

Chapter-10

Renewable Energy Technologies

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Abstract

Renewable energy technologies form the backbone of global efforts to transition away from fossil fuels toward sustainable, low-carbon energy systems. With rapid advancements in solar, wind, hydropower, biomass and geothermal technologies, renewable energy is becoming more efficient, affordable and accessible. This expanded chapter provides an in-depth examination of the scientific principles, technological developments, environmental impacts, global deployment trends and future prospects of renewable energy systems, supported by research-based insights.

Keywords: Renewable energy, solar energy, wind energy, hydropower, geothermal energy, biomass energy, energy storage, smart grids, sustainable development.

Introduction

Renewable energy systems are central to global decarbonization strategies, as the energy sector accounts for nearly 73% of anthropogenic greenhouse gas emissions (IPCC, 2022). As fossil fuel reserves decline and environmental constraints intensify, countries are transitioning toward cleaner energy pathways. Renewable energy sources including solar, wind, hydropower, biomass, and geothermal are naturally replenished and offer sustainable alternatives with lower life-cycle emissions (IEA, 2023).

Recent technological advances, particularly in energy storage, power electronics and digitalization, have accelerated the global deployment of renewables. By 2023, renewable energy contributed approximately 30% of global electricity generation, and projections indicate that this will surpass 50% by 2040 (IRENA, 2023).

1. Solar Energy Technologies

Solar energy is the most abundant renewable resource available on Earth. The solar radiation reaching the Earth's surface is approximately 173,000 terawatts over 10,000 times more than the world's total energy consumption. Solar energy technologies convert sunlight into heat or electricity through two primary mechanisms: photovoltaic systems and concentrated solar power systems.

1.1 Photovoltaic (PV) Systems

PV technology uses semiconductor materials primarily crystalline silicon to convert sunlight directly into electricity through the photovoltaic effect. Modern advancements include bifacial modules, perovskite-silicon tandem cells achieving efficiencies (Green *et al.*, 2022) above 30 % and thin-film technologies using CdTe or CIGS materials. Utility-scale PV installations are becoming dominant due to reduced manufacturing costs, improved inverters and AI-driven energy forecasting.

1.2 Solar Thermal Technologies

Solar thermal systems capture heat from sunlight for domestic, industrial or grid-scale applications. Concentrated Solar Power (CSP) uses mirrors to focus sunlight onto a receiver, producing steam to drive turbines. Technologies include parabolic troughs, central tower systems and linear Fresnel reflectors. CSP plants with molten salt storage can provide dispatchable power even during night time (Zhang *et al.*, 2020), improving grid stability.

2. Wind Energy Technologies

Wind energy converts kinetic wind energy into mechanical power, which is then transformed into electricity. Advances in turbine aerodynamics, generator technology and tower design have significantly reduced costs.

2.1 Onshore Wind

Onshore wind is among the cheapest renewable energy sources. Turbines today often exceed 4 - 6 MW capacity with rotor diameters over 150 meters, allowing greater energy capture. Remote sensing technologies such as LiDAR improve site assessment and performance monitoring.

2.2 Offshore Wind

Offshore wind farms exploit stronger and more consistent sea winds. Floating offshore turbines enable deployment in deep waters (>60 meters). Next-generation 15 - 20 MW turbines are expected to revolutionize offshore wind economics. Offshore substations and HVDC transmission lines facilitate integration with national grids.

3. Hydropower Technologies

Hydropower remains the largest source of renewable electricity worldwide. Technologies range from large-scale dams to small community-based micro-hydel plants.

3.1 Large Hydropower

Large hydropower plants provide reliable, continuous base load electricity. Their reservoirs support irrigation, flood control and water supply. However, they may impact ecosystems, sediment flow and human settlements.

3.2 Small, Mini and Micro Hydropower

Small-scale hydropower systems (up to 10 MW) are ideal for rural and remote areas (Paish, 2020). They require minimal infrastructure, have lower ecological impacts and offer decentralized energy solutions.

3.3 Emerging Hydropower Innovations

Run-of-river projects avoid large reservoirs, reducing environmental concerns. Pumped-storage hydropower acts as a large-scale energy storage system, stabilizing grids with high renewable penetration.

4. Biomass and Bioenergy Technologies

Biomass refers to organic material from plants, animals and waste streams that can be converted into energy. Modern biomass systems are engineered for high efficiency and low emissions.

4.1 Combustion, Pyrolysis and Gasification

Combustion remains the dominant method of biomass utilization. Gasification converts biomass into syngas, while pyrolysis produces bio-oil and biochar. Gasification is more

efficient than simple burning (Basu, 2018). These processes support electricity generation, heating and industrial applications.

4.2 Biofuels: Bioethanol, Biodiesel, and Biogas

Bioethanol is produced from sugarcane, corn and cellulose-rich feedstocks. Biodiesel is derived from vegetable oils, non-edible oils or animal fats through transesterification. Biogas, generated via anaerobic digestion of organic waste, can be upgraded to biomethane for grid injection or vehicle fuel (Khan *et al.*, 2021).

5. Geothermal Energy Technologies

Geothermal energy harnesses thermal energy stored beneath the Earth's surface. It is highly reliable, weather-independent, and suitable for both electricity and direct heating.

5.1 Hydrothermal Systems

Hydrothermal power plants use naturally available reservoirs of hot water or steam. They are commonly found in volcanic regions and tectonic plate boundaries.

5.2 Enhanced Geothermal Systems (EGS)

EGS technologies artificially create reservoirs in hot dry rock areas using hydraulic stimulation. They have the potential to greatly expand geothermal availability beyond naturally occurring hydrothermal sites.

6. Integrated and Emerging Renewable Technologies

The integration of renewables with digital and storage technologies is transforming the global energy landscape.

6.1 Green Hydrogen

Hydrogen produced by splitting water using electricity from renewable sources. It is considered a clean fuel for industries, transport, and energy storage (IRENA, 2022).

6.2 Energy Storage Systems

Essential for balancing intermittent sources like solar and wind. Storage solutions including lithium-ion batteries, sodium-sulphur batteries, flow batteries and pumped hydro-mitigate intermittency. Thermal energy storage (TES) is used in CSP and industrial processes.

6.3 Smart Grid Technologies

Smart grids incorporate digital monitoring, smart meters, AI-based load forecasting, and automated distribution management systems (DMS). They enable efficient integration of distributed renewable systems.

6.4 Hybrid Renewable Energy Systems

Hybrid systems combine solar-wind, solar-biomass, or solar-wind-storage technologies to maximize reliability and energy output. These improve reliability and reduce energy costs.

7. Environmental and Socioeconomic Impacts

Renewable energy reduces greenhouse gas emissions, improves air quality and enhances energy security. The renewable sector created over 12.7 million jobs worldwide in 2022 (IRENA, 2023). However, challenges include land-use conflicts, material sustainability issues and e-waste from solar modules and batteries (Dias *et al.*, 2016).

Challenges in Renewable Energy Adoption

Key Challenges -

- High initial installation costs
- Intermittent nature of solar and wind
- Need for large areas (solar farms, wind farms)
- Limited public awareness in some regions
- Storage and grid-integration issues

Solutions -

- Improved battery storage
- Better government policies and subsidies
- Smart grid development
- Increased research and innovation

Future Prospects

According to global energy predictions, renewable energy could supply more than 80% of electricity by 2050 (IEA, 2023). Advancements in AI-based grid management, high-efficiency materials, affordable storage technologies, and expansion of green hydrogen systems will lead to a cleaner and more sustainable energy future.

Conclusion

Renewable energy technologies are essential to achieving global climate and sustainability goals. Innovations such as perovskite solar cells, floating offshore wind turbines, EGS geothermal systems, and advanced energy storage are transforming the energy landscape. Strategic policies, research investment, and global collaboration will continue to accelerate the transition toward a low-carbon future.

Summary

- Renewable energy is essential for combating climate change and meeting future energy demand.
- Solar and wind technologies lead global renewable power generation.
- Bioenergy and geothermal provide reliable, continuous energy.
- Hydropower remains one of the most stable renewable sources.
- Emerging technologies such as hydrogen and hybrid systems show great promise.

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