

Power Plant Engineering

Lecture 11

Miscellaneous Topics

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

- i. Explain the fundamental principles and working mechanisms of solar energy conversion and photovoltaic power generation systems.
- ii. Describe the components, operation, and site selection criteria for hydro-power generation systems.
- iii. Discuss the formation, extraction methods, and applications of geothermal energy for electricity production.
- iv. Analyze the aerodynamic principles and performance factors influencing wind energy power generation.
- v. Compare the advantages, limitations, and efficiencies of major renewable energy sources.
- vi. Evaluate strategies for the integration and hybridization of multiple renewable energy sources into a sustainable power system.

Content

1. Solar Energy and Photovoltaic Power Generation
2. Hydro-Power Generation
3. Geothermal Power Generation
4. Wind Energy Power Generation
5. Comparative Analysis and Integration of Renewable Energy Sources

Summary

References

1. Solar Energy and Photovoltaic Power Generation

Overview of solar radiation and solar spectrum

- The sun is the primary source of energy for the Earth, emitting electromagnetic radiation due to nuclear fusion reactions in its core.
- This energy is the primary source for almost all energy systems on Earth.
- There are **three key terms** in solar energy and atmospheric science:
 1. **The solar constant:** It is the amount of solar radiation energy received per **unit time** on a **unit area** of surface perpendicular to the sun's rays at the outer edge of the Earth's atmosphere when the Earth is at its average distance from the Sun [1].
- Its value is approximately **1361 Watts per square meter** (W/m²).

1. Solar Energy and Photovoltaic Power Generation

Cont...

2. **Solar radiation**: It is the energy emitted by the sun, primarily in the form of electromagnetic waves.

- As solar radiation passes through the atmosphere, it is **absorbed**, **scattered** in different directions, and **reflected**, reducing the radiation reaching the surface.
- The sun emits radiation across a wide range of wavelengths ranging from ultraviolet (UV) to infrared (IR).
- The distribution of this power is not uniform and the **solar spectrum** includes:
 - ✓ **Ultraviolet (UV)**: < 400 nm (about 5% of total energy)
 - ✓ **Visible light**: 400–700 nm (about 43%)
 - ✓ **Infrared (IR)**: > 700 nm (about 52%)

Types of solar radiation

- a. **Direct (beam) radiation:** Solar energy received directly from the sun's rays without scattering.
- b. **Diffuse radiation:** Radiation scattered by clouds and particles in the atmosphere.
3. **Global radiation:** The sum of direct and diffuse radiation on a horizontal surface.
3. **Air Mass (AM):** It describes the path length that sunlight takes through the Earth's atmosphere relative to the shortest possible path (when the Sun is directly overhead).

Principles of Photovoltaic (PV) Conversion

- The photovoltaic effect is the **direct conversion of light** (photons) into **electricity** (voltage) using **semiconductor materials** that exhibit the **photovoltaic effect**.
- It is a physical and chemical phenomenon.
- **The key steps include:**
 1. **Absorption of sunlight** by the semiconductor.
 2. **Generation** of charge carriers (electrons and holes).
 3. **Separation** of charge carriers across the p-n junction.
 4. **Collection** or **current generation** of electrons through external circuitry to produce electric power.

Types of Solar Cells

1. Monocrystalline Silicon (Mono-Si)

- Made from a **single continuous crystal** structure.
- High efficiency.
- Higher cost but longer lifespan and better performance in low-light conditions.

2. Polycrystalline Silicon (Poly-Si)

- Made from **multiple silicon crystals** melted together.
- Lower efficiency but cheaper to produce.
- Blueish appearance and slightly lower temperature tolerance.

3. Thin-Film Solar Cells

- Made by depositing **thin semiconductor layers** (e.g., cadmium telluride (CdTe), amorphous silicon (a-Si), copper indium gallium selenide (CIGS) on substrates.
- Lightweight and flexible, with efficiencies of 10–15%.
- Suitable for large-scale or building-integrated applications.

4. Perovskite Solar Cells

- Emerging technology using hybrid organic–inorganic lead halide materials.
- High efficiency (over 25%) and low production cost.
- Challenges include **stability, toxicity, and scalability**.

PV System Components

- A complete PV system consists of several components that generate, control, store, and distribute electricity.

1. PV Modules (Panels)

- An array of interconnected PV cells encapsulated and protected from the environment.
- Converts solar energy into DC electricity.

2. Inverter

- Converts **DC** from solar panels to **AC** for grid or local use.

Types of Inverters:

- ✓ **String inverters** - One inverter for a whole string of panels (cost-effective).
- ✓ **Microinverters** - One small inverter attached to each individual panel.
- ✓ **Central inverters** - parallel strings are fed into one centralized inverter unit.

3. Batteries

- Store excess energy for use during low sunlight or at night.
- Common types:
 - ✓ **Lead-acid** - traditional, cheaper
 - ✓ **Li-ion** - modern, higher efficiency, longer lifespan, more expensive.

4. Charge Controllers

- Regulate voltage and current from PV panels to batteries.
- Prevents **overcharging** or **deep discharging**.

Types:

- ✓ Pulse Width Modulation (PWM)
- ✓ Maximum Power Point Tracking (MPPT)

5. Balance of System

- Includes mounting structures, wiring, circuit breakers, fuses, and grounding equipment.

1. Solar Energy and Photovoltaic Power Generation

Cont...

Components of Solar Photovoltaic System

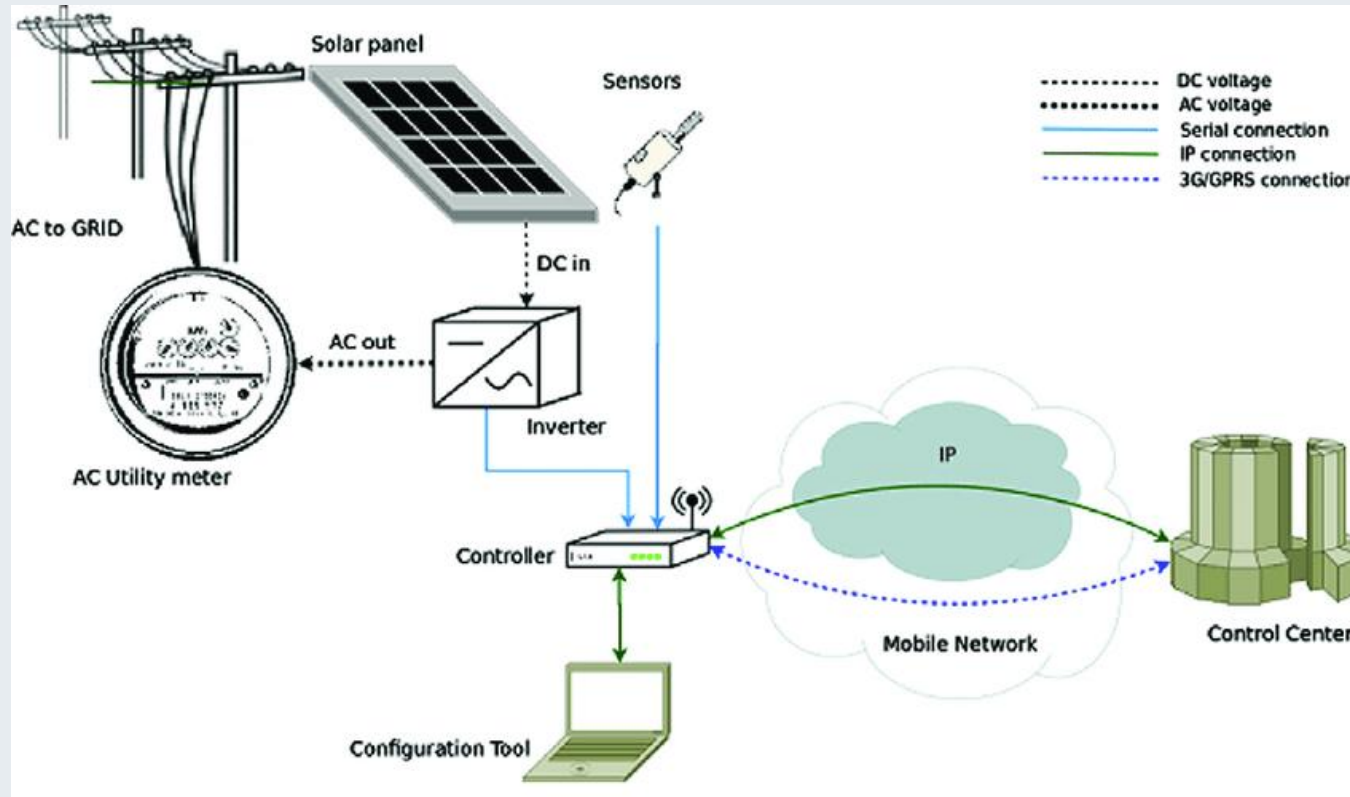


Figure 1: Components of Solar Photovoltaic System, Meliones, A., Apostolacos, S., & Nouvaki, A. Applied Computing & Informatics (2014)

url:<https://www.researchgate.net/publication/262194849/figure/fig15/AS:667896925655040@1536250444127/PV-System-components.png>

Configurations of photovoltaic (solar power) setups

There are three common configurations:

1. Grid-Connected (On-Grid) System

- The PV system is connected to the public electricity grid.
- Surplus electricity is fed to the grid (net metering).
- No battery storage required; inverter synchronizes with grid voltage and frequency.
- Used in urban and commercial installations.
- The most common type.

1. Solar Energy and Photovoltaic Power Generation

Cont...

2. Stand-Alone (Off-Grid) System

- The PV system operates independently of the utility grid.
- Require batteries for storage and charge controllers.
- Ideal for remote or rural areas without grid access.
- However, it has high cost due to batteries and requires careful sizing to match energy needs.

3. Hybrid Systems

- Combine PV with other sources (e.g., diesel generator or wind turbine).
- Improve reliability and power availability.

Efficiency Factors and Performance Evaluation

The key efficiency factors include:

1. **Temperature:** Efficiency decreases as temperature rises due to reduction in open-circuit voltage (V_{oc}).
2. **Solar Irradiance (Intensity of Sunlight):** Higher sunlight increases output up to saturation level.
3. **Angle of incidence:** Optimal when sunlight is perpendicular to the panel.
4. **Dust and shading:** Reduce light absorption and power output.
5. **Material properties:** Band gap energy, reflectivity, and recombination rates influence performance.

Efficiency Factors and Performance Evaluation

1. **Module Efficiency (η)**: is the ratio of the electrical power output of a solar PV module to the solar power input received by the module's surface area under standard test conditions (STC) [1].

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{mp} \times I_{mp}}{G \times A} \quad \text{Where, } G = \text{Irradiance} \left(\frac{\text{W}}{\text{m}^2} \right)$$

$A = \text{area (m}^2\text{)}$

2. **Performance Ratio** - It measures how well the system converts available solar energy into actual electrical output, including system losses.

- Mathematically,

$$PR = \frac{\text{Actual Energy Output of PV System}}{\text{Theoretical Energy Output under Ideal Conditions}} = \frac{E_{\text{actual}}}{E_{\text{theoretical}}}$$

3. **Capacity Factor** – It is a measure of how effectively a power plant or PV system generates electricity compared to its maximum possible output over a certain period.

- It indicates the utilization of installed capacity.

$$CF = \frac{\text{Actual Energy produced over Time Period}}{\text{Maximum Possible Energy Output over the Same Period}} = \frac{E_{\text{actual}}}{P_{\text{rated}} \times T}$$

Diverse Applications of Solar Energy

- Utility-Scale Solar Farms
- Commercial & Industrial Rooftops
- Residential Rooftops
- Off-Grid Applications
- Building-Integrated Photovoltaics (BIPV)
- Transportation
- Portable Electronics

2. Hydro-Power Generation

- Hydropower is the conversion of the **potential and kinetic energy** of water into **mechanical energy**, and subsequently into **electrical energy** [2].
- This flow drives turbines connected to **generators**, producing electrical energy.
- The process is clean, renewable, and relies on the **hydraulic head** (height difference) and **flow rate**.
- The basic idea is that water stored at a height (due to gravity) possesses **potential energy**.
- When released, it flows through a penstock, gaining **kinetic energy** as it moves downward.

2. Hydro-Power Generation

Cont...

- This kinetic energy is used to rotate a **turbine**, which drives a **generator** to produce electricity.
- **Potential Energy (PE)**

$$PE = mgh$$

Where: m = mass of water (kg)

g = acceleration due to gravity (9.81 m/s^2)

h = height difference (head) in meters

2. Hydro-Power Generation

Cont...

Classification of Hydropower Plants

- Hydropower plants are generally classified based on **head**, **capacity**, and **storage characteristics**.

1. Based on Head

Type	Head Range (m)	Example Turbine Type
Low Head	< 30 m	Kaplan, Propeller
Medium Head	30–300 m	Francis
High Head	> 300 m	Pelton

2. Hydro-Power Generation

Cont...

2. Based on Storage and Flow

a. Run-of-River (RoR) Plants

- i. Use natural river flow with little or no storage.
- ii. Depend on river discharge — electricity generation varies seasonally.
- iii. Environmentally less disruptive.

Example: Small hydro plants in mountainous regions.

b. Reservoir (Storage) Plants

- i. Have large dams that store water in reservoirs.
- ii. Can control flow and provide power on demand.
- iii. Used for base-load and peak-load supply.

2. Hydro-Power Generation

Cont...

c. Pumped Storage Plants

- i. Work as energy storage systems.
- ii. Water is pumped to an upper reservoir during low demand (using surplus energy) and released to generate power during peak demand.
- iii. Improve grid stability and load balancing.

Main Components of a Hydropower Plant

1. Dam

- Creates a reservoir to store potential energy of water.
- Controls water flow to the penstock.
- Also aids in flood control, irrigation, and recreation.

2. Hydro-Power Generation

Cont...

2. Penstock

- A large conduit or pipe that carries water under pressure from the reservoir to the turbine.
- Friction losses in penstock should be minimized.

3. Turbine

- Converts hydraulic energy into mechanical energy (shaft rotation).

4. Generator

- Converts mechanical energy from turbine shaft into electrical energy using electromagnetic induction.

5. Control Systems

- Include gates, valves, and electronic controllers for regulating water flow, turbine speed, and voltage output.

2. Hydro-Power Generation

Cont...

Components of a Hydro Power Generation

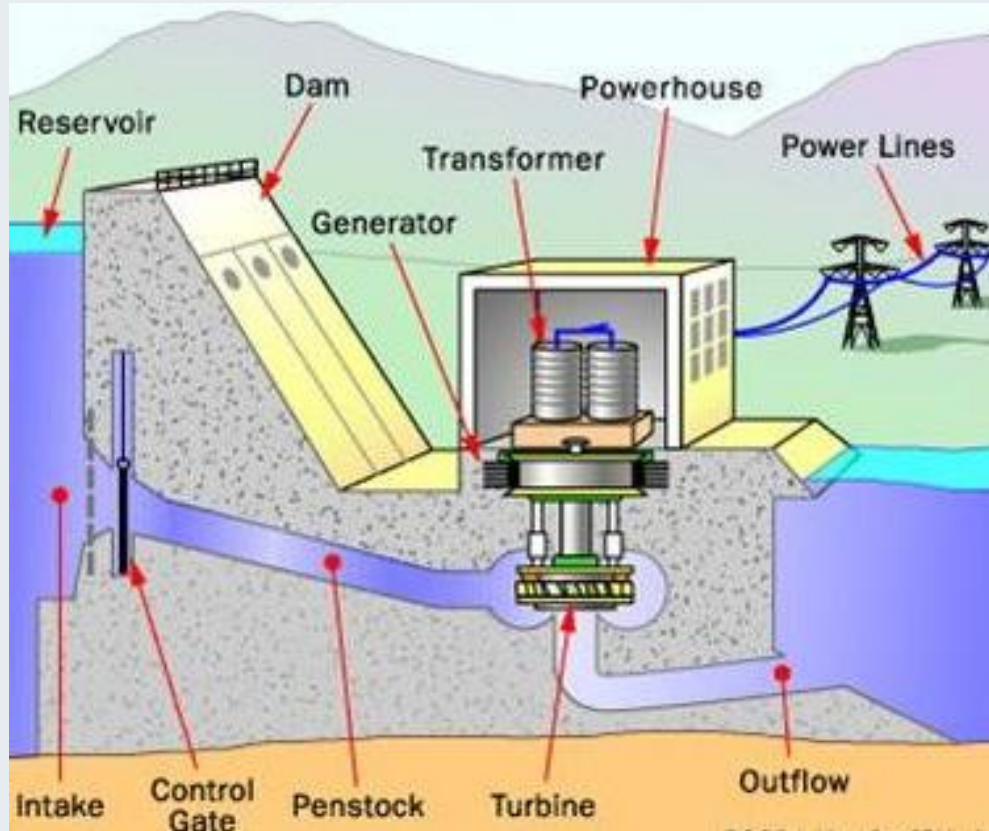


Figure 2: Components of a Hydro Power Generation, Anderson, Elliott, University of Alaska Fairbanks, (2015)

[url:https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRyIZsK2G89vEqKG5nGFzvjYUnKL2q1zCCUpYOZD5OWDeFlcgBe2KseDtsR&s](https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRyIZsK2G89vEqKG5nGFzvjYUnKL2q1zCCUpYOZD5OWDeFlcgBe2KseDtsR&s)

2. Hydro-Power Generation

Cont...

Types of Turbines and Their Operating Ranges

- Hydraulic turbines are selected based on **head** and **flow rate**.

Turbine Type	Head Range (m)	Flow Rate	Operation Principle	Typical Application
Pelton Wheel	300–1800	Low	Impulse turbine using water jets striking buckets	High-head, low-flow sites
Francis Turbine	30–600	Medium	Reaction turbine; radial and axial flow	Medium-head sites
Kaplan Turbine	2–40	High	Axial flow reaction turbine with adjustable blades	Low-head, high-flow sites

2. Hydro-Power Generation

Cont...

Site Selection Criteria

Key factors for hydropower site selection:

- Adequate water availability and reliable hydrology
- Suitable head and flow rate
- Geological stability and topography
- Accessibility and proximity to grid
- Environmental and social acceptability
- Economic feasibility and lifespan

2. Hydro-Power Generation

Cont...

Environmental and Social Impacts of Hydropower Projects

a. Environmental Impacts

- Alteration of river ecosystems and aquatic habitats
- Fish migration disruption (mitigated by fish ladders or bypasses)
- Sedimentation in reservoirs reducing capacity
- Water quality changes due to stagnation
- Greenhouse gas emissions from decaying biomass in reservoirs (especially in tropical zones)

b. Social Impacts

- Displacement of communities due to reservoir creation
- Loss of agricultural land and cultural heritage sites
- Changes in livelihoods (both negative and positive)
- Benefits include irrigation, flood control, and recreational use

3. Geothermal Power Generation

- Geothermal energy is the heat stored beneath the Earth's surface, originating from [3]:
 - **Residual heat** from the Earth's formation (~4.5 billion years ago)
 - **Radioactive decay** of isotopes (Uranium-238, Thorium-232, Potassium-40)
 - **Magma intrusion** and tectonic activity

- **Geothermal energy can be classified by Enthalpy (Heat Content):**

This is the most common engineering classification for power generation.

1. High-Enthalpy ($>150^{\circ}\text{C}$)
2. Medium-Enthalpy ($90^{\circ}\text{C} - 150^{\circ}\text{C}$)
3. Low-Enthalpy ($<90^{\circ}\text{C}$)

3. Geothermal Power Generation

Cont...

Types of Geothermal Reservoirs

1. Dry Steam Reservoirs

- Contain steam only (superheated)
- Steam directly drives the turbine

2. Wet Steam (Two-phase) Reservoirs

- Mixture of steam and hot water
- Steam separated before entering the turbine

3. Hot Water Reservoirs

- Contain liquid water at high pressure and temperature
- Used in flash steam or binary cycle systems depending on temperature

3. Geothermal Power Generation

Cont...

The key challenges in geothermal power generation are:

1. **Resource depletion** – If extraction exceeds natural recharge.
2. **Scaling and corrosion** – Due to dissolved minerals and gases (e.g., silica, H₂S).
3. **High initial cost** – Especially for exploration and drilling.
4. **Site specificity** – Only viable in geothermally active regions.
5. **Seismic risks** – From fluid reinjection (induced seismicity).

3. Geothermal Power Generation

Cont...

Environmental Aspects and Sustainability

Geothermal is one of the most environmentally benign energy sources.

■ Positive Aspects

- ✓ Low greenhouse gas emissions
- ✓ Small land footprint
- ✓ Continuous base-load energy source (unlike solar or wind)

■ Environmental Concerns

- ✓ Gas emissions: CO₂, H₂S, CH₄ (though much lower than fossil fuels)
- ✓ Thermal pollution: From discharged hot water
- ✓ Surface subsidence: Due to fluid withdrawal
- ✓ Noise and land use: During drilling

4. Wind Energy Power Generation

- Wind energy is the **kinetic energy** possessed by moving air masses in the atmosphere, which can be converted into **mechanical** or **electrical energy** using wind turbines [4].
- Differences in temperature and pressure create air movement.
- The total power available in the wind is not extractable.
- The fundamental equation for wind power is, i.e. the power available in the wind is:

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

Where: $\rho =$ Air density ($\approx 1.225 \frac{kg}{m^3}$ at sea level)

$A =$ Swept area of turbine blades (m^2)

$v =$ Wind velocity (m/s)

4. Wind Energy Power Generation

Cont...

- The turbine cannot capture all the wind's energy.
- The **Betz limit (Betz law)** shows the theoretical maximum efficiency of a wind turbine:

$$C_p(max) = 0.593$$

Thus, the extractable power is

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

Where C_p is the power coefficient (typically 0.35-0.45 in modern turbines)

4. Wind Energy Power Generation

Cont...

Classification of Wind Energy Systems

a. Based on Axis Orientation

1. Horizontal-Axis Wind Turbines (HAWTs)

- Rotor axis **parallel** to the ground and wind direction.
- Most common type used in large wind farms.
- Require yaw mechanism to face wind.

2. Vertical-Axis Wind Turbines (VAWTs)

- Rotor axis **perpendicular** to the ground.
- Accepts wind from any direction.
- Easier maintenance, but lower efficiency.

4. Wind Energy Power Generation

Cont...

b. Based on Power Output

Type	Power Range	Application
Micro	<1 kW	Battery charging, small devices
Small	1-50 kW	Rural electrification
Medium	50-500 kW	Distributed generation
Large	>500 kW-10 MW	Utility-scale wind farms

c. Based on Location

1. **Onshore wind farms:** Installed on land; lower cost but limited by terrain and land use.
2. **Offshore wind farms:** Located at sea; higher wind speeds, larger turbines, higher cost.

4. Wind Energy Power Generation

Cont...

Main Components of a Wind Turbine

1. Rotor Blades

- Capture wind energy and convert it to rotational motion.
- Typically 3 blades for balance and efficiency.
- Made of fiberglass or carbon fiber composites.

2. Hub

- Connects blades to the main shaft.
- Transfers torque from blades to gearbox.

3. Nacelle

- Houses main components at the top of the tower, including Gearbox, Generator, Shaft system, Brake and control systems

4. Wind Energy Power Generation

Cont...

4. Yaw Mechanism

- Rotates the nacelle to face the wind direction using sensors and motors.

5. Pitch Control System

- Adjusts blade angles to optimize lift and limit power output during high winds.

6. Tower

- Supports the rotor and nacelle.

7. Foundation

- Transfers loads to the ground; designed for static and dynamic stability.

4. Wind Energy Power Generation

Cont...

Aerodynamics and Operation of Wind Turbines

a. Lift and Drag Forces

- Wind turbine blades act as **airfoils**, generating lift perpendicular to the wind direction.
- **Lift force (L)** drives rotation and **drag force (D)** opposes motion.

- Tip-Speed Ratio (λ) $\lambda = \frac{\omega R}{v}$

Where: ω = rotational speed (rad/s)

R = rotor radius (m)

v = wind speed (m/s)

- Optimal performance occurs when $\lambda \approx 6 - 10$ for most HAWTs

4. Wind Energy Power Generation

Cont...

Types of Wind Power Plants

1. Standalone (Off-grid) Systems

- Used in remote areas.
- Often combined with batteries or diesel generators.

2. Grid-connected Systems

- Feed generated power directly into the grid.
- Require inverters and control electronics for synchronization.

3. Hybrid Systems

- Combine wind with solar, hydro, or diesel for reliability.

4. Wind Energy Power Generation

Cont...

Efficiency, Performance, and Power Output Calculation

1. Power Curve

- Characteristic curve showing output vs. wind speed.
- Key parameters:
 - Cut-in speed: 3–4 m/s
 - Rated speed: 10–15 m/s
 - Cut-out speed: 25 m/s

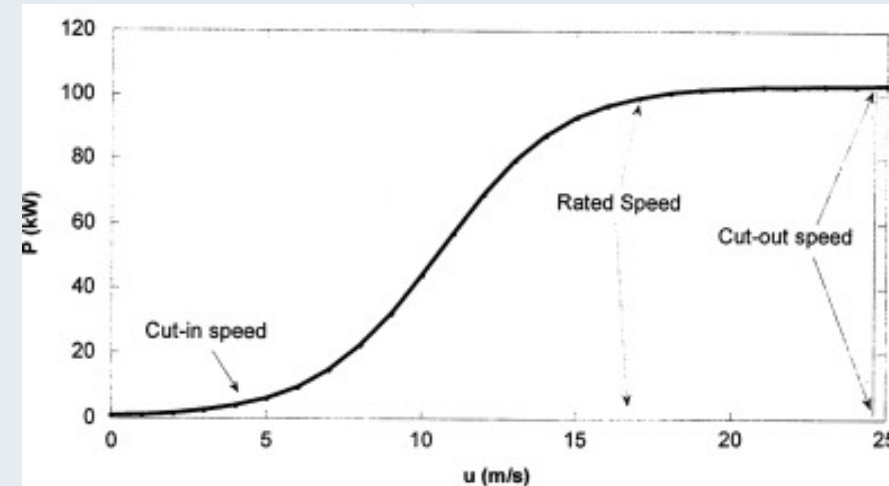


Figure 3: Wind Turbine Power Curve, M. Lydia, S. et. al, Renewable & Sustainable Energy Reviews, (2014)
url:<https://ars.els-cdn.com/content/image/1-s2.0-S1364032113007296-gr1.jpg>

- ### 2. Capacity Factor-
- is a measure of how efficiently a wind turbine or wind farm generates electricity compared to its **maximum possible output**.

$$CF = \frac{\text{Actual Energy Output}}{\text{Rated Capacity} \times \text{Time}}$$

4. Wind Energy Power Generation

Cont...

Site Selection Criteria

- **Wind Speed and Consistency** – Annual mean >6 m/s at hub height.
- **Topography** – Open plains, ridges, coastal areas ideal.
- **Accessibility** – For construction and maintenance.
- **Grid Proximity** – To minimize transmission losses.
- **Environmental and Social Impact** – Wildlife, noise, and visual concerns.

5. Comparative Analysis and Integration of Renewable Energy Sources

- Integration refers to the **technical and operational combination** of multiple renewable sources (and possibly storage systems) to provide **stable, reliable, and cost-effective power** [5].

Why Integration Is Important?

- Individual renewable energy technologies have intermittent or variable outputs.
- Integration enhances energy reliability, efficiency, and grid stability.
- Supports sustainable and low-carbon energy systems.

Integration Approaches

1. Hybrid Renewable Energy Systems

- Combination of **two or more** renewable sources, possibly with storage or backup generation.

Example: Solar–Wind–Diesel, Solar–Hydro, Wind–Biomass systems.

5. Comparative Analysis and Integration of Renewable Energy Sources

2. Grid-Connected Integration

- Renewable sources connected to national or regional grids.
- Requires grid codes, inverters, and energy management systems.

3. Off-Grid/Stand-Alone Integration

- Suitable for rural or remote electrification.
- Uses battery storage, load management, and possibly backup diesel generators.

4. Microgrids

- Localized energy networks integrating renewables, storage, and control systems.
- Can operate connected to or isolated from the main grid.

5. Comparative Analysis and Integration of Renewable Energy Sources

Strategies for Effective Integration

1. Diversified Energy Mix

- Combine base-load (hydro, geothermal) with variable (solar, wind).

2. Smart Grid Development

- Digital control, real-time monitoring, and flexible operation.

3. Forecasting and Scheduling

- Predict solar and wind output using meteorological data.

4. Policy and Market Mechanisms

- Feed-in tariffs, renewable portfolio standards, and carbon credits.

Summary

- Solar and photovoltaic power converts sunlight directly into electricity using solar cells with efficiency affected by irradiance and temperature.
- Hydro-power generation utilizes the potential and kinetic energy of flowing water to drive turbines and generate electricity.
- Geothermal power generation harnesses Earth's internal heat for steam production and power generation with high reliability.
- Wind energy power generation converts kinetic energy of moving air into electrical power through wind turbines.
- Integrated systems combines renewable sources and enhances reliability, stability, and sustainability of energy supply.

References

- [1]. Solar Energy and Photovoltaic Power Generation, Chetan Singh Solanki, PHI Learning Pvt. Ltd, 2013.
- [2]. Hydro Power Engineering, Dandekar, M. M., and Sharma, K. N Vikas Publishing House Pvt. Ltd, 2010.
- [3]. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, DiPippo, Ronald, Butterworth-Heinemann, 2016.
- [4]. Wind Energy Explained: Theory, Design and Application, Manwell, J. F., McGowan, J. G., and Rogers, A. L, John Wiley & Sons Ltd, 2010.
- [5]. Integration of Renewable Energy Sources: Engineering, Technology, and Sustainability, Jahangir, H., and Al-Turki, Y. A, Springer Nature, 2021.

Thank you !