American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-15, Issue-2, pp-17-19
www.ajer.org
Research Paper Open Access

Electricity Generation from Bioenergy: Technologies, Developments, and Economic Prospects

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Abstract.
Bioenergy*, derived from biomass, is a vital renewable resource with significant potential to contribute to global energy security and the transition towards low-carbon energy systems. This report aims to provide a comprehensive analysis of the latest research papers and academic studies on electricity generation from biomass, focusing on key technologies, developments in feedstock sources, and economic and environmental prospects. The review showed that thermal technologies such as* ***Direct Combustion*** *and* ***Gasification*** *are the most mature, while research is moving towards second, third, and fourth-generation feedstock's to reduce competition with food production. Although the Level zed Cost of Electricity (LCOE) for bioenergy remains relatively stable compared to some other renewable sources, its role in providing reliable,* ***carbon-neutral*** *base-load power makes it an indispensable component of the future energy mix.*

Date of Submission: 24-01-2026 Date of acceptance: 06-02-2026

I. Introduction

The world is witnessing a continuous increase in electricity demand, which puts increasing pressure on traditional fossil fuel-based energy sources In light of global challenges such as climate change and resource depletion, renewable energy sources have emerged as a strategic solution. **Bioenergy**, derived from organic materials such as plants, agricultural and animal residues, is one of the most diverse sources with the capacity to provide continuous base-load power.

Although bioenergy currently contributes less than 5% of the total global electricity supply, forecasts indicate that its role will significantly strengthen in the coming decades, especially in countries with abundant biomass resources such as the United States, Germany, and Brazil. This report aims to explore the current landscape of electricity generation from bioenergy, analyze the available technologies, and assess the economic and environmental feasibility of these technologies based on the latest research data.

II. Bioenergy Concept and Feedstock Classification

Biomass is defined as any organic material derived from living organisms or their residues, which can be converted into energy. The **Feedstocks** used in bioenergy production are classified into different generations, reflecting the evolution of sustainability strategies .

Generation	Description	Key Examples	Main Challenges
First Generation	Traditional food crops	Corn, sugarcane, vegetable oils	Competition with food production ("food vs. fuel conflict")
Second Generation	Non-food residues	Agricultural residues (straw), forestry residues (sawdust), lignocellulosic biomass	Efficiency of collection and pre-treatment
Third Generation	Aquatic microorganisms	Algae	Production and extraction costs, commercial scaling
Fourth Generation	Advanced feedstocks	Genetically modified materials, technologies coupled with **Bioenergy with Carbon Capture and Storage (BECCS)**	Cost, technological maturity, public acceptance

The shift towards second and third-generation materials is crucial to ensuring the sustainability of bioenergy and reducing negative impacts on food security and land use .

III. Biomass-to-Electricity Conversion Technologies

Biomass-to-electricity conversion technologies can be divided into three main categories: thermal, thermochemical, and biological technologies .

Thermal and Thermochemical Technologies

These technologies rely on heat to convert biomass into energy or an intermediate fuel:

1 **Direct Combustion:** This is the most mature and common technology. Biomass is burned directly in boilers to produce steam, which drives a turbine to generate electricity.
2 **Co-firing:** This involves burning biomass alongside fossil fuels (usually coal) in existing thermal power plants. This technology is a quick and effective solution to reduce carbon emissions without the need for costly new infrastructure .
3 **Gasification:** The process of converting biomass into a synthetic gas (**Syngas**) primarily composed of hydrogen and carbon monoxide. This gas can be used in internal combustion engines or gas turbines to generate electricity with higher efficiency than direct combustion.
4 **Pyrolysis:** Heating biomass in the absence of oxygen to produce bio-oil, biochar, and non-condensable gases. Bio-oil can be used as a liquid fuel for electricity generation.

IV. Biological Technologies

These technologies use microorganisms to convert biomass:

5 **Anaerobic Digestion:** The decomposition of organic materials (such as manure and municipal waste) in the absence of oxygen to produce **Biogas**, which is mainly composed of methane and carbon dioxide. Biogas can be used directly to generate electricity and heat.
6 **Microbial Fuel Cells (MFCs):** An emerging technology that converts the chemical energy stored in organic materials directly into electrical energy using bacteria as biocatalysts. This technology is still in the early stages of research and development .

V. Economic and Environmental Prospects

Economic Feasibility (LCOE)

According to the International Renewable Energy Agency (IRENA) report for 2024, bioenergy shows relative stability in costs, reflecting its technological maturity [4]. The following table compares the Levelized Cost of Electricity (LCOE) and Total Installed Costs (TIC) for bioenergy between 2010 and 2024:

Indicator	Unit	2010	2024	Percentage Change (2010-2024)
Total Installed Costs (TIC)	USD/kW	3,082	3,242	+5%
Capacity Factor	%	72%	73%	+1%
Levelized Cost of Electricity (LCOE)	USD/kWh	0.086	0.087	+1%

Although the LCOE for bioenergy ($0.087/kWh) is higher than some intermittent sources like solar PV ($0.043/kWh) and onshore wind ($0.034/kWh) in 2024, its ability to provide base-load power and its high capacity factor (73%) give it a competitive advantage in grid stability [4].

VI. Environmental Advantages

The most prominent environmental advantage of bioenergy is its designation as **carbon-neutral** under sustainable management. Plants absorb carbon dioxide from the atmosphere during growth, and approximately the same amount is released when they are burned for energy. Studies have shown that using biomass as fuel can reduce CO_2 emissions by up to 95% compared to fossil fuels.

VII. Challenges and Future Directions

Bioenergy faces a number of challenges that hinder its full deployment [2]:

7 **Logistical Challenges:** Low efficiency in the collection, transportation, and storage of biomass, which increases operating costs.
8 **Economic Competition:** Continued competition from low-cost fossil fuels in many markets.
9 **Sustainability and Land Use:** Competition for arable land between food production and first-generation biomass feedstock production.
10 **Capital Costs:** High initial investment costs for establishing advanced bioenergy power plants.

To address these challenges, future directions focus on:

- **Fourth-Generation Feedstock Development:** Focusing on **BECCS** (Bioenergy with Carbon Capture and Storage) technologies to make electricity generation from biomass **carbon-negative**, i.e., removing a net amount of CO2 from the atmosphere [3].
- **Improving Conversion Efficiency:** Developing advanced conversion technologies such as **Catalytic Pyrolysis** and integrating processes into **Integrated Biorefineries** to increase resource utilization efficiency [3].
- **Assessment Tools:** Utilizing **Life Cycle Assessment (LCA)** and **Integrated Assessment Models (IAMs)** to ensure comprehensive sustainability and guide government policies towards supporting sustainable bioenergy [3].

VIII. Conclusion

Bioenergy is a fundamental and reliable source for electricity generation, playing a crucial role in achieving global renewable energy goals. Current technologies have demonstrated maturity and efficiency, especially in combustion and gasification. With the continuous evolution towards second, third, and fourth-generation feedstocks, coupled with the integration of carbon capture technologies, bioenergy is poised to become not only a carbon-neutral source but a **carbon-negative** source in the future. Realizing this potential requires continued investment in research and development, as well as the establishment of strong policy frameworks that support the sustainable expansion of this vital industry.

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