Power Plant Engineering

Lecture 12

Miscellaneous Topics

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Lecture learning outcomes:

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

i. Explain the basic principles, sources, and conversion technologies involved in biomass power generation.

ii. Describe the working principles and safety aspects of nuclear power plants and their role in global energy supply.

iii. Analyze the causes and consequences of the greenhouse effect and its impact on climate change.

iv. Identify major types and sources of pollution resulting from energy production and industrial activities.

v. Discuss various pollution control methods and sustainable practices to reduce environmental impacts.

Content

1. Biomass Power Generation

Introduction to Biomass Energy

- Biomass energy refers to energy derived from organic materials — living or recently living plants, animals, and waste — that can be used as fuel to produce heat, electricity, or biofuels [1].
- It is a form of stored solar energy, as plants capture solar energy through photosynthesis, converting carbon dioxide and water into carbohydrates.
- When biomass is used for energy, this stored energy is released.
- It is considered a renewable source of energy because plants

  absorb CO_2 during growth, which offsets the CO_2 released

  when the biomass is burned or converted.

1. Biomass Power Generation

- Biomass provides about 9–14% of the world's primary energy supply, mostly in developing countries [1].
- It supports rural development and waste management while contributing to energy diversification.
- Plays a vital role in achieving net-zero carbon emissions and energy security goals.
- Biomass is the oldest source of energy for humanity, but its modern application for large-scale power generation is crucial for several reasons [2]:
  - ✓Renewability: Biomass can be replenished on a human timescale through sustainable management.

1. Biomass Power Generation

- ✓Energy Security: It reduces dependence on imported fossil fuels by utilizing domestic resources.
- ✓Waste Management: It offers a productive way to dispose of agricultural, urban, and industrial waste, reducing landfill use and methane emissions from decomposition.
- ✓Baseload Power: Unlike intermittent sources like solar and wind, biomass plants can provide a consistent, dispatchable supply of electricity.

1. Biomass Power Generation Cont…

Sources of Biomass

a. Wood and Agricultural Products

1. Virgin wood: Logging residues, wood chips, sawdust from forestry operations.
2. Energy crops: Fast-growing trees (e.g., willow, poplar) and grasses (e.g., miscanthus, switchgrass) cultivated specifically for energy production.
3. Agricultural residues: Straw, husks, shells, and bagasse (the fibrous residue from crushed sugarcane).

b. Animal Waste

1. Manure from poultry, cattle, and swine operations.

   This is a potent source of methane when processed anaerobically.

1. Biomass Power Generation Cont…

c. Municipal and Industrial Waste

1. Municipal solid waste: The organic fraction of household garbage (food scraps, yard waste, paper, wood).
2. Industrial waste: By-products from food processing, such as nut shells, olive pits, and wastewater sludge.

Biomass Conversion Technologies

- There are several technological pathways to convert the chemical energy in biomass into electricity.
- They can be broadly categorized into thermochemical and biochemical processes.

1. Biomass Power Generation Cont…

1. Thermochemical Conversion (Using Heat)

a. Direct Combustion

- Biomass is burned directly in a boiler to produce high-pressure steam.
- The heat is used to produce steam, which drives a steam turbine to generate electricity.
- The simplest and most common method.

Example: Wood-fired steam power plants.

Key reactions:

$$C_xH_y + O_2 \rightarrow CO_2 + H_2O + Heat$$

1. Biomass Power Generation Cont…

b. Gasification

- Converts solid biomass into producer gas (syngas) — a mixture of CO, H_2, CH_4, and CO_2 — by partial oxidation at high temperatures (800–1000°C) with limited air or oxygen.

- Syngas can be used in:
  - ✓Gas turbines,
  - ✓Internal combustion engines, or
  - ✓As feedstock for chemical synthesis (methanol, hydrogen).

  Main reactions:

$$C + O_2 \rightarrow CO$$

$$C + H_2O \rightarrow CO + H_2$$

1. Biomass Power Generation Cont…

c. Pyrolysis

- Thermal decomposition of biomass in absence of oxygen (400–600°C).
- Produces:
  - ✓Bio-oil (liquid fuel),
  - ✓Syngas, and
  - ✓Biochar (solid carbon residue).
- Fast pyrolysis produces mainly liquid fuels suitable for upgrading to transportation fuels.

1. Biomass Power Generation Cont…

2. Biochemical Conversion (Using Microorganisms)

a. Anaerobic Digestion

- Biochemical process using microorganisms to break down organic matter (animal waste, sewage, food waste) in oxygen-free conditions.
- Produces biogas (CH_4 + CO_2), which can be used for:
  - ✓Electricity generation,
  - ✓Heating, or
  - ✓Upgraded to biomethane for transport.
- The residue (digestate) is a useful biofertilizer.
- Ideal for high-moisture content feedstocks like wet waste.

1. Biomass Power Generation Cont…

Biomass Power Plant Components and Working Principles

- Let's take a direct combustion plant as a representative model.

a. Feedstock Preparation

- Biomass must be collected, transported, and processed to ensure uniform size and moisture content.
- Common preparation steps:
  - Drying (to reduce moisture < 15–20%),
  - Chipping or shredding, and
  - Pelletizing for uniform combustion.

1. Biomass Power Generation Cont…

b. Boiler or Reactor

- Combustion boiler: Burns biomass to generate high-pressure steam.
- Gasifier or pyrolyzer: Converts biomass to gas or oil intermediates for combustion or upgrading.

c. Turbine-Generator System

- Steam from the boiler drives a steam turbine, which rotates a generator to produce electricity.
- In gasification-based systems, syngas may be burned in a gas turbine or engine.

1. Biomass Power Generation Cont…

d. Emission Control Systems: Include:

- Cyclones or bag filters – remove particulates.
- Scrubbers – reduce SOx, NOx, and acid gases.
- Electrostatic precipitators – capture fine ash.

- Modern plants meet strict environmental standards for air quality.

e. Condenser and Cooling System:

- After passing through the turbine, the low-pressure steam is condensed back into water in a condenser and pumped back to the boiler to begin the cycle again.

Simplified Process Flow:

- Feedstock → Combustion/Gasification → Steam/Syngas → Turbine → Generator → Electricity

1. Biomass Power Generation Cont…

Advantages and Limitations of Biomass Energy

- Advantages

1. Renewable and sustainable – Biomass can be continuously replenished through responsible forestry and agriculture.
2. Carbon neutral – CO_2 released during combustion is balanced by CO_2 absorbed during plant growth.
3. Waste utilization – Converts agricultural, animal, and municipal wastes into useful energy.
4. Energy security – Reduces dependence on imported fossil fuels.
5. Rural development – Creates local employment and economic growth.

1. Biomass Power Generation Cont…

- Limitations

1. Feedstock logistics – Collection, transportation, and storage can be costly and complex.
2. Low energy density – Biomass has lower calorific value compared to fossil fuels.
3. Land-use issues – Large-scale cultivation of energy crops may compete with food production.
4. Seasonal availability – Biomass feedstock supply may vary by season.
5. Air emissions – Though cleaner than coal, biomass combustion still emits particulates and NOx.

1. Biomass Power Generation Cont…

- Environmental and Economic Impacts

a. Environmental Impacts

1. Lifecycle Emissions

- Biomass emits CO_2 when burned, but if sourced sustainably, net emissions are near zero.
- Unsustainable practices (deforestation, transport, fertilizer use) increase emissions.

2. Biodiversity and Soil Health

- Energy crop monocultures may affect biodiversity and soil nutrients.

3. Air Pollution

- Particulate matter, CO, and volatile organic compounds (VOCs) can be emitted if combustion is inefficient.

1. Biomass Power Generation Cont…

b. Economic Impacts

1. Capital and Operating Costs
   - Higher initial costs than fossil-fuel plants, but lower fuel costs in the long term.
2. Job Creation
   - Provides employment in feedstock supply chains, plant operation, and maintenance.
3. Energy Pricing
   - Can stabilize local energy costs by reducing reliance on imported fuels.
4. Sustainability and Incentives
   - Many governments provide feed-in tariffs, carbon credits, or tax incentives to encourage biomass use.

2. Nuclear Power Generation

Fundamentals of Nuclear Energy and Radioactive Decay

- Nuclear energy is the energy released from the nucleus of an atom through nuclear reactions—either fission (splitting of heavy nuclei) or fusion (combining of light nuclei) [3].
- In power generation, fission is primarily used.
- Basic Atomic Structure:
  - ✓Atom: Consists of protons and neutrons (nucleus) and electrons orbiting around it.
  - ✓Isotopes: Atoms of the same element with different numbers of neutrons (e.g., Uranium-235 and Uranium-238).

2. Nuclear Power Generation Cont…

Radioactive Decay

- Radioactive isotopes spontaneously transform into more stable forms by emitting radiation:
  - ✓Alpha decay (α): Emission of helium nuclei (2 protons, 2 neutrons).
  - ✓Beta decay (β): Conversion of a neutron into a proton with emission of an electron.
  - ✓Gamma decay (γ): Release of high-energy electromagnetic radiation.

Binding Energy

- The energy that holds the nucleus together.
- According to Einstein's equation:

$$E = mc^2$$

2. Nuclear Power Generation Cont…

- A small loss of mass during nuclear reactions converts to a large amount of energy.
- Energy Density:
  - ✓1 kg of Uranium-235 releases ≈ 8×10^{13} J of energy.
  - ✓Equivalent to burning about 3,000 tons of coal.

Nuclear Fission Process and Chain Reaction Control

Nuclear Fission

- Nuclear fission is the process of splitting a heavy, unstable atomic nucleus into two or more lighter nuclei.
- This process releases a tremendous amount of energy because the resulting lighter nuclei have a higher binding energy per nucleon.

2. Nuclear Power Generation Cont…

Chain Reaction

- Each fission event releases neutrons that can cause further fissions.
  - ✓Controlled chain reaction → steady energy release (power plant).
  - ✓Uncontrolled chain reaction → explosion (atomic bomb).

Control mechanisms for the chain reaction:

1. Control Rods: Made of neutron-absorbing materials (cadmium, boron, hafnium) to regulate the number of free neutrons.
2. Moderator: Slows down fast neutrons to thermal energies for efficient fission (materials: water, heavy water, graphite).
3. Coolant: Removes heat from the reactor core (water, gas, or liquid metal).
4. Reactor Geometry: Maintains optimal neutron flux and reactivity.

2. Nuclear Power Generation Cont…

Criticality Conditions

- Subcritical: Chain reaction dies out.
- Critical: Steady-state reaction (desired).
- Supercritical: Exponential growth (unsafe).

Components and Operation of a Nuclear Power Plant

1. Reactor Core:
   - Contains fuel rods (U-235 or Plutonium-239 (Pu-239)).
   - Moderator slows down neutrons.
   - Control rods adjust reactivity.
2. Coolant System:
   - Circulates coolant to remove heat from the core.
   - Transfers heat to a secondary loop to generate steam.

2. Nuclear Power Generation Cont…

3. Steam Generator
   - Converts feedwater to steam using reactor heat (in pressurized systems).
4. Turbine-Generator
   - Steam drives the turbine, converting thermal energy to mechanical energy.
   - Generator converts mechanical energy into electrical energy.
5. Condenser
   - Cools exhaust steam from the turbine back into water.
6. Containment Structure
   - Reinforced concrete dome enclosing the reactor to prevent radiation leakage.
7. Safety Systems
   - Emergency cooling, shutdown systems, and containment isolation.

2. Nuclear Power Generation Cont…

The operation principle is:

- Nuclear fission in the reactor core produces heat → coolant absorbs heat → steam generated → drives turbine → electricity produced → steam condensed and recycled.

- The typical efficiency is 30–35% [2].

Types of Nuclear Reactors

1. Pressurized Water Reactor (PWR)

- Uses ordinary (light) water as coolant and moderator.
- Water in the reactor is kept under high pressure (≈15 MPa) to prevent boiling.
- Heat is transferred to a secondary loop through a steam generator.

2. Nuclear Power Generation Cont…

2. Boiling Water Reactor (BWR)
   - Water acts as both coolant and moderator.
   - Water boils directly in the reactor core, producing steam that drives the turbine.
   - Simpler design but with radioactive steam path.
3. Pressurized Heavy Water Reactor (PHWR)
   - Uses heavy water (D_2O) (deuterium, a heavier isotope of hydrogen) as moderator and coolant.
   - Can use natural uranium as fuel.
   - Allows refueling during operation.

2. Nuclear Power Generation Cont…

4. Gas-Cooled Reactors (AGR, HTGR)
   - Uses carbon dioxide or helium as coolant and graphite as moderator.
   - Operates at high temperatures for improved efficiency.

5. Fast Breeder Reactor (FBR)
   - No moderator; uses fast neutrons.
   - Fuel: plutonium-239 or uranium-238.
   - Breeds more fissile material (Pu-239) from U-238.
   - Coolant: liquid sodium.

6. Advanced and Next-Generation Reactors
   - Small Modular Reactors (SMRs): Compact, safer, and easier to deploy.
   - Generation IV Reactors: Focus on safety, sustainability, and waste minimization (e.g., molten salt reactors, gas-cooled fast reactors).

2. Nuclear Power Generation Cont…

Nuclear Waste Management, Safety, and Future Trends

1. Nuclear Waste Types
   - Low-level waste: Lab clothing, tools (short-lived radioactivity).
   - Intermediate-level waste: Reactor components, chemical sludge.
   - High-level waste: Spent fuel rods and reprocessing waste (highly radioactive, long-lived).
2. Waste Management Techniques
   - Short-term storage: Cooling pools at reactor sites (5–10 years).
   - Interim storage: Dry casks in shielded facilities.
   - Long-term disposal: Deep geological repositories (hundreds of meters underground).
   - Reprocessing: Recovery of usable uranium and plutonium from spent fuel.

2. Nuclear Power Generation Cont…

3. Safety Systems and Standards
   - Defense-in-depth: Multiple layers of protection.
   - Emergency Core Cooling System (ECCS): Prevents meltdown.
   - Containment Integrity: Prevents radiation leakage.
   - International Oversight: IAEA safety standards and inspections.

4. Accidents and Lessons
   - Three Mile Island (1979) (USA) – Partial meltdown, no fatalities.
   - Chernobyl (1986) (Ukraine)– Reactor explosion due to design flaws and operator error.
   - Fukushima Daiichi (2011) (Japan) – Tsunami-induced power loss leading to core meltdowns.

→ Lesson: Redundant safety systems and emergency preparedness are critical.

3. Greenhouse Effect

- The Greenhouse Effect is a natural process where certain gases in the Earth's atmosphere trap heat from the sun, preventing it from escaping back into space, thus keeping our planet warm enough for life to exist [4].
- When the Sun’s energy reaches the Earth’s atmosphere, some of it is reflected back to space while the rest is absorbed and re-radiated by greenhouse gases.
- This process maintains the Earth’s average temperature at about 15°C, making it suitable for life.
- Without it, the average surface temperature would be around

–18°C, too cold for most living organisms.

3. Greenhouse Effect Cont…

- However, human activities, particularly the burning of fossil fuels and deforestation, have enhanced this effect, leading to global warming and climate change.

Mechanism of the Greenhouse Effect

1. Incoming Solar Radiation
   - The Sun emits shortwave radiation (mainly visible and ultraviolet light). About 30% of this radiation is reflected back by clouds, aerosols, and the Earth's surface (albedo effect).
2. Absorption by the Earth's Surface
   - The remaining 70% is absorbed by the land and oceans, warming the planet.

3. Greenhouse Effect Cont…

3. Re-radiation of Infrared Energy
   - The warmed surface emits longwave infrared radiation back toward space.
4. Absorption and Re-emission by Greenhouse Gases
   - Greenhouse gases (GHGs) absorb part of this outgoing infrared radiation and re-radiate it in all directions — including back toward the Earth's surface.
5. The Net-Effect
   - This process traps heat in the lower atmosphere, maintaining a stable and life-supporting temperature — known as the greenhouse effect.

3. Greenhouse Effect Cont…

Major Greenhouse Gases and Their Sources

- Not all greenhouse gases are created equal.
- They differ in their effectiveness at trapping heat (Global Warming Potential - GWP) and their lifetime in the atmosphere.
  - CO_2 is the most abundant anthropogenic greenhouse gas and contributes most to global warming.
  - Methane has a higher warming potential but shorter atmospheric lifetime (~12 years).
  - Fluorinated gases are potent but released in small quantities.

3. Greenhouse Effect Cont…

Role of Human Activities in Enhancing the Greenhouse Effect

- The natural greenhouse effect is life-sustaining.
- The problem we face today is the enhanced greenhouse effect, also known as anthropogenic global warming.
- Human activities, particularly since the Industrial Revolution, have drastically increased the concentration of GHGs in the atmosphere.
- The primary mechanism is the disruption of the global carbon cycle.
- The enhanced greenhouse effect refers to the strengthening of the natural greenhouse effect due to human-induced increases in greenhouse gases.

3. Greenhouse Effect Cont…

Key Human Activities

1. Burning of Fossil Fuels
   - Major source of CO_2 emissions.
   - Power generation, transport, industry, and heating contribute heavily.
2. Deforestation and Land Use Change
   - Trees act as carbon sinks; cutting them down reduces CO_2 absorption.
   - Burning forests releases stored carbon.
3. Agricultural Practices
   - Rice paddies and ruminant livestock emit large amounts of CH_4.
   - Fertilizer use increases N_2O emissions.

3. Greenhouse Effect Cont…

4. Industrial Activities

- Cement production, chemical manufacturing, and refrigeration release CO_2 and fluorinated gases.

5. Waste Management

- Decomposing organic waste in landfills emits methane.
- Poor waste burning adds CO_2 and black carbon.

3. Greenhouse Effect Cont…

Environmental and Climatic Consequences of Global Warming

- The enhanced greenhouse effect leads to global warming, which in turn causes major environmental, climatic, and social consequences.

a. Climatic Consequences

- Increase in global average temperature (~1.2 ℃ rise since pre-industrial times).
- Melting of glaciers and polar ice caps → rise in sea levels.
- Changes in precipitation patterns → floods, droughts, and storms.
- Ocean warming and acidification → coral bleaching, marine ecosystem disruption.
- Increased frequency of extreme weather events — hurricanes, heatwaves, wildfires.

3. Greenhouse Effect Cont…

b. Environmental and Ecological Effects

- Loss of biodiversity — species migration or extinction due to habitat shifts.
- Desertification — expansion of arid zones and soil degradation.
- Forest dieback — especially in tropical regions.

c. Socioeconomic Impacts

- Threats to food security — crop yield reductions.
- Water scarcity — altered hydrological cycles.
- Health problems — heat stress, spread of vector-borne diseases.
- Displacement — “climate refugees” from flood-prone or drought-hit areas.

3. Greenhouse Effect Cont…

Mitigation and Adaptation Strategies for Reducing Greenhouse Gas Emissions

a. Mitigation Strategies

- Mitigation aims to reduce or prevent the emission of greenhouse gases and enhance natural sinks.

1. Transition to renewable energy
2. Energy efficiency
3. Carbon capture and storage
4. Reforestation and afforestation
5. Sustainable agriculture and waste management
6. Policy and international agreements

3. Greenhouse Effect Cont…

b. Adaptation Strategies

- Adaptation involves adjusting human and natural systems to minimize damage from climate impacts.

Examples:

- Building sea walls and flood defenses in coastal areas.
- Developing drought-resistant crops and improving irrigation.
- Enhancing disaster preparedness and early warning systems.
- Promoting water conservation and efficient resource management.
- Urban planning that includes green spaces and heat management systems.

4. Pollution and Its Control

- Pollution is the introduction of harmful substances or energy into the environment, resulting in adverse effects on living organisms and ecosystems [5].
- These harmful agents are called pollutants, which may be solids, liquids, gases, noise, heat, or radiation.

Classification of Pollution

- Pollution can be classified based on the medium affected:

1. Air Pollution

- Contamination of the atmosphere by gaseous, liquid, or solid wastes that alter its natural composition.
- Major air pollutants: CO, CO_2, SO_2, NOx, hydrocarbons (HC), particulate matter ($PM_{2.5}$, PM_{10}), lead, ozone.

4. Pollution and Its Control

Cont…

2. Water Pollution

- It is the introduction of harmful substances into rivers, lakes, oceans, or groundwater, degrading water quality.
- Water pollutants include organic waste, chemicals, heavy metals (Mercury (Hg), Lead (Pb), Cadmium (Cd)), oil, fertilizers, pathogens.

3. Soil Pollution

- It is the degradation of the earth's surface due to the presence of chemicals or waste materials.
- Soil pollutants includes pesticides, herbicides, heavy metals, plastics, industrial waste, solid waste.

4. Pollution and Its Control

Cont…

Air Pollution Control Methods

- Air pollution control involves capturing, removing, or reducing pollutants from emissions before they enter the atmosphere.

i. Filtration - Mechanical separation of particulate matter from gas streams using porous media.

ii. Scrubbing - Polluted gas comes into contact with a liquid (usually water) that absorbs or neutralizes pollutants.

iii. Electrostatic Precipitation - Uses electric fields to charge dust particles, which are then attracted to oppositely charged plates.

4. Pollution and Its Control

Cont…

Policies, Standards, and Sustainable Pollution Control Strategies

a. Environmental Policies and Regulations

Example: Global Initiatives such as:

- Paris Agreement (2015): Reduce greenhouse gas emissions.
- Basel Convention (1992): Controls transboundary movement of hazardous waste.
- Montreal Protocol (1989): Controls ozone-depleting substances.

b. Sustainable Pollution Control Strategies

1. Cleaner production: Minimizing waste at the source by efficient process design.

4. Pollution and Its Control

Cont…

2. Green technologies: Renewable energy adoption, low-emission fuels.
3. Waste minimization and recycling: Circular economy approaches.
4. Afforestation and urban green spaces: Natural air purification and noise reduction.
5. Public awareness and environmental education: Promoting behavioral change and responsible consumption.

Summary

- Biomass power generation utilizes organic materials like crop residues, wood, and waste to produce renewable energy through combustion, gasification, or anaerobic digestion.
- Nuclear power generation generates electricity from controlled nuclear fission reactions within reactors, offering high energy output with low greenhouse gas emissions.
- Greenhouse effect describes how greenhouse gases trap heat in the Earth's atmosphere, influencing global temperatures and driving climate change.
- Pollution and its control examines sources and types of pollution (air, water, soil, noise) and their harmful effects on ecosystems and human health.
- Integrating clean and efficient energy systems with pollution control is key to reducing environmental impact and ensuring long-term ecological balance.

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Thank you !