacitors** and compare them with conventional battery storage systems.

4. **Explain the operation and thermodynamic principles of fuel cells**, including Gibbs free energy, entropy, and efficiency.

5. **Evaluate hydrogen energy systems** including hydrogen production, storage, applications, and associated challenges.

Book/NPTEL link Reference:

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3. Mukund R Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd

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6. https://www.nptelvideos.com/lecture.php?id=8517https://www.nptelvideos.com/lecture.php?id=8517

ASSIGNMENT TOPICS:

➢ Case Study: Availability of Wind Energy Resources in India

UNIT-4: INTRODUCTION TO DG AND ITS GRID INTEGRATION

Introduction: Need for Distributed generation, renewable sources in distributed generation, current scenario in Distributed Generation, Planning of DGs – Siting and sizing of DGs – optimal placement of DG sources in distribution systems. Grid integration of DGs: Different types of interfaces - Inverter based DGs and rotating machine-based interfaces - Aggregation of multiple DG units. Energy storage elements: Batteries, ultracapacitors, flywheels.

Course Objectives

The course aims to:

1. Understand the technical impacts of Distributed Generation (DG) on transmission and distribution systems in modern power networks.
2. Study the influence of DG on protection systems, including protective relaying coordination and fault level variations.
3. Analyze the effects of DG on system stability, particularly transient and dynamic stability of distribution networks.
4. Examine economic and regulatory aspects of DG, including electricity markets, deregulation issues, and operational challenges.
5. Understand control strategies for DG systems, including voltage control, reactive power management, power quality improvement, and reliability assessment.

INTRODUCTION:

Distributed generation (DG) refers to the application of small generators, typically ranging from 15 to 10,000 kW, located throughout a power system to serve consumers. The following content, drawn from the provided textbook excerpts, addresses the key components of distributed generation planning and integration.

Distributed Generation (DG) refers to generating electricity from small-scale, decentralized energy systems located close to the point of use, such as residential, commercial, or industrial locations. These systems include solar panels, wind turbines, gas turbines, and other small-scale generators. The goal of distributed generation is to reduce dependency on traditional large-scale power plants, enhance grid efficiency, and contribute to sustainability by utilizing renewable energy sources.
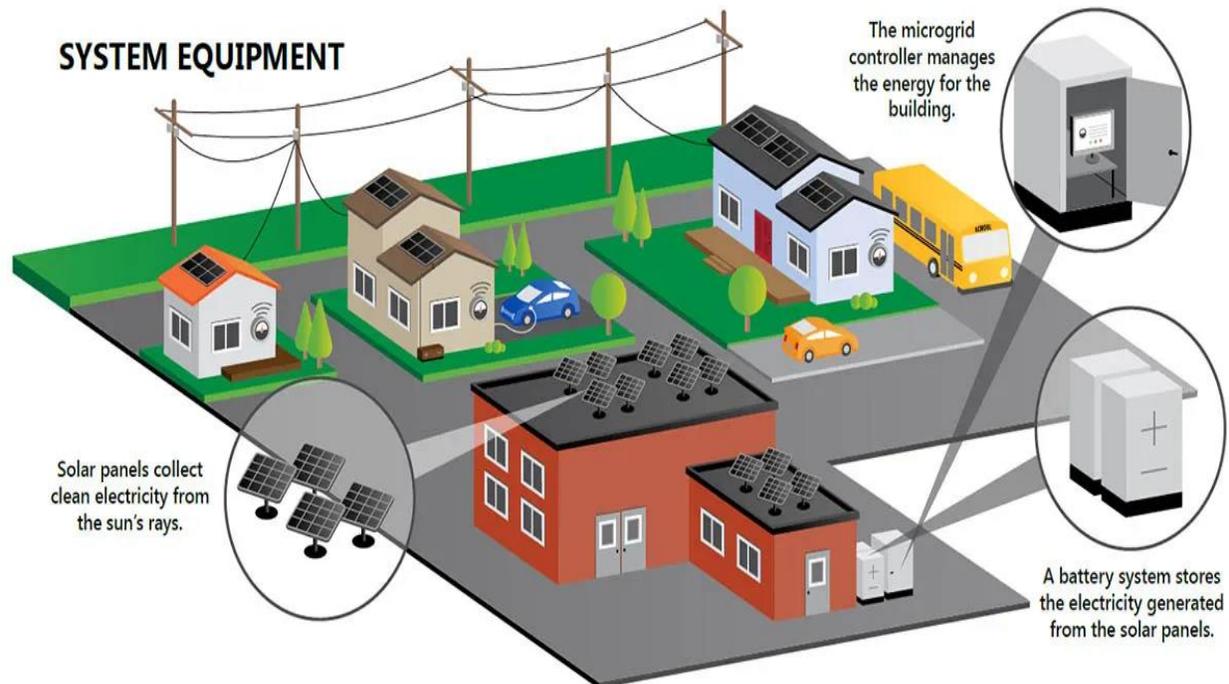
How DG Works:

The basic principle behind DG is simple: instead of generating electricity at a central location and then transmitting it over long distances to the end-user, DG involves generating electricity closer to where it will be used.

There are various types of DG systems, but they all share the common goal of reducing transmission and distribution losses, improving grid stability and security, and reducing the environmental impact of electricity generation.

Advantages:

• Reduced transmission and distribution losses

• Improved grid stability and security

• Reduced environmental impact

• Increased efficiency.

Disadvantages:

• Initial investment cost

• Maintenance cost

Difference Between Distributed Generation and Centralized Generation
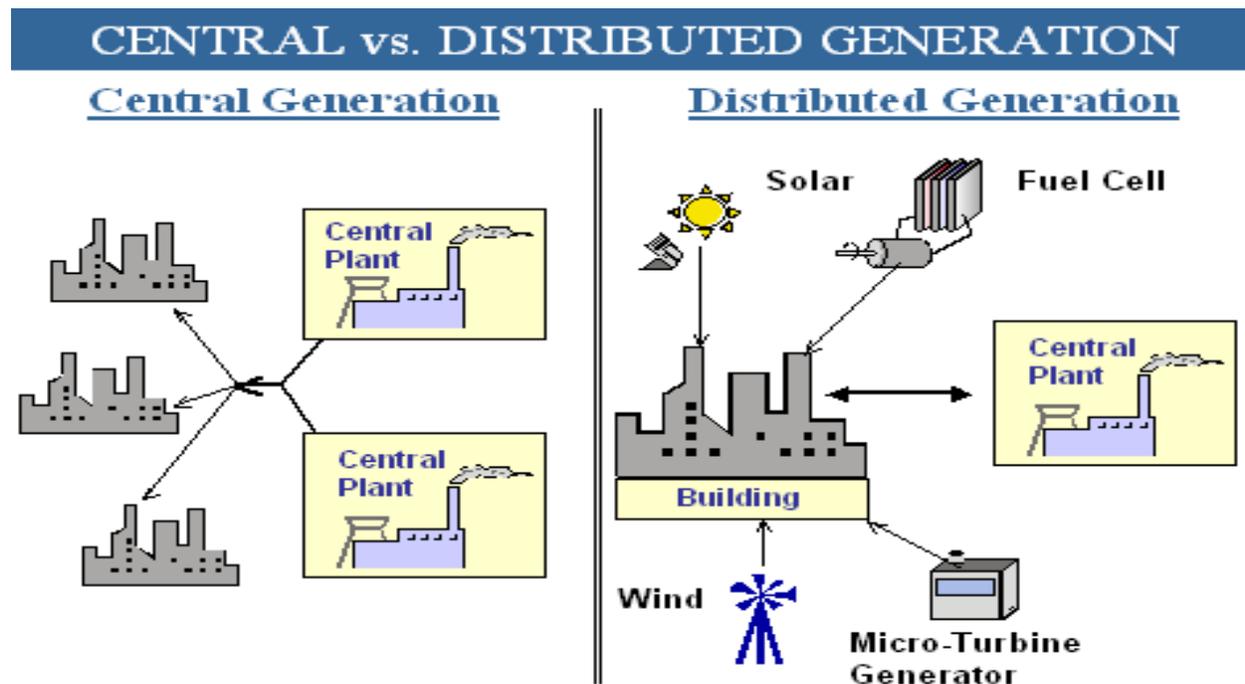
Distributed generation differs from traditional centralized power generation in several ways:

- **Scale and Location:** DG systems are smaller and located near the point of consumption, unlike large-scale power plants that are located far from users.
- **Efficiency:** DG reduces transmission losses, as electricity is generated close to where it is used. Centralized plants, on the other hand, experience losses due to long-distance transmission.
- **Grid Load:** DG can help alleviate stress on the grid by distributing

NEED FOR DISTRIBUTED GENERATION:

The most significant **need for distributed generation (DG)** arises from its ability to serve consumers directly at or near their site of use, which allows for the **avoidance of transmission and distribution (T&D) costs**. According to the provided material, the need for DG is driven by the following economic, technical, and environmental factors:

1. Avoidance of Transmission and Distribution (T&D) Costs

- Traditional power systems require vast, expensive T&D infrastructure to deliver power from large central plants to consumers.

- **Proximity is often more important than generation efficiency**; DG only needs to be more economical than the combined cost of central station generation plus the capital and operating expenses of the T&D system.

- The inflation-adjusted cost of delivering power through a T&D system increased by approximately **35% between 1955 and 2000**, significantly increasing the "avoided cost" value that DG provides.

- T&D systems are responsible for a large portion of **service reliability problems**, which DG can bypass by being located on-site.

2. Efficient Alternative to Aging Infrastructure

- While large central plants benefit from physics-based economies of scale, many existing utility station generators are 20 to 50 years old and use outdated technology.

- Modern DG units utilize **advanced materials and computerized controls** that allow them to achieve fuel-to-power efficiencies that equal or exceed the average performance of the aging utility infrastructure.

- Technological advances have reduced the economy-of-scale advantage that large generators once held from roughly 60% to about 30% at the close of the 20th century.

3. Tailorable Reliability and Power Quality

- DG offers a flexible way to choose a **wide range of combinations of cost and reliability** that the standard grid cannot easily match.

- Users who are sensitive to costs but not interruptions can choose lower-cost DG options with higher failure risks.

- Conversely, sensitive commercial or industrial users can install **redundant DG units** to achieve premium reliability (e.g., only a few minutes of annual outage) at a lower cost than reinforcing the utility grid to the same standard.

- DG units can provide **voltage support and regulation**, helping to smooth out transients that occur when large appliances start up.

4. Modularity and Business Flexibility

- Most DG units are modular, meaning they are **standardized and factory-assembled**, which simplifies engineering and lowers installation costs.

- Because these units are available "off-the-shelf" with **little lead time**, DG owners can install only the capacity they need today and expand incrementally as demand grows.

- This modularity **reduces business risk** and allows for deferred spending, making it an attractive investment in a competitive or uncertain market.

5. Solving Geographical and Infrastructural Challenges

- **Urban Reinforcement:** In metropolitan areas where the existing grid is near capacity, the incremental cost to upgrade underground cables and substations can be seven times the normal cost; DG can defer or avoid these expensive upgrades.

- **Remote/Rural Locations:** For sites far from the grid, such as isolated ranches or mountain communities, the cost of extending lines is often prohibitive, making DG the **only reasonable alternative**.

- **Developing Regions:** In countries lacking a developed fossil-fuel delivery infrastructure, renewable DG (wind, solar, hydro) provides "green" energy without the need for expensive fuel imports or pipelines.

6. Environmental and Aesthetic Needs

- DG provides a way to avoid constructing T&D rights-of-way through **environmentally sensitive or wilderness areas**.

- Specific technologies, such as fuel cells and photovoltaics (PV), offer **clean and silent operation**, making them ideal for high-density areas where noise and emissions are a concern.

7. Competitive Market Niches

- In a de-regulated power industry, DG offers a way for power retailers to bypass utility transportation costs and offer customized service packages.

- DG is estimated to offer reliability and economy that cannot be matched by traditional systems in approximately **25% to 30% of the retail electric market**.

RENEWABLE SOURCES IN DISTRIBUTED GENERATION:

Renewable energy sources are frequently categorized as **distributed generation (DG)** because their typically small size (often less than 5,000 kW and frequently under 500 kW) makes them convenient to connect to lower-voltage distribution parts of the grid. The primary motivation for these units is usually "green" energy production rather than local peaking or reliability.

The following detailed notes categorize the renewable sources and planning considerations found in the material:

1. Solar Thermal Power Generation (STES)

Solar thermal conversion systems use mirrors to concentrate reflected sunlight to produce intense heat energy.

- **Mechanism:** Heat is used to produce steam for a traditional steam-turbine generator or to power a Stirling-cycle reciprocating engine.

- **Concentration Types:**
  - **Heliostats:** Mirrors arrayed around a central tower mounted receiver.
  - **Trough Mirrors:** Parabolic mirrors that focus light on receiver pipes; these can be fixed or use tracking systems.

- **Storage and Dispatchability:** STES is often **dispatchable** because it can easily integrate thermal energy storage using molten salt or super-heated oil tanks. This allows it to function through periods of no sunlight.

- **Efficiency:** Net solar-to-electrical efficiency is roughly 12% to 14%.

2. Photovoltaic (PV) Generation

PV systems convert light energy directly into DC electric power using semiconductor cells, typically connected in series and parallel to form arrays.

- **Mechanism:** Direct current (DC) output must be converted to alternating current (AC) via electronic inverters for grid connection or AC appliances.

- **Advantages:** Modular, silent, clean (no pollutants or vibration), and requires no fuel delivery.

- **Disadvantages:** High initial cost and non-dispatchable without electrical storage (batteries).

- **Sizing and Planning:** Since solar output fades before daily peak demand times in many regions, PV units often require significant battery storage to successfully defer transmission and distribution (T&D) costs.

3. Wind-Powered Generation

Wind turbines remove kinetic energy from the air to produce mechanical rotation, which spins an electric generator.

- **Advantages:** No fuel cost, non-polluting, and potentially a 24-hour source of energy.

- **Disadvantages:** Unpredictable energy production, high initial cost, and higher environmental impact (noise and aesthetics) than solar power.

- **Interfaces:** Modern units often use **induction generators** because they are robust and automatically synchronize with the grid, or DC generators with power electronics to handle variable wind speeds.

4. Low-Head Hydro

Hydro-electric power is a mature technology that can be applied at "low-head" sites with elevation differences of as little as 12 feet.

- **Nature of Supply:** Most are "run of river" plants without reservoirs, meaning output varies seasonally with rainfall.

- **Pros and Cons:** While robust and capable of 24-hour production, they face environmental concerns regarding aquatic life and changes to waterways.

5. Other Renewable Resources

- **Biomass and Trash Burning:** These units burn foliage, trash, or specific "fuel crops" like bamboo or high grasses. They are typically 24-hour, dispatchable units because the fuel can be harvested and stored on-site.

- **Geothermal:** Utilizes thermal energy from molten rocks below the earth's surface to produce steam. It is a mature, fully dispatchable technology.

- **Tidal Power:** Harnesses wave or water-height energy action; however, these systems are generally not yet commercially competitive.

PLANNING AND EVALUATION CONSIDERATIONS:

Planning for renewable DG differs from fossil fuels because the energy resource is not controllable and often semi-predictable.

- **Siting:** Dikted by local geography and weather, such as finding steady wind or maximum river flow.

- **Study Detail Levels:**

    o **Level 1 (Screening):** Analyzes annual totals for initial siting.

    o **Level 2 (Statistical):** Uses statistical distribution of the resource over the year to analyze energy potential and unit sizing.

    o **Level 3 (Simulation):** Recommended for final evaluation; uses hourly temporal availability models to account for nighttime (solar) or calm periods (wind) and storage needs.

- **Economic Sensitivity:** Renewable systems are highly sensitive to the **discount rate** and **evaluation period** because they have very high initial costs but zero continuing fuel costs. Long planning periods (20+ years) and low discount rates favor renewable alternatives.

CURRENT SCENARIO IN DISTRIBUTED GENERATION:

The "current scenario" of distributed generation (DG), as characterized in the provided source material, reflects a period of **dramatic technological and business revolution** in the power engineering field. While large central station plants remains the dominant method for worldwide power production, DG has emerged as a critical alternative due to shifting economic and technical factors.

1. Industry Revolution and Structure

- The electric utility industry is undergoing a fundamental shift in its technology and business structure, extending capabilities far beyond traditional utility systems.

- The ability for consumers—including homeowners, businesspersons, and industrial plant managers—to **produce power at their own sites** is effecting a major change in industry organization and way of doing business.

- **De-regulation** is fostering a environment of commercial and technological competition at the retail level, which drives continuous experimentation and improvement in the DG arena.

2. Technological Competitive Edge

- While central station plants traditionally benefited from physics-based economies of scale, modern DG units now utilize **advanced materials and computerized controls**.

- Modern DG units can achieve fuel-to-power efficiencies that equal or exceed the performance of the **aging utility infrastructure**, where many central station generators are between 20 and 50 years old.

- Advances in automation mean that smaller units no longer require on-site human operators for safe, reliable, and efficient operation, drastically changing the labor-cost disparity that once favored large plants.

3. Market Niches and Economic Viability

- DG currently offers reliability and economy that cannot be matched by traditional systems in approximately **25% to 30% of the retail electric market**.

- The "economy of scale" advantage that large generators once held over small generators was cut roughly in half by the close of the 20th century, shrinking from a 60% advantage to approximately 30%.

- The inflation-adjusted cost of delivering power through transmission and distribution (T&D) systems increased by about **35% between 1955 and 2000**, making the "avoided cost" value of DG significantly higher than in previous decades.

4. Siting and Application Trends

- DG is increasingly used as a **substitute for costly T&D additions** in developed metropolitan areas where existing systems are near capacity and reinforcement costs are prohibitive.

- In remote or rural locations, DG is often the only reasonable alternative because the initial investment required for lengthy utility power lines is too high.

- There is a growing market for **"premium power"** among commercial and industrial users who require higher levels of reliability and power quality than the standard grid can provide.

5. The Role of Renewables

- Renewable energy sources (wind, solar, hydro) are frequently categorized as DG because their **modular nature and small size** (often less than 500 kW) make them convenient for connecting to low-voltage distribution grids.

- The primary motivation for these units is often **"green" energy production** and environmental sensitivity rather than just local peaking or reliability.

- In developed nations, there is an emerging "green power" market where approximately 10% of residential consumers are willing to pay a premium for renewable energy.

PLANNING OF DGS

The planning of **Distributed Generation (DG)** is a complex decision-making process aimed at identifying the best resources, locations, and schedules to meet specific energy goals. Unlike traditional utility planning, which focuses on massive central stations, DG planning is typically **site-specific and project-oriented**, focusing on the needs of individual sites or small communities.
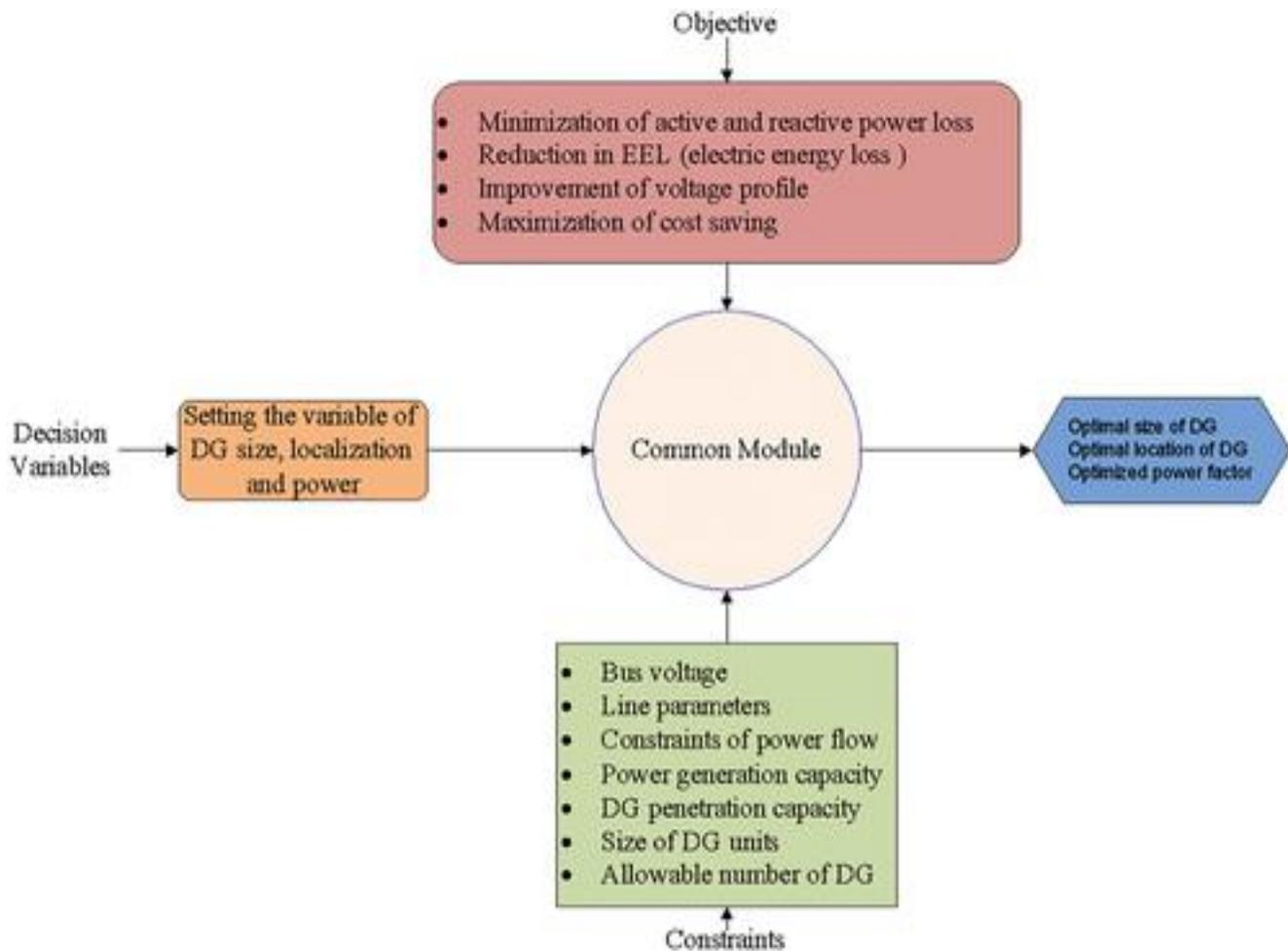
The following detailed notes summarize the planning process, siting/sizing considerations, and evaluation methods from the material:

1. The Five-Step Planning Process

Effective planning follows a structured hierarchy to ensure objective decision-making:

- **Step 1: Identify the Problem:** Explicitly define the scope (e.g., providing power to a specific new subdivision).

- **Step 2: Determine the Goals:** Specify what must be accomplished, such as finding the lowest-cost option with a specific reliability target.

- **Step 3: Identify Alternatives:** Explore all available options, including different DG technologies, grid connections, and the **"do nothing"** alternative, which serves as a baseline for justification.

- **Step 4: Evaluate the Alternatives:** Assess each option against common **criteria** (must-meet standards like voltage) and **attributes** (qualities to minimize, like cost).

- **Step 5: Select the Best Alternative:** Ensure the definition of "best" matches the initial goals and that the evaluation method accurately distinguishes between close cases.

SITING AND SIZING OF DGS:

The planning of Distributed Generation (DG) involves two critical decisions: **siting** (identifying the best location) and **sizing** (determining the appropriate capacity). The following detailed content is drawn from the provided material:

1. Siting of DGs (Optimal Placement)

Siting involves identifying locations where DG can provide the maximum economic or technical benefit.

- **Spatial Load Analysis:** Planners use spatial load analysis to identify where load is located and how much capacity is needed in specific localities. This helps determine where DG units can be most effective in serving demand locally.

- **Targeting High-Cost Areas:** Optimal siting often focuses on areas where the **incremental cost of utility expansion** is high. These costs can vary by a factor of seven to one across a system due to factors like aging infrastructure, underground cable limitations (in urban cores), or geographic isolation (remote islands).

- **Renewable Resource Constraints:** For renewable DGs, siting is dictated by local geography and weather. Planners must find specific spots for steady wind, maximum run-of-river water flow, or high, consistent levels of sunlight. For instance, wind consistency can vary by a factor of two within just one mile depending on the specific hilltop or terrain slope.

- **Environmental and Human Proximity:** Siting must account for environmental impacts, such as noise and vibration. "Human-friendly" units like fuel cells are easier to site because they are clean and silent, allowing for indoor installation or placement in densely populated areas.

2. Sizing of DGs (Capacity Selection)

Sizing is the process of determining the net kW or kVA output required to meet a specific goal.

- **Non-Coincident Load Dynamics ("Needle Peaks"):** Small DG units (under 80 kW) assigned to single sites see **non-coincident load behavior**, characterized by rapid transitions and short-duration "needle peaks". These peaks are caused by large appliances cycling on and off.

- **Capacity Margins:** Because they lack the "smoothing" effect of the larger grid, a small DG unit serving an individual home often requires a capacity **three times higher** than the average peak coincident demand of the site. For example, a home with a 4kW coincident peak may require a 12 kW DG unit to handle instantaneous needle peaks.

- **Transformer Ratings as a Poor Proxy:** Planners cannot assume that the rating of a service transformer indicates the required size for a DG unit. Transformers can handle momentary peaks far above their rating due to thermal inertia, whereas smaller dispersed generators lack this smoothing action.

- **Modularity and Sizing:** Most DG units are available in small, standard modular sizes. Planners can pick the number and sizes of units at a site to tailor reliability; for example, using two 500 kW units instead of one 1,000 kW unit provides different availability characteristics.

- **Staging for Growth:** Modularity allows for **staged sizing**. Instead of installing a large unit today, a planner can install only the capacity needed for current demand and expand incrementally as demand grows, reducing financial risk.

3. Interaction with Energy Storage

Sizing is often a balance between generating capacity and energy storage.

- **Storage-Generation Balance:** Adding energy storage (batteries, flywheels, or capacitors) can "smooth out" the load curve. This allows the DG unit to be sized closer to the average demand rather than the needle peak, running at a steady, efficient level while the storage handles the spikes.

- **Ride-Through and Dispatchability:** When sizing for renewables (PV or wind), storage must be sized to "ride-through" periods of no sunlight or wind. The generation unit must have sufficient capacity to serve the load *and* recharge the storage simultaneously during productive hours.

4. Planning Methods for Siting and Sizing

The material recommends three levels of detail for evaluating sizing and siting:

1. **Level 1: Screening:** Used for initial siting, focusing on annual energy totals to identify feasible locations.

2. **Level 2: Statistical Studies:** Uses the distribution of the resource over a year to refine unit sizing and identify expected output levels.

3. **Level 3: Simulation:** Recommended for final sizing, using hourly temporal models to capture start-up dynamics, recharge cycles, and the interaction of multiple modular units.

OPTIMAL PLACEMENT OF DG SOURCES IN DISTRIBUTION SYSTEMS:

Optimal placement and siting of Distributed Generation (DG) units focus on identifying locations where DG provides the maximum economic and technical benefit, often by serving as a substitute for expensive transmission and distribution (T&D) additions.

The following content regarding optimal placement is drawn from the provided material:

1. Targeting High-Cost Expansion Areas

Optimal placement often targets areas within a utility system where the **incremental cost of expansion** is significantly higher than average.

- **Cost Variance:** Incremental costs to reinforcement the grid can vary across a single power system.

- **Urban Cores:** In developed metropolitan areas, existing infrastructures may be near capacity. Upgrading underground cables and substations in these "urban islands" can be prohibitively expensive (up to six times the normal cost), making them optimal sites for DG placement to defer or avoid these T&D upgrades.

- **Rural and Remote Sites:** Locations far from the existing grid are optimal for DG because the fixed cost of extending lengthy T&D lines is often more than double the cost of installing on-site DG.

Techniques for DG sizing and sitting

Traditional method
- Graphical method
- Iterative based method
  - Power Flow
  - Linear regression
  - DLF
- Linear programming
  - MIL programming
  - Non-linear programming
- Analytical based method
  - New index method
  - Loss minimization method
  - Combined Index
  - SSCFLCP
- Probability based method
  - BPFD and MIF
  - Monte carlo & diagonal band coupla

Artificial intelligence based methods
- Artificial Neural Network
- Artificial Eco system Optimizer
- Genetic algorithm
- Chaotic bat algorithm
- Improved wild horse technique
- Dragonfly optimization
- Hower pollination algorithm
- Particle swarm optimization
- Equilibrium optimization

Hybrid methods
- Bus location index and Modified moth flame optimization
- Artificial bee colony and genetic algorithm
- improved grey wolf optimization and Particle swarm optimization and dimension learning-based hunting
- Electrostatic discharge, loss sensitivity factor and voltage stability index
- Power loss index, whale optimization algorithm
- weighted improved PSO and GSA
- Intelligent Water Drop and Genetic Algorithm

Software analysis based
- HOMER
- HOGA
- ETAP

❖ Traditional Methods

These are the foundational mathematical and deterministic approaches. They are often used for simpler networks or as benchmarks for newer algorithms.

- **Graphical Method:** Uses visual plots and curves to identify optimal points.

- **Iterative Based Method:** Uses repeated calculations (like **Power Flow** or **Linear Regression**) to converge on a solution.

- **Linear Programming:** Mathematical modelling to find the best outcome in a linear relationship, including Mixed-Integer Linear (MIL) and Non-linear variations.

- **Analytical Based Method:** Uses direct mathematical formulas (e.g., **Loss Minimization Method**) to calculate positions without heavy iteration.

- **Probability Based Method:** Accounts for uncertainty and randomness, utilizing tools like **Monte Carlo simulations**.

  ❖ **Artificial Intelligence (AI) Based Methods**

Also known as meta-heuristic or nature-inspired algorithms, these are designed to solve complex, non-linear optimization problems that traditional math might struggle with.

- **Evolutionary/Genetic: Genetic Algorithm (GA)** mimics natural selection.

- **Swarm Intelligence:** Includes **Particle Swarm Optimization (PSO)** and **Dragonfly Optimization**, which mimic the collective behavior of animal groups.

- **Neural Networks: Artificial Neural Networks (ANN)** learn patterns from historical data to predict sizing/siting needs.

- **Modern Heuristics:** Newer techniques like the **Artificial Ecosystem Optimizer** and **Equilibrium Optimization**.

  ❖ **Hybrid Methods**

Hybridization involves combining two or more techniques to offset the weaknesses of one with the strengths of another. Usually, this involves pairing an AI algorithm with a traditional sensitivity factor or another AI algorithm. Examples from the chart include:

- **AI + AI:** Combining **Artificial Bee Colony** with **Genetic Algorithms**.

- **AI + Analytical:** Combining **Whale Optimization** with a **Power Loss Index**.

- **Enhanced AI:** Using **Modified Moth Flame Optimization** or **Improved Grey Wolf Optimization** to speed up convergence and avoid getting stuck in "local optima."

  ❖ **Software Analysis Based**

These are dedicated industry-standard software tools that come with built-in modules for simulating and optimizing power systems.

- **HOMER:** Widely used for microgrid design and renewable energy integration.

- **ETAP:** A powerful analytical platform for the design, simulation, and operation of generation and distribution systems.

- **HOGA:** Specifically focused on the optimization of hybrid renewable systems.

2. Spatial Load Analysis and Locational Optimization

Planners use spatial load analysis to determine exactly where capacity is needed relative to customer demand.

- **Locational Resource Mix:** Integrated Resource Planning (IRP) methods attempt to adjust the mix of resources (DG, Demand-Side Management, and T&D) on a locational basis to ensure the resource allocation is **optimal in every location**.

- **Load Mapping:** By **identifying where total peak demand is located** (e.g., in a major city centre exceeding 1 MW/acre), planners can site DG units to serve that specific demand locally, bypassing the T&D "chain" and its associated costs and losses.

3. Geographic and Resource Constraints (Renewables)

For renewable DG sources (wind, solar, hydro), optimal placement is strictly dictated by local geography and weather patterns.

- **Resource Predictability:** Siting involves finding specific spots for steady wind, maximum run-of-river flow, or consistent sunlight.

- **Wind Siting:** Optimal placement for wind farms often involves hillsides where turbines can be located in a "string" or "farm" to maximize kinetic energy recovery without interfering with one another.

- **Hydro Siting:** Low-head hydro sites are optimally placed where elevation differences of as little as 12 feet exist in rivers.

4. Environmental and Aesthetic Siting

The "friendliness" of the technology influences its placement in dense or sensitive areas:

- **Clean and Silent Units:** Technologies like **fuel cells** and **photovoltaics (PV)** are easier to site in densely populated urban areas because they produce no pollutants, noise, or vibration. Fuel cells, for example, can be installed indoors or hidden in small enclosures.

- **Avoiding Sensitive Areas:** DG can be optimally placed to avoid the need for T&D rights-of-way through environmentally sensitive or wilderness areas.

GRID INTEGRATION OF DGS:

Grid integration, or utility interconnection, allows Distributed Generation (DG) units to operate in conjunction with the local electric power system. This integration provides technical and economic advantages but also introduces specific engineering complexities and costs.
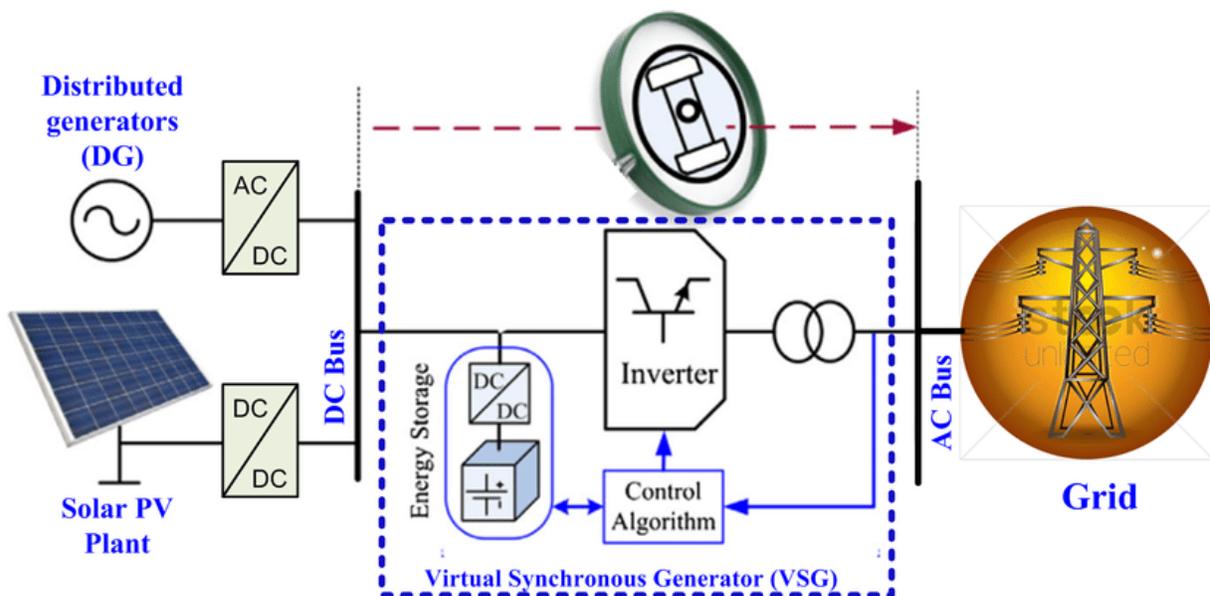
Advantages of Grid Interconnection

- **Improved Voltage Regulation:** Power grids are designed to be near-perfect voltage sources. While a standalone DG unit may struggle to track rapid "needle peak" shifts from large appliances, causing "voltage flicker," a grid-connected system uses the utility to provide instant transient response, maintaining stable voltage.

- **Enhanced Reliability:** A combined DG-grid system typically offers higher reliability than either source alone. Most power grids in developed nations provide availability exceeding 99.95%, which is difficult for a single DG unit (typically 94–98% available) to match without significant local redundancy.

- **Economic Optimization:** DG owners can save money by producing their own power during high-price peak periods and buying cheaper utility power during off-peak times.

- **Profit from Power Sales:** Interconnection enables DG owners to sell surplus power back into the grid, potentially offsetting their own energy costs.

Challenges and Disadvantages

- **Interconnection Costs:** Utilities levy significant charges for grid access, including annual capacity fees based on peak demand. These fees can sometimes make grid-only or DG-only options more attractive than combined systems.

- **Complex Protective Equipment:** Operating in parallel with the grid requires sophisticated control, metering, and protection equipment to prevent the DG from feeding faults in the grid (and vice-versa). This typically more than doubles the cost of the electrical interface compared to isolated operation.

- **Vulnerability to Grid Disturbances:** Grid-connected units are exposed to lightning strikes and voltage sags caused by remote faults (e.g., trees hitting power lines during storms), which can trip sensitive DG control systems and shut the unit down.

Interconnection Operational Methods

DG planners must choose between two primary methods of operation when connected to the grid:

- **Parallel Operation:** Both the DG and the grid are simultaneously connected to the load. This eliminates interruptions if one source fails, but it requires the most expensive control and coordination equipment. The DG unit must often be kept running (even if not producing power) to remain synchronized.

- **Switched (Rollover) Operation:** Only one source is connected to the load at a time. If the primary source fails, the system "rolls over" to the backup. This is simpler and less expensive, but it results in a brief service interruption during the switching period.

Smoothing Load Spikes

For small, individual customer sites, grid integration acts as a form of "**non-coincident load smoothing**." The DG unit can run at its most efficient constant output level, while the utility grid handles the rapid, sharp "needle peaks" of appliance activity that the DG unit might not be able to track alone.

DIFFERENT TYPES OF INTERFACES - INVERTER BASED DGS AND ROTATING MACHINE-BASED INTERFACES:

The provided source material describes two primary categories of electrical interfaces used for integrating distributed generation (DG) units into power systems: those based on rotating machinery and those that are inverter-based (electronic interfaces).

Rotating Machine-Based Interfaces

Rotating machine interfaces utilize traditional spinning generators to convert mechanical motion into electric power. The specific type used often depends on the prime mover (e.g., a piston engine or gas turbine) and the requirements for grid synchronization.
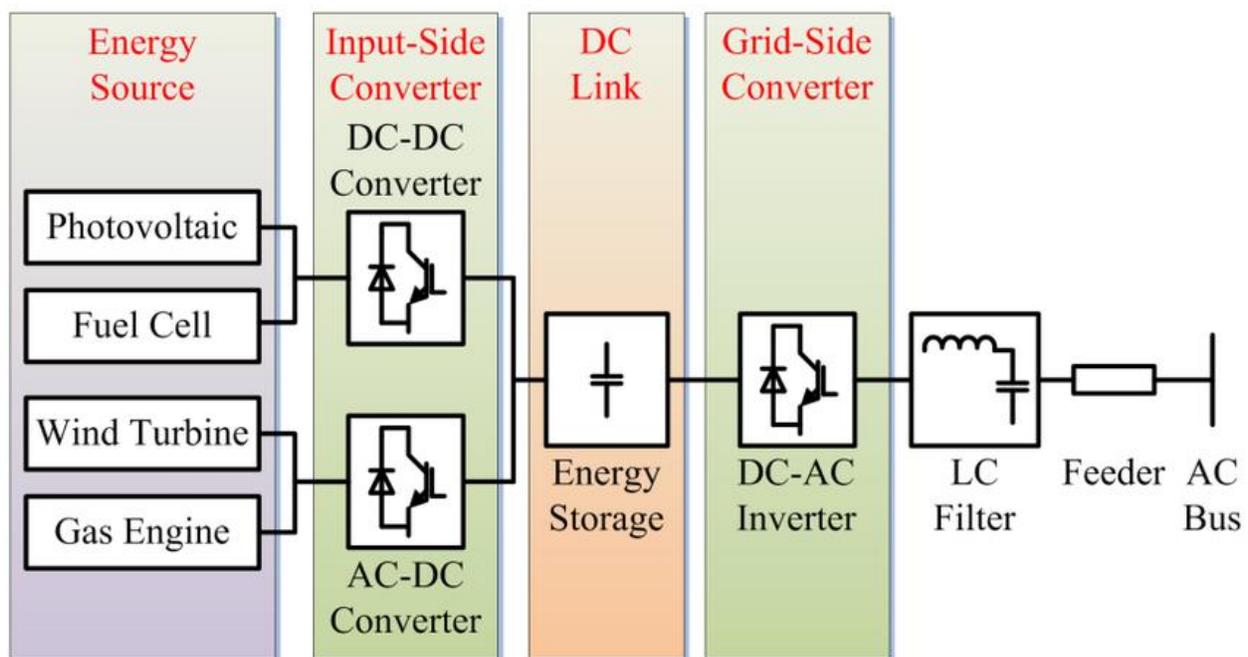
- **Synchronous AC Generators:** These are scaled-down versions of generators used in large central power plants. They are highly efficient, durable, and reliable. However, they must be driven at a constant speed corresponding to the line frequency (e.g., 1,800 or 3,600 RPM for 60 Hz), which requires precise engine speed control via a governor system. They are typically used for reciprocating engines and utility or mini gas turbines.

- Induction (Inductive) AC Generators: These generators are very robust and have the advantage of being "automatically synchronizing" when connected to the grid. Unlike synchronous generators, they do not require a speed governor because they can produce line frequency even if driven at slightly different speeds. Their main disadvantage is that they require reactive power (VARs) from

the grid to operate, meaning they act as a reactive load while being a real power source.

- Written Pole Synchronous Generators: These are essentially variable-speed synchronous generators. They use a special stator coil to "write" magnetic poles onto a ferrite rotor dynamically. This allows them to maintain a constant output frequency regardless of variations in rotor speed, providing superior frequency control.

Inverter-Based (Electronic) Interfaces

Inverter-based interfaces are required for DG units that inherently produce Direct Current (DC) or for variable-speed machines where the generated frequency does not match the grid frequency.

- DC Generators with DC-AC Converters: Some rotating DG units, such as micro-turbines and variable-speed wind turbines, use a high-RPM DC generator as an intermediate step. This raw DC power is often "dirty" and pulsed, requiring electronic conversion and filtering to produce high-quality AC power. This setup allows the prime mover to run at variable speeds to maximize fuel economy.

- Solid-State DC Sources: Technologies like Fuel Cells and Photovoltaics (PV) produce clean, continuous DC power. This output must be passed through a DC-AC inverter and a filter system to be compatible with standard AC appliances or the utility grid.

- Energy Storage Integration: One major advantage of inverter-based interfaces is that they permit the parallel use of energy storage, such as batteries. Both the DG source and the storage unit can be connected to the same DC-AC converter, allowing the system to handle sharp "needle peak" loads that exceed the generator's capacity.

Comparison of Interface Characteristics

- Control and Power Quality: Inverter-based systems use power electronics to "wave-shape" the outgoing electricity, which can provide near-perfect voltage regulation and eliminate sags or surges. Rotating machines rely on the utility grid for instant transient response and voltage stability.

- Versatility: Electronic converters allow a single DG model to produce power at different frequencies (e.g., switching between 50 and 60 Hz) simply by adjusting a switch, whereas rotating machines are usually fixed to a specific frequency by their design and speed.

- Complexity: Parallel operation with the grid is more complex for both types, requiring sophisticated protection equipment to prevent the DG from feeding grid faults and vice-versa. This typically doubles the cost of the interface compared to standalone operation.

AGGREGATION OF MULTIPLE DG UNITS:

The aggregation of multiple Distributed Generation (DG) units, often referred to as **modularity**, is a fundamental characteristic of DG planning and application. Most DG units are factory-assembled standardized modules designed to be used either individually or grouped together at a single site to meet larger capacity requirements.

The following sections detail the economic and technical aspects of aggregating multiple DG units based on the source material:

Economic Advantages of Aggregation

- **Shared Infrastructure Costs:** Assembling multiple units of the same type at one site creates an economy of scale even if the individual units are small.facility costs—such as insulation, DC-AC conversion, protection, and control systems—can be shared, which lowers the overall capital and maintenance cost per kilowatt compared to installing a single unit of equivalent total capacity.

- **Incremental Expansion and Staging:** Aggregation allows owners to install only the capacity required for today's needs and expand incrementally as demand grows. By staggering the installation of modular units (e.g., installing one 550 kW unit initially and a second years later), a planner can defer capital spending, which reduces business risk and takes advantage of the time value of money.

- **Cost Savings in Growth Scenarios:** In cases where load is expected to grow, using modularized units installed on a schedule can result in total lifetime cost savings of approximately **10% to 15%** compared to installing the full capacity upfront.

Reliability and Availability Impact

- **Redundancy and Failure Characteristics:** Aggregating multiple units changes the availability profile of the power supply. For example, while two 550 kW units may have a higher probability that *some* capacity will be out (partial failure) compared to one 1,100 kW unit, they drastically reduce the likelihood of a **total power failure** because it is mathematically rare for both independent units to fail simultaneously.

- **Tailorable Reliability:** Planners can pick the number and sizes of units at a site to reach specific reliability targets. Adding a "reserve margin" (e.g., using five 275 kW units to serve an 1,100 kW load) ensures that the full demand can still be met even if one unit is down for repair or maintenance.

- **Maintenance Flexibility:** With multiple units, maintenance can be scheduled sequentially so that only one unit is out of service at a time, ensuring continuous power availability to the site.

Technical Integration and Control

- **Clustering Facilities:** Large generating units are often clustered to share fuel loading, switching, and operating facilities, which lowers the cost per unit of generation.

- **Control Systems:** Grouped units require coordinated control and protection systems, particularly if they are intended to operate in parallel with the utility grid.

- **Interleaving "Needle Peaks":** Aggregating multiple consumer loads (load aggregation) also benefits DG aggregation. As more consumers are added to a group, their individual "needle peak" demands interleave, resulting in a smoother coincident load curve that is easier for aggregated DG units to serve efficiently.

Typical Modular Configurations

Reciprocating engine designs are particularly amenable to modular application; for instance, a manufacturer might use a standardized cylinder design to offer a range of units (e.g., 4, 8, 12, or 16 cylinders) that produce between 275 kW and 1,100 kW. Similarly, fuel cells are often aggregated into "stacks" to achieve the desired voltage and capacity.

Energy storage elements: Batteries, ultracapacitors, flywheels:

Energy storage systems are used to augment distributed generation (DG) in three primary ways: stabilization (smoothing rapid load fluctuations), ride-through (providing power when the DG unit is unavailable, such as solar at night), and dispatchability (allowing non-dispatchable units to meet specific sales schedules).

1. Battery Storage

Batteries store electrical energy as chemical energy by using current to rearrange ions in an electrolyte.

- Mechanism: They are modular units that produce direct current (DC) and require a DC-AC converter to interface with most DG systems and loads.

- Cycling and Lifetime: Battery life is measured in charge-discharge cycles. "Deep cycling" (discharging almost completely) significantly reduces service life; for example, a lead-acid battery may tolerate 3,000 partial cycles but only 125–200 deep cycles.

- Types of Batteries:

  - Lead-Acid: The most popular and lowest-cost option ($125/kWh). They are robust but have the lowest energy and power densities, are mildly toxic, and their performance degrades at low temperatures.

  - Nickel-Metal Hydride: Offers two to three times the energy density of lead-acid but at a higher cost ($375/kWh).

  - Lithium Polymer: Provides high energy density and can be manufactured in "sheets," but it is expensive ($550/kWh) and must be heated to 70°C to operate.

  - Sodium-Sulfur (NaS): Theoretically possesses very high energy and power density, but it operates at 250–400°C and uses highly corrosive materials.

2. Capacitor Storage (Supercapacitors)

Capacitors store energy as a voltage potential in an electric field between two conducting plates.

- Mechanism: "Supercapacitors" use carbon electrodes and an electrolyte solution to achieve energy densities approaching those of batteries while maintaining the high power density of traditional capacitors.

- Advantages: They have no moving parts, require no cooling or heating, and have service lifetimes measured in decades. They are immune to the lifetime degradation caused by frequent cycling.

- Power Density: They have extremely high power density and can release energy near-instantly, making them ideal for energy stabilization to handle sharp "needle peaks" in consumer demand.

- Disadvantages: They have relatively low energy density compared to batteries (requiring more space per kWh) and require expensive electronics to control the rapid voltage drop during discharge.

3. Flywheel Storage

Flywheels store energy mechanically as kinetic energy in a rapidly spinning rotating mass.

- Mechanism: A motor-generator spins the flywheel to store energy and draws power back from it as the mass slows down.

- Types:

    - High-Speed: Small diameter, spinning at over 50,000 RPM using exotic materials; compact but more expensive.

    - Low-Speed: Larger diameter, spinning around 7,000 RPM; more straightforward design and amenable to cost reduction through mass production.

- Advantages: They are silent, possess a long lifetime, and—like capacitors—are immune to deep-cycling degradation. They have energy densities comparable to "new" battery types like lithium polymer.

- Disadvantages: They have a relatively poor power density, meaning they cannot give up energy as rapidly as capacitors or SMES. The motor-generator and electronic controls represent the majority of the system cost.

Qualitative Comparison of Storage Methods

System Type	Energy Density $(kWhr/ft^3)$	Power Density (kW/ft^3)	Efficiency (24 hr %)	Lifetime (Years)
Lead-Acid Battery	2.0	3.0	92%	8
Lithium Polymer	6.0	6.0	88%	7
Super-Carbon Capacitor	1.5	5000.0	94%	30
Low-Speed Flywheel	8.0	20.0	90%	30
Thermal (STES)	5.0	0.5	82%	30

Course Outcomes:

After completion of this unit, students will be able to:

1. Explain the technical impacts of distributed generation on transmission and distribution power systems.

2. Analyze the effect of DG integration on protective relaying schemes and system protection coordination.

3. Evaluate transient and dynamic stability issues in distribution systems with distributed generation.

4. Discuss economic factors and market challenges associated with the deployment of DG in deregulated power systems.

5. Apply voltage control and reactive power control techniques to improve power quality and reliability in DG-based systems.

Book/NPTEL link Reference:

1. G N Tiwari, Solar Energy: Fundamentals, Design, Modeling and Applications, Narosa, 2002.

2. Mukund R Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd

3. H. Lee Willis, Walter G. Scott, ―Distributed Power Generation – Planning and Evaluation‖, Marcel Decker Press, 2000.

4. Gilbert M. Masters, ―Renewable and Efficient Electric Power Systems‖, 2nd Edn., IEEE Press, Wiley, 2013.

5. N. Jenkins, J.B. Ekanayake and G. Strbac, ―Distributed Generation‖, 1st Edn, The Institution of Engineering and Technology, London, 2010.

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1. https://archive.nptel.ac.in/courses/121/106/121106014/
2. https://onlinecourses.nptel.ac.in/noc22_ch27/preview
3. https://www.nptelvideos.com/lecture.php?id=8517https://www.nptelvideos.com/lecture.php?id=8517

ASSIGNMENT TOPICS:

1. Study and analyze how Distributed Generation affects transmission and distribution systems, including changes in power flow, voltage profile, and fault levels.
2. Analyze the challenges in protective relay coordination when distributed generators are connected to distribution networks.
3. Explain how DG penetration affects system stability, including transient stability and dynamic performance of distribution systems.
4. Discuss various voltage control methods used when DG units are integrated into distribution networks.
5. Explain the importance of reactive power management in maintaining voltage stability and power system efficiency in DG-based networks.

2 mark Questions:

1. Define Distributed Generation (DG).
2. List any two technical impacts of DG on power systems.
3. How does distributed generation affect transmission systems?
4. What is the impact of DG on distribution network voltage profile?
5. Define deregulation in the power sector.
6. What are the protection issues caused by DG integration?
7. What is relay coordination in power system protection?
8. Define transient stability in power systems.
9. What is dynamic stability in distribution systems?
10. List two market challenges associated with distributed generation.
11. What are the limitations of distributed generation systems?
12. What is voltage control in DG integrated systems?
13. Define reactive power control.
14. What are harmonics and how do they affect power quality?
15. Define reliability in DG based power systems.

10-mark question:

S.NO.	CO	QUESTIONS	BT
		UNIT-4: INTRODUCTION TO DG AND ITS GRID INTEGRATION	
1	**4**	Define Distributed Generation (DG). Explain the need for distributed generation in modern power systems, highlighting technical, economic, and environmental motivations?	**L4**
2	**4**	a) Explain the role of renewable energy sources in Distributed Generation. b) Discuss solar PV, wind, biomass, and small hydro as DG sources with suitable block diagrams?	**L3**
3	**4**	a) Discuss the current scenario of Distributed Generation in electrical power systems. b) Explain trends, penetration levels, and challenges faced by utilities with increasing DG integration?	**L4**
4	**4**	Explain the planning of Distributed Generation systems. Discuss objectives, constraints, and the step-by-step methodology adopted in DG planning?	**L3**
5	**4**	a) Explain the concepts of siting and sizing of DG units in distribution networks. b) Discuss the impact of proper and improper siting and sizing on system performance?	**L5**
6	**4**	Explain different optimization techniques for optimal placement of DG sources in distribution systems. Discuss objectives such as loss minimization, voltage profile improvement, and reliability enhancement?	**L4**
7	**4**	Describe the working principles and characteristics of: (a) Inverter-based DG interfaces. (b) Rotating machine-based DG interfaces	**L3**
8	**4**	Explain the concept of aggregation of multiple DG units. Discuss coordinated control, microgrids, and virtual power plants in DG aggregation?	**L5**

9	4	Discuss the working principle, advantages, limitations, and applications of: (a) Batteries (b) Ultracapacitors (c) Flywheels	L4
10	4	Explain the grid integration of Distributed Generation systems. Discuss major technical issues such as synchronization, protection coordination, islanding, and power quality?	L3

Prepared by

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Professor-EEE

UNIT-5: TECHNICAL IMPACT, ECONOMIC AND CONTROL ASPECTS OF DG

Technical impacts of DGs: Transmission systems, Distribution systems, De-regulation – Impact of DGs upon protective relaying – Impact of DGs upon transient and dynamic stability of existing distribution systems Economic and control aspects of DGs: Market facts, issues, and challenges - Limitations of DGs. Voltage control techniques, Reactive power control, Harmonics, Power quality issues. Reliability of DG based systems – Steady-state and Dynamic analysis.

Objective:

1. To understand the technical impact of Distributed Generation (DG) on transmission and distribution systems.
2. To analyze the effect of DG integration on protection schemes, including protective relaying coordination.
3. To study the impact of DG on system stability, including transient and dynamic stability in distribution networks.
4. To examine economic and regulatory aspects of DG, including market structure, deregulation, and associated challenges.
5. To understand control and power quality issues in DG systems such as voltage control, reactive power management, harmonics, and reliability analysis.

The technical impacts of Distributed Generation (DG) units are broad, affecting everything from local power quality to the overall reliability and protection of the distribution system. Based on the provided sources, the technical impacts can be categorized into power quality, system reliability, operational dynamics, and grid integration challenges.

1. Impact on Power Quality

- **Voltage Regulation and Flicker:** Standalone DG units, particularly small ones serving individual households, often struggle to track the rapid, sharp shifts in demand known as **"needle peaks"**. When large appliances start up, these units may not react instantly, leading

to **voltage flicker** or sags that can fall outside the recommended **CBEMA envelope**. This can cause digital equipment like computers and clocks to reset.

- **Smoothing via Grid or Storage:** Grid interconnection or energy storage (like batteries or ultracapacitors) can mitigate these issues. The grid acts as a **"non-coincident load smoother,"** providing instant transient response to handle appliance startup spikes that a DG unit might miss.

- **Electronic Interface Filtering:** Inverter-based DGs (e.g., PV or fuel cells) produce DC power that must be converted to AC. While these electronic interfaces allow for precise power shaping, the raw DC output from units like micro-turbines can be "dirty" or pulsed, requiring significant **filtering and shunting** to ensure high output power quality.

2. Impact on Reliability and Availability

- **Individual vs. Grid Availability:** A single high-quality DG unit typically has a service availability of **94% to 98%**, whereas the traditional utility grid often exceeds **99.95%**.

- **Modularity and Redundancy:** The aggregation of multiple modular DG units changes the failure profile. While using multiple small units increases the statistical probability of a **partial failure** (some capacity out), it drastically reduces the likelihood of a **total power failure** compared to a single large unit.

- **Starting Probability:** For units used in peaking applications, the probability of **failing to start** is a critical reliability factor. Units that start frequently face higher equipment stress, as starting requires more components (like starter motors and control circuits) to function flawlessly compared to continuous operation.

3. Operational and Efficiency Impacts

- **Schedule Dynamics:** The fuel efficiency of a DG unit is heavily impacted by its operating schedule. **Starting and stopping** a unit consumes fuel for warmup without producing power, and thermal energy is lost as the engine block cools after shutdown.

- **Load Tracking:** Efficiency suffers when units are forced to track rapidly fluctuating non-coincident loads. For small units, this constant acceleration and deceleration can result in **50% to 80% more fuel usage** than what would be predicted by a smooth coincident load curve.

- **Wear and Tear:** Frequent cycling and tracking of "needle peaks" increase mechanical stress, potentially shortening the service lifetime of reciprocating engines and micro-turbines.

4. Grid Integration and Protection Challenges

- **Increased Fault Duty:** Integrating DG units can increase the **fault duty** (short-circuit current) of the system. This may require upgrading existing circuit breakers to higher-rated, more expensive models.

- **Vulnerability to External Faults:** Grid-connected DG units are exposed to disturbances far from their site. For instance, a temporary fault on a utility line (like a tree branch brushing a wire) can cause a **voltage sag** that trips sensitive DG control systems, shutting the unit down even if the fault is cleared in milliseconds.

- **Protection Complexity:** Parallel operation with the grid requires sophisticated protective equipment to prevent the DG from feeding grid faults and vice versa. This equipment often **doubles the cost** of the electrical interface compared to isolated operation.

- **Phase Imbalance:** Radial distribution feeders are often unbalanced; ignoring this in DG planning can lead to underestimated losses and poor voltage regulation, as DG units may exacerbate or be affected by these imbalances.

- A traditional power system's primary mission is to produce power at central generating stations and deliver it to consumers in a ready-to-use form. To achieve this, the system is structured in a hierarchical manner designed to "lower voltage and split" the electrical pathways as power moves from the bulk generation level toward individual customers.

- Transmission Systems

- The transmission system is the highest level of the power delivery chain, operating as a network of three-phase lines.
- Function and Stability: In addition to moving bulk power, major transmission lines are designed for system stability. They provide a strong electrical tie between generators, allowing them to stay synchronized and ensuring the system can pick up load smoothly if a generator fails.
- Operating Characteristics: Transmission lines generally operate at voltages between 115 kV and 765 kV. Individual line capacities typically range between 50 MVA and 2,000 MVA.
- Network Structure: Unlike distribution systems, transmission systems are configured as networks, meaning there is more than one electrical path between any two points. This redundancy is maintained for reliability; if one line fails, power can be rerouted through an alternative path to prevent interruptions.
- Costs: Transmission costs are based on a per-mile rate and a termination cost at the substations. These can range from $50,000 per mile for low-voltage sub-transmission to over $1,000,000 per mile for high-capacity 500 kV construction.
- Distribution Systems
- The distribution system begins at the substation level and delivers power to the ultimate consumer. Unlike the transmission level, most distribution systems are radial, meaning there is only one path from the substation to the customer, as a network configuration at this level is prohibitively expensive.
- Sub-transmission: These lines take power from transmission switching stations to distribution substations. They typically operate between 34.5 kV and 230 kV with capacities ranging from 30 MVA to 250 MVA.
- Substations: These serve as the meeting point between the transmission grid and the distribution system. Their most important components are substation transformers, which convert high-voltage transmission power to lower primary distribution voltages.
- Feeders and Laterals:

- Feeders route power from the substation through the service area at primary distribution voltages (commonly 12.47 kV in North America). They can be overhead lines or underground cables.
- Laterals are short line segments that branch off the primary feeders to route power directly into neighborhoods, typically serving a few dozen homes.
- Service Level: This is the final step where service transformers lower the voltage to utilization levels (e.g., 120/240 V). Because power travels efficiently for only about 200 feet at these voltages, transformers must be located very close to every customer.
- Technical and Economic Comparisons
- Reliability: Service reliability generally drops as one move closer to the customer. Roughly 60% of service interruptions are caused by the failure of distribution equipment located within a half-mile of the consumer.
- Cost Trends: The total inflation-adjusted cost of delivering power through transmission and distribution (T&D) systems increased by approximately 35% between 1955 and 2000.
- Spatial Variation: Delivery costs are not uniform; they can vary by a factor of seven to one across a utility system depending on location, equipment condition, and local construction restrictions.
- Upgrade Expenses: It consistently costs more to upgrade existing T&D facilities to a higher capacity (e.g., 33/kW) than it did to build that capacity originally (10/kW), creating significant economic opportunities for Distributed Generation (DG) to defer these upgrades.

De-regulation – Impact of DGs upon protective relaying:

The transition toward a de-regulated electric industry is fundamentally changing the role of Distributed Generation (DG) and its technical requirements for protective relaying. De-regulation fosters competition at the retail level, allowing power retailers to use DG to bypass traditional utility transportation costs and offer customized, tiered reliability and power quality options to consumers.

The impact of integrating DGs into this new marketplace on protective relaying is detailed below:

Economic and Operational Context of De-regulation

- Tiered Reliability: In a competitive market, providers move away from a "one-size-fits-all" reliability structure to offer a range of combinations of cost and reliability. This makes DG an attractive tool for providing "premium power" or low-cost, lower-reliability options.
- Bypassing T&D Costs: Power retailers (such as ESCOs or Load Aggregators) utilize DG to avoid transmission and distribution (T&D) capacity fees and ancillary service charges levied by regulated "wire companies".
- Operational Flexibility: Parallel operation with the grid allows DG owners to sell surplus power back into the marketplace, which requires more sophisticated bidirectional metering and protection.

Impact on Protective Relaying and System Protection

Interconnecting DG units with the utility grid—especially for parallel operation—introduces significant engineering complexities. The protective relaying must be "smarter" and more sophisticated, often more than doubling the cost of the electrical interface compared to isolated operation.

- Bidirectional Fault Protection: DG units and the utility grid must be protected from one another's failures.
  - o Grid Protection: A DG unit can "feed" a fault that occurs on the utility grid, potentially causing damage to system equipment and creating a severe safety hazard for utility crews attempting to repair the problem.

- o DG Protection: If a DG unit experiences an internal fault while connected to the grid, the utility system will supply power into that fault, which can result in fires or the total destruction of the DG unit.
- Increased Fault Duty: Integrating generation into the distribution system increases the fault duty (short-circuit current). This may require upgrading existing utility circuit breakers to models with higher ratings and costs to ensure they can safely interrupt these higher currents.
- Vulnerability to Remote Grid Disturbances: DG protective relaying often struggles to distinguish between local faults and remote grid events. For example, a temporary fault on a utility line (such as a tree branch brushing a wire) causes a voltage sag. Sensitive DG relaying may interpret this as a safety risk and trip the unit off-line, leaving the owner without power during the very storms when the grid is most vulnerable.
- Automatic Synchronization and Reactive Power:
    - o Synchronous Generators: These require precise governor control and relaying to ensure they are synchronized with the grid frequency before connection.
    - o Induction Generators: These are "automatically synchronizing" and have a built-in safety advantage: because they require reactive power (VARs) from the grid to operate, they will not "feed a fault" upstream. A fault on the line between the generator and the system instantly terminates its power production by cutting off its VAR supply.
- Phase Imbalance: Most radial distribution feeders are unbalanced. Protective relaying for DG must account for this; ignoring phase imbalance can lead to poor voltage regulation and unexpected tripping of the DG unit.

Market facts, issues, and challenges - Limitations of DGs:

The integration of Distributed Generation (DG) units into existing distribution systems introduces complex technical, economic, and control challenges. Based on the provided materials, here is a detailed analysis of these aspects.

Impact on Transient and Dynamic Stability

Traditional power systems rely on the transmission grid to provide a strong electrical tie between generators, ensuring they stay synchronized and can pick up load smoothly during fluctuations, a concept known as stability of operation. In contrast, DG units, particularly when operating in isolation or at the edges of a distribution system, face significant stability challenges:

- Transient Response and Load Tracking: Standalone DG units must track nearly instantaneous plus-and-minus load shifts that can be as large as 60% of their capacity. Unlike the large utility grid, which acts as a "near-perfect" voltage source, DG units have a noticeable transient response delay when reacting to shifts in demand.
- Voltage Regulation and Flicker: As demand varies, a DG unit's controller must adjust the fuel flow or throttle to stabilize voltage. This delay can lead to voltage flicker or sags that fall outside recommended standards (like the CBEMA envelope), potentially causing digital equipment to reset.
- Vulnerability to External Faults: Grid-connected DG units are sensitive to transient events on the utility system, such as voltage sags caused by trees brushing against lines during storms. A DG controller might interpret a sag as a load increase and accelerate its output, only to face an overvoltage condition and trip off-line when the fault clears, often leaving the owner without power precisely when the grid is most at risk.

- Rotational Inertia: Heavy rotors or flywheels intended to provide mechanical energy storage often have reaction times too slow to track rapid load swings, which further degrades power quality and voltage regulation.

Economic Aspects of DGs

The economic justification for DG often rests more on its proximity to the consumer than on its generation efficiency.

- Avoidance of T&D Costs: DG "wins" economically when its production cost is lower than the combined cost of central station generation plus the transmission and distribution (T&D) costs required to deliver that power. T&D costs increased by roughly 35% between 1955 and 2000, raising the "avoided cost" value of DG.
- Modularity and Risk Management: Most DG units are factory-assembled, "off-the-shelf" modules. This modularity allows owners to install only the capacity needed for current demand and expand incrementally as load grows, which reduces business risk and allows for deferred spending.
- Tailorable Reliability: DG offers a flexible way to choose a range of cost and reliability combinations that the grid cannot match. For example, high-reliability service (only a few minutes of outage annually) can often be achieved more cheaply via redundant DG units than by reinforcing the utility grid to the same standard.
- Economic Evaluation Factors: Accurate DG planning requires discounting future costs and energy production to determine a valid present worth (PW). Sensitivity to fuel costs is significant; a 50% change in fuel price can impact the total evaluated cost by approximately 25%.

Control Aspects of DGs

Control systems are critical for ensuring that DG units operate safely and efficiently, especially when integrated with a grid.

- Automation and Monitoring: Modern computerized control systems and remote data communications allow DG units to be self-operating and automatic, eliminating the need for constant on-site human supervision.
- Speed and Frequency Regulation: In rotating machine interfaces, quick-reacting electronic governors are necessary to maintain the constant speed required for synchronous AC power.
- Power Electronics: Units that produce DC (like fuel cells or photovoltaics) or variable-speed turbines require DC-AC converters. These interfaces permit the parallel use of energy storage (e.g., batteries), which can handle "needle peak" loads while allowing the generator to run at a steady, efficient level.
- Interconnection Protection: Grid-connected systems require sophisticated control and protective relaying to prevent the DG from feeding faults into the grid (and vice versa). This equipment often doubles the cost of the electrical interface compared to isolated operation.
- Two-Dimensional Control: More complex technologies, such as Solar Thermal Electric Storage (STES), require control systems that can simultaneously manage both varying temperatures and fluid flows to maintain optimal output.

Voltage control techniques, Reactive power control, Harmonics, Power quality issues:

Power quality and control are critical aspects of distributed generation planning, as smaller units often lack the inherent stability provided by the vast utility grid. The following notes detail the techniques and issues identified in the source material:

Voltage Control Techniques

- **Substation Regulation**: Traditional distribution substations utilize substation transformers equipped with tap-changing mechanisms and control equipment to maintain voltage within a very narrow band (typically ±0.5%), regardless of transmission-side fluctuations.

- **DG Unit Controllers**: Standalone DG units must monitor their own output voltage and use automatic controllers to adjust the throttle or fuel flow in response to demand shifts. However, these units often have a noticeable transient response delay, leading to temporary voltage drops when large appliances start up.

- **Power Electronics**: Inverter-based DGs (such as PV or fuel cells) use DC-AC converters that can precisely "wave-shape" power, providing near-perfect voltage regulation through advanced electronic controls.

- **Grid Smoothing**: Parallel grid interconnection allows the utility to act as a "non-coincident load smoother," providing instant transient response to handle sharp spikes that a DG unit might otherwise miss.

Reactive Power (VAR) Control

- **Induction Generators:** These units are robust and automatically synchronize with the grid, but they require reactive power (VARs) from the system to operate. They essentially act as a reactive load while being a real power source.

- **Synchronous Generators:** These units can be designed to produce a great deal of VAR output in addition to real power, though doing so can cause the generator windings to become quite hot, sometimes requiring liquid cooling.

- **Capacitor Correction**: Capacitors are used in shunt or series on AC systems to provide reactive power adjustment. Large industrial T&D extensions often require dedicated capacitor banks near the load to maintain power factor standards.

Harmonics

- **Generation Sources**: Some DGs, like micro-turbines, produce "dirty" or pulsed DC power that contains a mixture of frequencies.
- **Filtering in Converters:** DC-AC converters use chopper circuits to create square waves, which are then passed through high-pass filters to remove higher harmonic components and leave only pure 60-cycle power.
- **Load Sensitivity:** While some appliances like water heaters can productively turn harmonics into heat, digital equipment and computers are highly sensitive to harmonic contamination.

Power Quality Issues

- **Voltage Flicker:** This refers to momentary voltage variations caused by a DG's inability to track rapid "needle peak" shifts instantly. This can cause visible dimming of lights and slowing of motors.
- **Voltage Sags and the CBEMA Curve:** Brief drops in voltage—often caused by remote grid faults—can be indistinguishable from interruptions to sensitive equipment. The CBEMA envelope is a standard guideline for what voltage sags and surges business equipment should tolerate; however, many modern devices are more sensitive than the curve specifies.
- **Impact of Storage:** Energy storage with a fast time constant (like batteries or ultracapacitors) can fill in needle peaks, allowing the DG unit to run at a steady, efficient level while maintaining high power quality.
- **SMES for Premium Quality:** Superconducting Magnetic Energy Storage (SMES) is used for applications requiring "near-perfect" quality. SMES units can react within 40 microseconds to "wave-shape" outgoing power into a perfect sine wave, shielding the load from all grid disturbances.

In the context of power engineering, reliability is defined as the fraction of time that service is available, often referred to as continuity of service. Distributed Generation (DG) offers a unique value proposition because it allows reliability to be tailored to specific consumer needs in ways a standardized grid cannot easily match.

Availability Comparison: DG vs. Utility Grid

A significant challenge for DG planners is that the standard electric grid provides extremely high levels of service availability, typically 99.96% or better in developed nations.

- Individual DG Performance: High-quality DG units generally have a service availability of approximately 94% to 98%, accounting for both unexpected failures and scheduled maintenance.
- The Reliability Gap: Because single DG units are less reliable than the grid, achieving grid-level reliability (or better) with on-site generation requires redundancy, sometimes involving up to 100% additional capacity.
- Niche Advantages: DG "wins" at both ends of the reliability spectrum. It can provide a low-cost option for users who don't mind occasional interruptions, or premium reliability (e.g., only a few minutes of annual outage) for sensitive industrial users through redundant configurations.

Modularity and Redundancy

Most DG units are factory-assembled, standardized modules. Aggregating these units at a single site fundamentally changes the reliability profile:

- Partial vs. Total Failure: While having multiple small units increases the statistical probability that *some* capacity will be out (partial failure), it drastically reduces the

likelihood of a total power failure because independent units rarely fail simultaneously.

- Reserve Margin: Planners can pick the number and sizes of units to reach specific goals. For example, using six 275 kW units to serve an 1,100 kW load ensures that service is maintained even if one or more units fail.
- Maintenance Flexibility: Modularity allows for scheduled maintenance to be performed on one unit while others remain in service, minimizing the impact on availability.

Grid Integration and Reliability

Interconnecting a DG unit with the local utility grid can further enhance reliability, though it introduces technical complexities:

- Parallel Operation: Both the DG and grid are connected to the load simultaneously. If the DG fails, the grid provides instant transient response, ensuring no interruption of power.
- Rollover (Switched) Operation: Only one source is connected at a time. If the primary source fails, the system "rolls over" to the backup. While simpler and less expensive than parallel operation, this results in a brief service interruption during switching.
- Vulnerability to External Faults: Grid-connected DGs are sensitive to transient events far from their site. For instance, a temporary fault on a utility line can cause a voltage sag that trips sensitive DG control systems, potentially leaving the owner without power during storms when the grid is most vulnerable.

Critical Reliability Factors

- Starting Probability: For units used in peaking or backup roles, the probability of failing to start is a critical reliability factor often ignored in base-load models.

Starting requires more components (starter motors, control circuits) to function flawlessly compared to continuous operation.

- Renewable Resource Constraints: For solar or wind DG, the unpredictability and natural cycles of the energy resource (e.g., the sun not shining at night) are much larger constraints on availability than equipment failure. Reliable service from these sources typically requires energy storage (batteries or flywheels) to "ride-through" periods of resource unavailability.

Evaluation Methods

Reliability is assessed through various indices, most notably SAIFI (frequency of interruption) and SAIDI (total duration of interruption). Predictive analysis methods for DG include:

- State Enumeration: Identifying all possible combinations of unit status (in or out of service) and computing their probabilities.
- Monte Carlo Simulation: "Rolling the dice" against probability distributions to predict a series of random failure and repair events over many simulated years.
- Markov (State-Transition) Models: Representing the DG system as moving between various states (Operating, Failed, Awaiting Repair) to determine expected temporal patterns of failure.

Steady-state and Dynamic analysis:

In the planning and evaluation of Distributed Generation (DG) systems, the distinction between steady-state and dynamic analysis is critical for understanding reliability, fuel economy, and power quality.

Steady-State Analysis

Steady-state analysis is primarily used in reliability evaluation to define the long-term average performance of a system.

- Definition of Availability: Availability is defined as the steady-state probability that electrical service will be available to the consumer, or the fraction of time a unit is capable of performing its required function.
- Predictive Reliability: Standard reliability models often use steady-state probability-of-failure figures to calculate the expected hours per year a unit will be out of service.
- Focus: It typically ignores the moment-to-moment fluctuations in load and generation, focusing instead on whether a unit is "In" or "Out" of service over a lengthy reporting period.

Dynamic Analysis (Schedule and Transient Dynamics)

Dynamic analysis is required when planners must account for time-varying schedules, rapid load transitions, and the physical response times of DG equipment.

- Scheduling Dynamics: Most DGs do not run at constant output but follow a production schedule. Dynamics like starting and stopping a unit for peaking applications significantly impact performance.
  - Fuel Efficiency Impact: Frequent starting and stopping consumes fuel for warmup and run-up without producing power, while thermal energy is lost as the engine block cools after shutdown. These dynamics can degrade fuel economy by 15% to 25% compared to steady-state operation.
- Transient Response and Load Tracking: Small DG units must track nearly instantaneous plus-and-minus load shifts that can be as large as 60% of their capacity.
  - Transient Delay: Rotating machines (piston engines or turbines) have a noticeable transient response delay as they "catch up" to demand.
  - Voltage Quality: If a DG unit cannot react quickly enough to a "needle peak" demand shift, it causes voltage flicker or sags that may fall outside

recommended standards (like the CBEMA envelope) and reset digital equipment.

- Machine-Specific Dynamics: Detailed dynamic analysis must model thermal temperature gradients, wear, and emissions on a fine temporal scale. For instance, a unit's fuel economy is markedly worse when "cold" than when it has reached stable operating temperatures.

Analytical Methods and Simulation

While steady-state figures can be estimated with simple probability tables, dynamic behavior requires temporal simulation.

- Temporal Resolution: Dynamic studies use "time slices" that range from hourly (for scheduling) to minute-by-minute (for startup dynamics) or even sub-second intervals (for transient machine analysis).
- Modelling Requirements: Advanced simulations must include the dynamic transient response characteristics of both electrical and mechanical factors, such as motor in-rush currents or control system reaction times.
- Non-Coincident Load: Simulation is essential for modeling "needle peak" behavior in dispersed generation, as standard 15- or 30-minute demand sampling will smooth out the very dynamics that cause DG system failure.

Outcome:

1. Explain the technical impacts of distributed generation on transmission and distribution systems.
2. Evaluate the effects of DG penetration on protection coordination and relaying systems.
3. Analyze the transient and dynamic stability performance of distribution networks with DG integration.
4. Assess economic, market, and regulatory issues associated with DG deployment.

5. Investigate voltage control, reactive power control, harmonics, power quality, and reliability aspects of DG-based power systems.

BOOK/NPTEL LINK REFERENCE FOR UNIT -1

1. G N Tiwari, Solar Energy: Fundamentals, Design, Modelling and Applications, Narosa, 2002.

2. Mukund R Patel, Wind and Solar Power Systems: Design, Analysis, and Operation, 2nd

3. https://archive.nptel.ac.in/courses/121/106/121106014/

4. https://onlinecourses.nptel.ac.in/noc22_ch27/preview

5. https://www.nptelvideos.com/lecture.php?id=8517https://www.nptelvideos.com/lecture.php?id=8517

ASSIGNMENT TOPICS:

1. Explain the technical impacts of Distributed Generation on transmission and distribution systems.
2. Discuss the economic and control aspects of Distributed Generation systems.

QUESTION BANK:

S.No.	CO	Questions	BT
UNIT-5: TECHNICAL IMPACT, ECONOMIC AND CONTROL ASPECTS OF DG			
1	5	a) Explain the technical impacts of Distributed Generation (DG) on transmission systems. b) Discuss effects on power flow, congestion, voltage profile, short-circuit levels, and system losses?	L4
2	5	Discuss the technical impacts of DGs on distribution systems and Explain how DG penetration affects voltage regulation, reverse power flow, protection coordination, and power quality?	L3
3	5	Explain the concept of power system deregulation. Discuss the impact of DGs in a deregulated electricity market, highlighting operational, economic, and regulatory challenges?	L4
4	5	Explain the impact of Distributed Generation on protective relaying. Discuss issues related to relay coordination, fault current variation, blinding of protection, and false tripping with suitable diagrams?	L3

5	5	Explain the impact of DGs on transient and dynamic stability of existing distribution systems? Discuss the influence of inverter-based and rotating-machine-based DGs on system stability?	L5
6	5	a) Explain the market facts, issues, and challenges associated with Distributed Generation. b) Discuss tariff structures, market participation of DGs, ancillary services, and regulatory barriers?	L4
7	5	Discuss the limitations of Distributed Generation systems. Explain technical, economic, environmental, and operational constraints that restrict large-scale DG deployment?	L3
8	5	Discuss the role of inverters, on-load tap changers, capacitor banks, and FACTS devices?	L5
9	5	Explain the harmonic issues and power quality problems introduced by DGs. Discuss sources of harmonics, their effects on equipment, and mitigation techniques?	L4
10	5	Explain the reliability of DG-based power systems. Discuss steady-state and dynamic analysis of DG systems with respect to continuity of supply, fault tolerance, and system resilience?	L3

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