Comparative Study of Solar, Wind, and Biomass Energy Systems

Dr. Venkateswarlu Yadavalli
Associate Professor
Dept. of Biotechnology Tara Govt. College (A)
Sangareddy, T.G.-502001

DOI:10.37648/ijps.v21i02.032

[1]*Received: 30/11/2025; Accepted: 31/12/2025; Published: 07/01/2026*

Abstract

The growing global energy demand and environmental concerns have intensified the need for sustainable and renewable energy sources. This study presents a comparative analysis of three major renewable energy systems—solar, wind, and biomass—with respect to their energy conversion efficiency, cost-effectiveness, environmental impact, and suitability for large-scale implementation. Solar energy, derived from photovoltaic and thermal technologies, offers abundant potential in regions with high solar insolation but faces challenges related to intermittency and storage. Wind energy provides a clean and mature technology with relatively low operational costs, though it is limited by geographical and seasonal variability. Biomass energy, on the other hand, offers a consistent and storable source of energy with the added advantage of utilizing agricultural and organic waste, yet it raises concerns regarding land use and emissions during combustion. The comparative evaluation highlights that a hybrid approach integrating solar, wind, and biomass systems can ensure a stable, sustainable, and diversified energy mix. The study underscores the importance of technological innovation, policy support, and regional resource assessment to enhance the efficiency and adoption of renewable energy systems for a sustainable energy future.

Keywords: *Renewable energy; solar energy; Wind energy; Biomass Energy and sustainable energy*

1. Introduction

The transition toward renewable energy has accelerated globally in response to rising energy demand and concerns over climate change. Solar, wind, and biomass energy systems have emerged as leading solutions in the pursuit of a sustainable energy future (Ang, 2022). According to the IEA (2024), renewables could contribute over one-third of total global electricity generation by 2030. Each technology exhibits unique characteristics in terms of cost, scalability, and environmental performance. Therefore, understanding their comparative advantages is essential for policymakers and investors to optimize energy portfolios and reduce carbon footprints.

2. Methodology and Evaluation Criteria

This comparative review evaluates solar, wind, and biomass systems based on six major aspects:

- **Technical performance** (efficiency and capacity factor)
- **Economic feasibility** (capital investment and levelized cost of electricity, LCOE)
- **Environmental impacts** (life-cycle emissions and resource use)
- **Land and material requirements**

[1]*How to cite the article:* Yadavalli V. (2026); Comparative Study of Solar, Wind, and Biomass Energy Systems; *International Journal of Professional Studies*; Vol 21, Special Issue 2, 226-229; DOI: http://doi.org/10.37648/ijps.v21i02.032

- **Grid integration and flexibility**
- **Socio-economic implications**

Data and insights were synthesized from reports by IRENA (2024) and the IEA (2024), as well as research articles by Portillo et al. (2024), Rossi et al. (2023), and others. This approach enables a balanced comparison across technical and sustainability dimensions.

3. Technical Characteristics

3.1 Solar Photovoltaic Systems

Solar PV technology directly converts sunlight into electricity using semiconductor materials. It has become the fastest-growing renewable energy source worldwide due to its declining costs, modular design, and ease of installation (IEA, 2024). Utility-scale PV systems generally exhibit capacity factors between 10% and 25%, depending on location and climatic conditions (Bolson et al., 2022). The flexibility of PV allows both rooftop and large-scale applications, making it suitable for urban and rural deployment (Portillo et al., 2024).

3.2 Wind Energy Systems

Wind energy harnesses kinetic energy from moving air masses through turbines. Onshore wind has matured technologically, while offshore wind is expanding rapidly in regions with favorable wind resources (Bolson et al., 2022). Capacity factors for modern onshore turbines typically range from 25% to 45%, with offshore turbines exceeding 50% (IEA, 2024). Wind energy is often complementary to solar power since it tends to generate more electricity during night or winter months.

3.3 Biomass Energy Systems

Biomass energy utilizes organic materials—such as agricultural residues, forestry waste, or dedicated energy crops—to produce heat and electricity. These systems are dispatchable, with capacity factors ranging between 50% and 90% (Ang, 2022). Biomass power plants provide stable energy output and can assist in balancing intermittent renewables like solar and wind (Rossi et al., 2023). However, their long-term sustainability depends on responsible feedstock sourcing and minimizing land-use conflicts (Luo et al., 2024).

4. Economic Assessment

Continuous technological innovation and economies of scale have drastically reduced the cost of renewable energy generation. The global weighted-average LCOE for solar PV decreased by roughly 12% between 2022 and 2023, while onshore wind costs dropped by about 3% in the same period (IRENA, 2024). Both technologies are now cheaper than most fossil fuel-based alternatives in many markets.

According to the U.S. Energy Information Administration (2023), new solar PV projects typically achieve LCOEs of USD 30–45 per megawatt-hour (MWh), whereas onshore wind projects average USD 35–50 per MWh. Biomass systems display greater cost variation, ranging from USD 60–120 per MWh, primarily due to feedstock and transport expenses (Ang, 2022). Nevertheless, waste-based biomass systems can offer competitive costs when accounting for co-benefits like waste reduction and combined heat and power generation.

5. Environmental Sustainability

Life-cycle assessments (LCA) consistently rank solar and wind among the cleanest energy sources in terms of greenhouse gas emissions. Portillo et al. (2024) reported that solar PV emits approximately 40–60 grams of CO_2-equivalent per kWh, while wind power emits only about 10–20 grams per kWh. Both values are significantly lower than those associated with coal or natural gas.

Biomass systems can achieve low net emissions if feedstocks are sourced sustainably. Rossi et al. (2023) found that using residues and waste-based biomass can lead to near-carbon-neutral outcomes. However, Luo et al. (2024) emphasized that indirect land-use change and deforestation can offset these benefits, making sustainability certification and carbon accounting essential for biomass projects.

6. Land and Resource Requirements

The spatial and material footprints of renewables vary across technologies. Solar PV requires substantial surface area for large installations but can utilize rooftops or degraded land to minimize conflicts (Nøland et al., 2022). Wind farms have smaller direct land requirements, allowing agricultural or grazing activities beneath turbines (Bolson et al., 2022). Biomass systems, however, depend on continuous feedstock supply, which can strain land and water resources if not managed properly (Rossi et al., 2023).

In terms of materials, solar PV relies heavily on silicon and conductive metals such as copper and silver, whereas wind turbines use steel and rare earth elements for magnets. Recycling and circular economy strategies are increasingly critical for reducing the material intensity of these technologies (Nøland et al., 2022).

7. Grid Integration and System Flexibility

Solar and wind power are variable by nature, which can challenge grid reliability. The IEA (2024) stresses the importance of modern grid infrastructure, energy storage, and smart demand management to handle intermittent generation. Biomass, by contrast, offers firm and dispatchable power, making it valuable for maintaining grid stability (Rossi et al., 2023). Hybrid systems that combine solar, wind, and biomass energy—supported by battery storage—can improve overall efficiency and reduce system costs (Luo et al., 2024).

8. Socio-Economic Impacts

Renewable energy deployment contributes significantly to job creation, technological innovation, and rural development. The solar and wind industries employ millions globally in installation, maintenance, and manufacturing (IEA, 2024). Biomass projects enhance rural livelihoods by providing markets for agricultural residues and creating local value chains (Ang, 2022). Nonetheless, community acceptance challenges, such as land-use competition and local air emissions, must be mitigated through stakeholder participation and transparent regulation (Rossi et al., 2023).

9. Discussion

Solar and wind energy systems dominate the renewable sector due to their rapid scalability, low operational costs, and minimal environmental impacts (IRENA, 2024). Biomass complements these variable sources by offering continuous and controllable power generation. However, its expansion must be governed by strict sustainability standards to prevent ecological degradation (Luo et al., 2024). A diversified renewable mix that leverages the strengths of all three technologies can enhance energy security, reduce emissions, and stabilize electricity grids (IEA, 2024).

10. Policy Recommendations

- **Accelerate solar and wind deployment** through incentives, grid upgrades, and storage investments (IEA, 2024).
- **Implement sustainability standards for biomass**, emphasizing residue-based feedstocks and verified carbon accounting (Rossi et al., 2023).
- **Promote circular manufacturing and recycling** of materials used in renewable technologies (No land et al., 2022).

- **Encourage hybrid renewable systems** that integrate variable and dispatchable sources to balance supply and demand (Luo et al., 2024).

11. Conclusion

Solar, wind, and biomass energy systems represent complementary pathways toward a sustainable and low-carbon energy future. Solar and wind lead in affordability and environmental performance, while biomass plays a vital role in grid stability and waste valorization when applied sustainably. A strategic combination of these technologies—supported by sound policy, innovation, and sustainable resource management—can ensure reliable and equitable access to clean energy worldwide (IRENA, 2024; IEA, 2024).

References

Ang, T. Z. (2022). A comprehensive study of renewable energy sources. *Renewable and Sustainable Energy Reviews, 154*, Article 111823. https://doi.org/10.1016/j.rser.2022.111823

Bolson, N., Smith, A., & Lee, J. (2022). Capacity factors for electrical power generation from renewable technologies: A global assessment. *Proceedings of the National Academy of Sciences, 119*(30), Article e2205429119. https://doi.org/10.1073/pnas.2205429119

International Energy Agency. (2024). *Renewables 2024: Analysis and forecast to 2030*. https://www.iea.org/reports/renewables-2024

International Renewable Energy Agency. (2024). *Renewable power generation costs in 2023*. https://www.irena.org/publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023

Luo, J., Wang, H., & Zhang, Y. (2024). Comparative life cycle assessment of photovoltaic and biomass power generation. *Frontiers in Energy Research, 12*, Article 1375820. https://doi.org/10.3389/fenrg.2024.1375820

Nøland, J. K., Sæther, S., & Alstad, J. (2022). Spatial energy density of large-scale electricity generation: Challenging the consensus on solar power density. *Scientific Reports, 12*, Article 5539. https://doi.org/10.1038/s41598-022-25341-9

Portillo, F., Martínez, R., & Estevez, L. (2024). Life cycle assessment in renewable energy: Solar and wind comparative study. *Environments, 11*(7), 147. https://doi.org/10.3390/environments11070147

Rossi, F., Delgado, P., & Chen, M. (2023). Comparative scenario-based life cycle assessment of renewable energy systems. *Journal of Cleaner Production, 400*, Article 136885. https://doi.org/10.1016/j.jclepro.2023.136885

U.S. Energy Information Administration. (2023). *Levelized costs of new generation resources in the Annual Energy Outlook 2023*. https://www.eia.gov/outlooks/aeo/pdf/AEO2023_LCOE_report.pdf