Lecture 1.3

Energy Conversion in Various Power Plants

Agenda

- Principles of Energy Conversion
- Thermal Power Plants (Steam/Rankine)
- Gas Turbine Power Plants (Brayton)
- Combined Cycle Power Plants
- Hydroelectric Power Plants
- Nuclear Power Plants
- Renewable Power Plants (Wind/Solar)
- Efficiency and Losses

Principles of Energy Conversion

First Law of Thermodynamics

Energy cannot be created or destroyed, only transformed from one form to another.

- **General Conversion Pathway:** Primary Energy (Chemical/Nuclear/Potential/Kinetic) $\rightarrow$ Thermal/Kinetic Energy $\rightarrow$ Mechanical Energy $\rightarrow$ Electrical Energy.
- **The role of the Prime Mover:** A turbine or engine that converts fluid energy into mechanical shaft work.
- **The role of the Generator:** Converts mechanical shaft work into electrical energy via electromagnetic induction (Faraday's Law).

Steam Power Plants (Rankine Cycle)

- **Primary Source:** Chemical energy in coal, biomass, or oil.
- **Conversion Step 1 (Boiler):** Chemical energy $\rightarrow$ Thermal energy (heat of combustion) $\rightarrow$ Internal energy of steam (high pressure and temperature).
- **Conversion Step 2 (Steam Turbine):** Internal energy of steam $\rightarrow$ Kinetic energy (in nozzles) $\rightarrow$ Mechanical work (rotor blades).
- **Conversion Step 3 (Generator):** Mechanical work $\rightarrow$ Electrical energy.

Major Losses

Condenser heat rejection (latent heat of vaporization), boiler exhaust gases.

Gas Turbine Power Plants (Brayton Cycle)

- **Primary Source:** Chemical energy in natural gas or liquid fuels.
- **Conversion Step 1 (Combustion Chamber):** Chemical energy $\rightarrow$ Thermal energy of high-temperature combustion gases.
- **Conversion Step 2 (Gas Turbine):** Thermal energy of gases $\rightarrow$ Mechanical work.

Net Output

Self-Consumption: A significant portion (up to 50%) of turbine work is used to drive the air compressor.
Net Output: Remaining mechanical work drives the generator to produce electrical energy.

Combined Cycle Power Plants (CCPP)

Overview

Integration of Brayton and Rankine cycles to maximize energy extraction.
Process: Exhaust heat from the gas turbine (Brayton) is utilized in a Heat Recovery Steam Generator (HRSG).

- **Energy Flow:** High-temperature exhaust (500-600°C) $\rightarrow$ HRSG $\rightarrow$ Produces steam $\rightarrow$ Drives steam turbine (Rankine).
- **Efficiency Boost:** Converts previously wasted exhaust heat into useful mechanical work, raising overall plant efficiency to over 60%.
- **Environmental Impact:** Lower specific fuel consumption and reduced greenhouse gas emissions per MW compared to separate cycles.

Hydroelectric Power Plants

- **Primary Source:** Potential energy of water stored at an elevation (head).
- **Conversion Step 1 (Penstock):** Potential energy ($m \cdot g \cdot h$) $\rightarrow$ Kinetic energy ($\frac{1}{2}mv^2$) as water flows downwards.
- **Conversion Step 2 (Hydraulic Turbine):** Kinetic and pressure energy $\rightarrow$ Mechanical rotational energy.
- **Turbine Types:** Impulse (Pelton) for high head/low flow; Reaction (Francis, Kaplan) for medium/low head.
- **Conversion Step 3 (Generator):** Mechanical energy $\rightarrow$ Electrical energy.

Efficiency

Very high overall efficiency (85-90%) as no thermodynamic cycle (heat conversion) is involved.

Nuclear Power Plants

- **Primary Source:** Nuclear binding energy released via controlled nuclear fission (e.g., U-235).
- **Conversion Step 1 (Reactor Core):** Nuclear energy $\rightarrow$ Thermal energy (heat generated by fission fragments and radiation).
- **Conversion Step 2 (Heat Exchanger/Steam Gen.):** Thermal energy of primary coolant $\rightarrow$ Internal energy of steam in secondary loop.
- **Conversion Step 3 & 4:** Follows standard Rankine cycle (Steam Turbine $\rightarrow$ Mechanical work $\rightarrow$ Generator $\rightarrow$ Electrical energy).

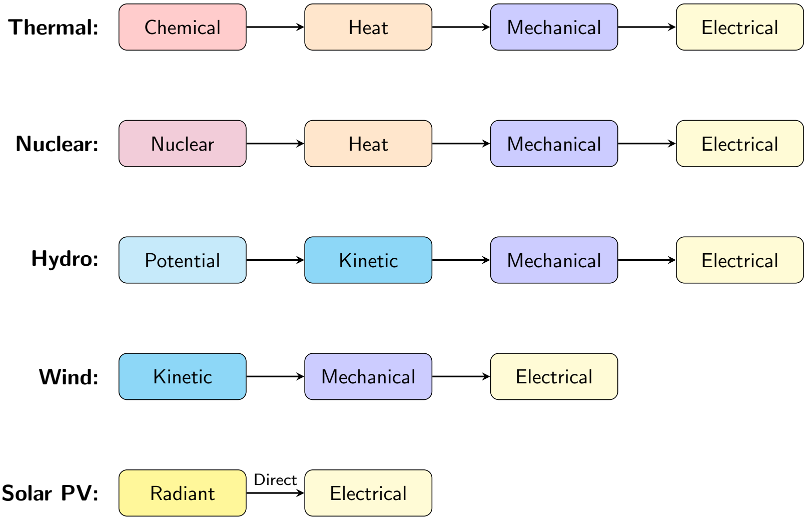
Key Differences

Lower steam temperatures/pressures compared to advanced fossil plants due to material and safety constraints.

Wind Power Plants

- **Primary Source:** Kinetic energy of moving air masses (wind).
- **Theoretical Limit:** Betz Limit dictates that a maximum of 59.3% of the wind's kinetic energy can be extracted by a turbine.
- **Conversion Step 1 (Rotor Blades):** Aerodynamic lift/drag forces convert wind kinetic energy $\rightarrow$ Mechanical rotational energy.
- **Conversion Step 2 (Drivetrain/Gearbox):** Matches low rotor speed to high generator speed (often bypassed in Direct Drive systems).
- **Conversion Step 3 (Generator):** Mechanical energy $\rightarrow$ Electrical energy (often requiring power electronics for grid synchronization).

Energy Conversion Pathways Comparison



Overall Efficiency and Losses

Efficiency Formula

Overall Efficiency = (Electrical Energy Output) / (Primary Energy Input)

- **Thermodynamic Losses:** Dictated by the Second Law; heat rejected to the sink (condenser/atmosphere) in thermal plants.
- **Mechanical Losses:** Friction in bearings, windage losses in rotating machinery, pump/compressor work.
- **Electrical Losses:** I^2R (copper) losses in generator windings, magnetic core losses.
- **Auxiliary Power Consumption:** Energy consumed by plant equipment (pumps, fans, coal crushers) reduces net output.

Summary

- ✓ Energy conversion in power plants involves transforming primary energy into electrical energy through intermediate thermal, kinetic, or mechanical stages.
- ✓ Thermal and Nuclear plants utilize thermodynamic cycles (Rankine, Brayton) subject to Carnot efficiency limits.
- ✓ Combined cycles achieve superior efficiency by cascading heat flows.
- ✓ Hydro and Wind plants rely on mechanical conversions, bypassing thermodynamic constraints but facing other limits (e.g., Betz limit).

Next Lecture Preview

Topic: 1.3 Load curves and associated terms

Understanding base load and peak load demand.

- Calculation of load factor, capacity factor, and diversity factor.
- How energy demand variations impact plant dispatch and operation.