International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 09 Issue 07 July 2026
DOI: 10.47191/ijcsrr/V9-i7-21, Impact Factor: 8.048
IJCSRR @ 2026
www.ijcsrr.org

Levelized Cost of Energy Analysis for Power Generation Technologies in Afghanistan: A Comparative Techno-Economic Assessment

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ABSTRACT: Afghanistan faces significant challenges in achieving reliable, affordable, and sustainable electricity supply while remaining heavily dependent on imported electricity. Despite possessing abundant renewable energy resources, including solar, wind, and hydropower, comprehensive economic assessments of electricity generation technologies under Afghan conditions remain limited. This study presents a comparative Levelized Cost of Energy (LCOE) analysis of six power generation technologies relevant to Afghanistan's energy sector: Solar Photovoltaic (PV), Wind, Hydropower, Combined Cycle Gas Turbine (CCGT), Coal-Fired Power Plants, and Biomass. A discounted cash flow methodology is employed using technology-specific technical and economic parameters representative of Afghanistan. The analysis incorporates capital expenditure, operation and maintenance costs, fuel costs, capacity factors, plant lifetimes, and financing conditions. Sensitivity analysis is performed across a range of weighted average cost of capital (WACC) values from 5% to 18% to evaluate the impact of financing risk on generation costs. Results indicate that hydropower exhibits the lowest LCOE, followed by utility-scale solar PV and wind power. Renewable technologies demonstrate strong economic competitiveness while simultaneously achieving near-zero operational carbon emissions. The findings highlight the importance of low-cost financing and provide evidence-based guidance for future energy planning, investment prioritization, and sustainable electricity sector development in Afghanistan.

KEYWORDS: Afghanistan, energy economics, energy policy, hydropower, levelized cost of energy, renewable energy, solar PV, wind energy.

1. INTRODUCTION

Afghanistan's electricity sector continues to face considerable challenges in providing reliable and affordable electricity services to its population. Access to electricity remains uneven, particularly in rural regions, while the country remains highly dependent on imported electricity from neighboring countries. Recent energy sector assessments indicate that imported electricity supplies approximately 70–80% of Afghanistan's grid-connected electricity demand, raising concerns regarding energy security, supply reliability, and long-term economic sustainability [1], [2].

At the same time, Afghanistan possesses significant indigenous energy resources that remain largely underutilized. According to the Afghanistan Renewable Energy Master Plan (AREMP), the country has solar energy potential exceeding 300 GW, wind energy potential of approximately 67 GW, and theoretical hydropower potential of around 23 GW [3]. Furthermore, biomass resources derived from agricultural residues and livestock waste provide additional opportunities for renewable electricity generation. The effective utilization of these resources could significantly reduce import dependence while supporting economic development and environmental sustainability [4].

The Levelized Cost of Energy (LCOE) has become one of the most widely used metrics for evaluating and comparing electricity generation technologies. LCOE represents the discounted lifetime cost of constructing, operating, and maintaining a power plant divided by the total discounted electricity generation over its operational lifetime [5], [6]. By incorporating both capital and operating expenditures into a single metric, LCOE facilitates consistent comparison among technologies with different technical characteristics and cost structures.

Although LCOE is a valuable economic indicator, it does not fully account for system integration costs, transmission expansion requirements, grid flexibility needs, or reliability considerations associated with different generation technologies [7]. Nevertheless, it remains a fundamental tool employed by energy planners, investors, and policymakers worldwide.

In Afghanistan, project financing conditions significantly influence the economic viability of electricity generation technologies. Factors such as political uncertainty, limited access to capital markets, infrastructure constraints, and elevated investment risks contribute to relatively high financing costs compared to developed economies [1], [8]. Consequently, economic assessments must explicitly account for financing conditions when evaluating future generation options.

Despite growing interest in renewable energy development, comprehensive LCOE studies covering multiple electricity generation technologies under Afghanistan-specific conditions remain limited. To address this gap, this study conducts a comparative techno-economic assessment of six power generation technologies relevant to Afghanistan's future energy mix. The study further evaluates the impact of financing costs through sensitivity analysis and examines the trade-off between economic performance and carbon emissions.

The primary contributions of this study are:

1. Development of an Afghanistan-specific comparative LCOE framework.
2. Evaluation of six major electricity generation technologies using consistent assumptions.
3. Assessment of financing risk through WACC sensitivity analysis.
4. Investigation of the relationship between electricity generation cost and environmental performance.
5. Provision of policy recommendations for sustainable energy planning in Afghanistan.

2. METHODOLOGY

2.1 Levelized Cost of Energy Formulation

The LCOE is calculated using the discounted cash flow approach, which considers all project costs over the facility lifetime [5], [9]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX \times CRF + FOM}{(1+r)^t} + \sum_{t=1}^{n} \frac{(VOM + Fuel) \times E_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

- CAPEX = Capital expenditure ($/kW)
- FOM = Fixed operation and maintenance cost ($/kW-year)
- VOM = Variable operation and maintenance cost ($/MWh)
- Fuel = Fuel cost ($/MWh)
- (E_t) = Annual energy generation (MWh)
- (r) = Discount rate
- (n) = Plant lifetime (years)

The Capital Recovery Factor (CRF) is calculated as:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

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The simplified LCOE expression used in this study is:

$$LCOE = \frac{CAPEX \times CRF + FOM}{E_{annual}} + VOM + Fuel$$

Where $E_{annual} = \frac{8760 \times CF}{1000}$ and CF denotes the capacity factor.

2.2 Technology Assumptions

Table I summarizes the technical and economic parameters used in the analysis.

Table I. Techno-Economic Parameters of Power Generation Technologies

Technology	CAPEX ($/kW)	FOM ($/kW-yr)	VOM ($/MWh)	Fuel ($/MWh)	CF (%)	Lifetime (yr)
Solar PV	850	11	0	0	20	25
Wind	1200	22	0	0	30	25
Hydro	1700	25	0	0	55	50
CCGT	800	12	3	55	85	30
Coal	1600	25	4	35	80	35
Biomass	2000	35	8	52	75	25

The assumptions were derived from recent reports published by IRENA, IEA, NREL, EIA, and regional energy studies [2], [10]– [12].

2.3 Sensitivity Analysis

To evaluate the impact of financing conditions, WACC values ranging from 5% to 18% are considered. This range reflects concessional financing scenarios as well as high-risk investment conditions characteristic of developing economies [8], [10].

2.4 Environmental Assessment

Operational carbon dioxide emissions are considered for each technology based on IPCC and IEA emission factors [13].

3. RESULTS AND DISCUSSION

3.1 Comparative LCOE Analysis

Figure 1 presents the calculated Levelized Cost of Energy (LCOE) values for the six power generation technologies considered in this study. The results indicate significant differences in economic competitiveness among the evaluated technologies.

Hydropower exhibits the lowest LCOE at approximately **34 $/MWh**, making it the most economically attractive option under the assumed Afghan conditions. Although hydropower projects generally require relatively high initial capital investments, their long operational lifetimes and favorable capacity factors allow these costs to be distributed over large amounts of electricity generation. This finding is consistent with global studies reporting hydropower as one of the least-cost sources of electricity where suitable water resources are available [7], [10].

Solar PV and wind power demonstrate very similar LCOE values of approximately **51.7 $/MWh** and **54.8 $/MWh**, respectively. The small difference between the two technologies suggests that both can play important roles in Afghanistan's future energy mix. Afghanistan's high solar irradiation and favorable wind resources in northern provinces support the deployment of these technologies as economically competitive alternatives to conventional fossil-fuel generation.

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Coal-fired generation achieves an LCOE of approximately **62.8 $/MWh**, while CCGT reaches approximately **69.7 $/MWh**. Although both technologies benefit from high-capacity factors and dispatchable operation, their competitiveness is reduced by fuel costs, which represent a major portion of total generation costs. This dependence on fuel introduces additional uncertainty because future fuel prices may fluctuate significantly.

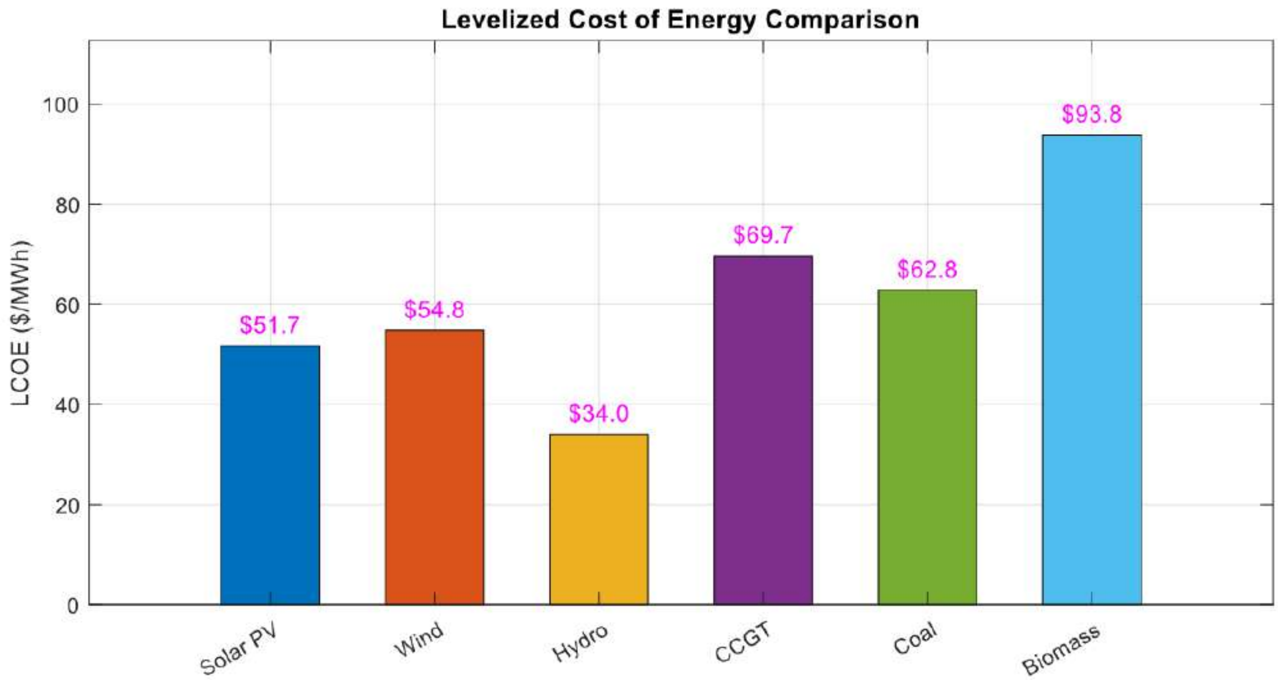

Figure 1. Levelized Cost of Energy (LCOE) values for the six power generation technologies

Biomass exhibits the highest LCOE at approximately **93.8 $/MWh**, indicating limited economic attractiveness under current assumptions. The high cost is primarily associated with substantial capital requirements and fuel collection, transportation, and processing expenses.

Overall, Figure 1 clearly demonstrates that renewable energy technologies, particularly hydropower, solar PV, and wind power, provide the most competitive electricity generation options for Afghanistan.

3.2 LCOE Cost Breakdown Analysis

Figure 2 illustrates the contribution of different cost components to the total LCOE for each technology. The analysis reveals fundamental differences in cost structures between renewable and fossil-fuel-based generation technologies.

For Solar PV, Wind, and Hydropower, annualized capital costs constitute the largest share of total LCOE. In the case of Solar PV, capital expenditures account for nearly 90% of the total generation cost. Similarly, Wind and Hydropower exhibit strong dependence on capital investment while requiring negligible fuel expenditures. Consequently, these technologies are highly sensitive to financing conditions but relatively immune to fuel price fluctuations.

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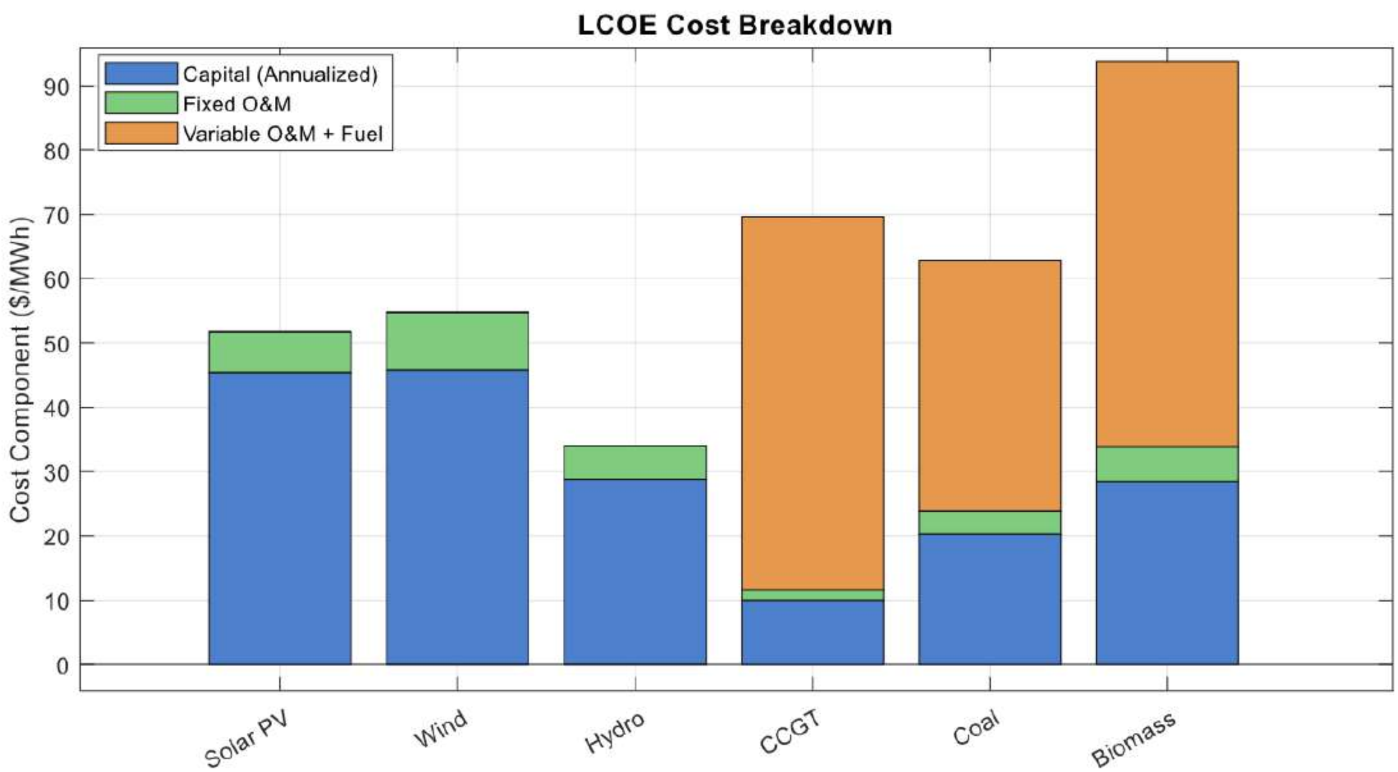

Figure 2. Levelized Cost of Energy (LCOE) Cost Breakdown for the six power generation technologies

Conversely, CCGT and Coal demonstrate fuel-dominated cost structures. For CCGT, fuel and variable operation and maintenance costs account for the majority of total LCOE, exceeding 80% of total generation costs. Coal exhibits a similar trend, although its fuel cost contribution is somewhat lower than that of CCGT. This cost structure exposes fossil-fuel technologies to fuel market volatility and import dependency risks.

Biomass presents a mixed cost structure characterized by both substantial capital costs and significant fuel expenditures. The combination of these two cost drivers explains the comparatively high LCOE observed for biomass generation.

The results shown in Figure 2 have important policy implications. While renewable technologies require larger upfront investments, they provide greater long-term price stability because they are not exposed to fuel price fluctuations. This characteristic is particularly important for Afghanistan, where fuel supply chains can be affected by economic and geopolitical uncertainties.

3.3 Sensitivity Analysis to Cost of Capital

Figure 3 illustrates the impact of varying discount rates (WACC) from 5% to 15% on the LCOE of each technology. The figure demonstrates that financing conditions significantly affect the economic competitiveness of electricity generation technologies.

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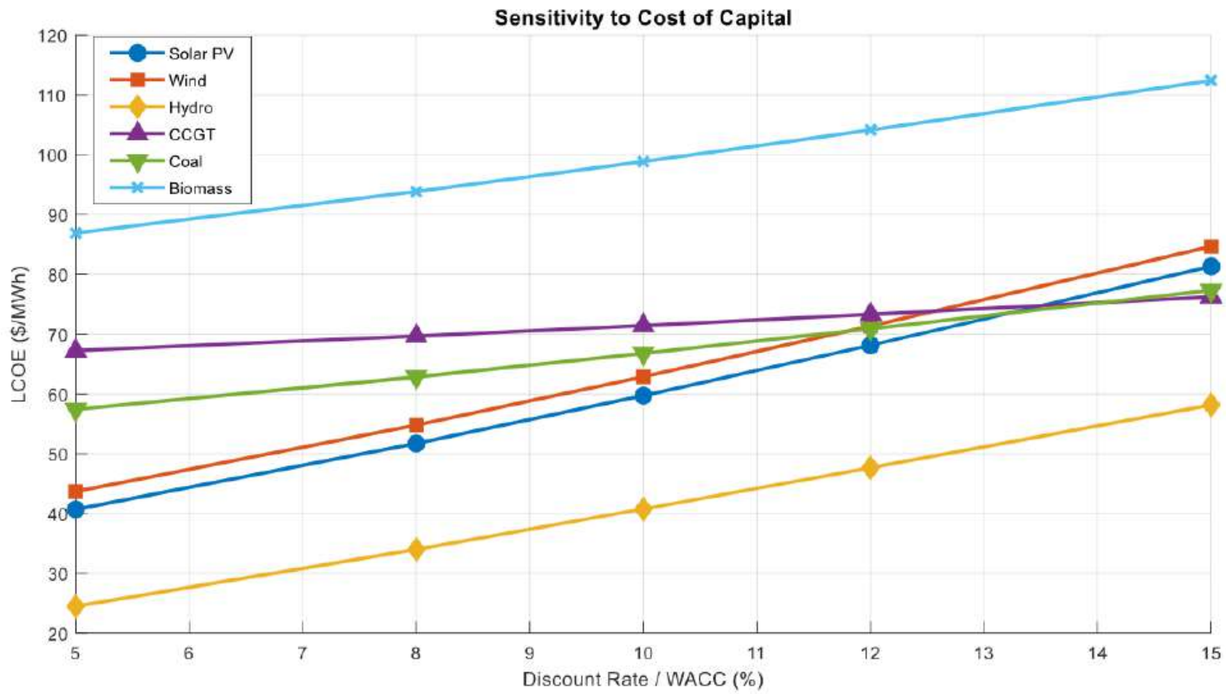

Figure 3. The impact of varying discount rates (WACC) from 5% to 15% on the LCOE of each technology.

Renewable technologies exhibit the highest sensitivity to discount rate changes. Solar PV, Wind, and Hydropower experience substantial increases in LCOE as WACC rises because their cost structures are dominated by upfront capital investments. For example, Solar PV increases from approximately **40.7 $/MWh** at 5% WACC to approximately **81.33 $/MWh** at 15% WACC. Similar trends are observed for Wind and Hydropower.

Biomass shows the strongest sensitivity among all technologies, increasing from approximately **86.92 $/MWh** to more than **112.42 $/MWh** across the examined WACC range. This behavior results from its combination of high capital costs and ongoing fuel expenditures.

In contrast, Coal and CCGT exhibit comparatively lower sensitivity to discount rate variations. Because fuel costs constitute a significant proportion of total generation costs, changes in financing costs have a smaller relative effect on total LCOE.

The findings indicate that reducing financing costs through concessional loans, government guarantees, risk-sharing mechanisms, and international development funding could substantially improve the competitiveness of renewable energy projects in Afghanistan. Therefore, financial policy may be as important as technological advancement in accelerating renewable energy deployment.

3.4 Cost–Emission Trade-Off Analysis

Figure 4 presents the relationship between electricity generation costs and carbon dioxide emissions for the evaluated technologies. This figure provides valuable insights into the trade-off between economic and environmental performance.

The most favorable region of the graph is located in the lower-left corner, where both generation costs and emissions are minimized. Hydropower occupies the most advantageous position, combining the lowest LCOE with zero operational carbon emissions. Solar PV and Wind are located nearby, demonstrating similarly low emissions and competitive generation costs.

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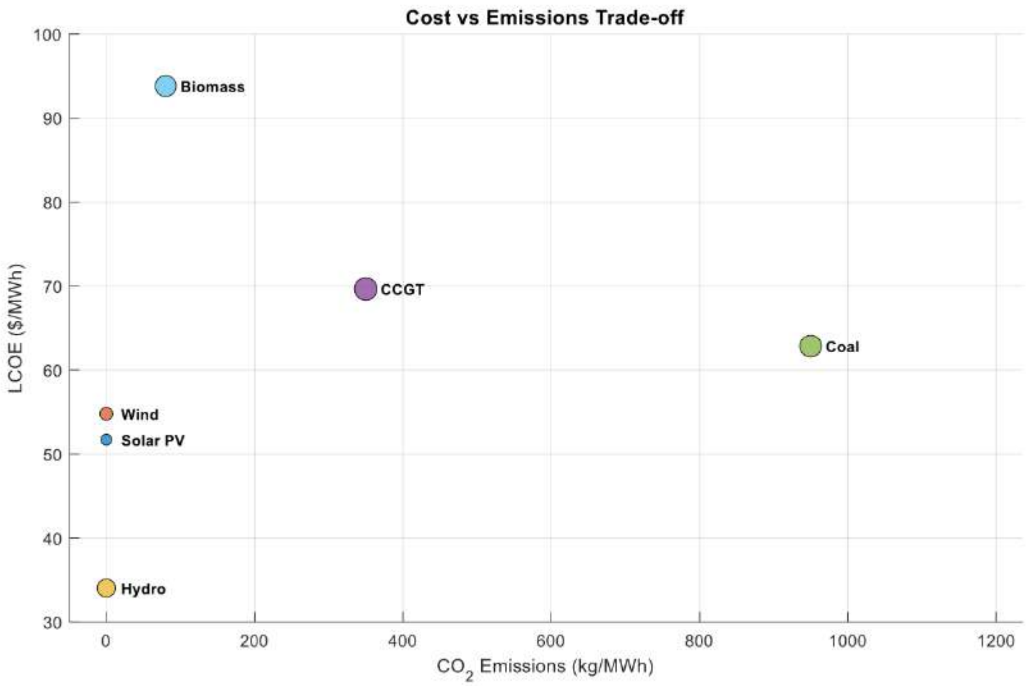

Figure 4. The relationship between electricity generation costs and CO_2 emissions for the evaluated technologies.

Coal appears in the upper-right portion of the figure, indicating high carbon emissions (approximately 950 kg CO_2/MWh) despite only moderate economic competitiveness. This result highlights the environmental disadvantages of coal-fired electricity generation and suggests that future coal investments may face increasing sustainability concerns.

CCGT occupies an intermediate position, producing substantially lower emissions than coal while maintaining moderate generation costs. Consequently, natural gas generation may serve as a transitional technology during the gradual expansion of renewable energy resources. Biomass exhibits relatively low emissions but significantly higher generation costs than other renewable technologies. Although biomass can contribute to energy diversification and rural development, its economic competitiveness remains limited under the assumptions adopted in this study.

The overall trend observed in Figure 4 suggests that renewable energy technologies simultaneously achieve favorable economic and environmental performance. This finding supports the prioritization of hydropower, solar PV, and wind energy in Afghanistan's long-term energy development strategy.

3.5 Overall Policy Implications

Collectively, Figures 1–4 demonstrate that Afghanistan possesses an opportunity to simultaneously improve energy security, reduce dependence on imported electricity, and decrease carbon emissions through expanded deployment of renewable energy technologies. Hydropower emerges as the most economically attractive option, while Solar PV and Wind provide flexible and scalable alternatives suitable for both grid-connected and decentralized applications.

The sensitivity analysis further indicates that financing conditions play a decisive role in renewable energy competitiveness. Therefore, policies aimed at reducing investment risk and facilitating access to low-cost capital may provide greater benefits than direct operational subsidies. These findings support a national energy strategy centered on renewable resource development, supported by targeted financial and regulatory mechanisms.

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3.6 Implications for Afghanistan's Energy Sector

The results demonstrate that renewable energy technologies can significantly reduce Afghanistan's dependence on imported electricity while simultaneously lowering greenhouse gas emissions.

3.7 Financing Challenges

The sensitivity analysis indicates that financing costs strongly influence the competitiveness of capital-intensive renewable technologies. Access to concessional financing could substantially accelerate renewable energy deployment.

3.8 Study Limitations

The present analysis does not explicitly include:

3.8.1 Grid integration costs.
3.8.2 Energy storage requirements.
3.8.3 Transmission expansion costs.
3.8.4 Inflation uncertainty.
3.8.5 Fuel price volatility scenarios.

Future studies should incorporate these factors through integrated power system planning models.

4 CONCLUSIONS

This study presents a comprehensive LCOE analysis for six power six power generation technologies in the Afghan contex, providing critical insights for energy policy and investment decisions. The key findings are summarized as follows:

1. **Hydroelectric power** offers the lowest LCOE at 34$/MWh, supported by its long operational lifetime and high-capacity factor. Afghanistan's substantial hydro potential should be prioritized in national energy planning.
2. Solar PV and Wind demonstrate competitive LCOE values of 51.7 $/MWh and 54.8 $/MWh, respectively, with zero CO_2 emissions. These technologies represent viable options for decentralized and grid-connected generation across Afghanistan's diverse geography.
3. Fossil fuel technologies (CCGT at 69.7 $/MWh and Coal at 62.8 $/MWh) exhibit higher costs due to fuel expenses and carry significant environmental burdens, with Coal emitting 950 kg CO_2/MWh.
4. Biomass records the highest LCOE at 93.8 $/MWh, limiting its economic viability without substantial policy support.
5. Sensitivity analysis reveals that renewable technologies are highly sensitive to financing conditions, with LCOE increasing by 50-75% as WACC rises from 5% to 15%. Securing low-cost financing is critical for renewable energy deployment in Afghanistan.
6. Cost-emissions trade-off analysis demonstrates that renewable technologies offer superior environmental performance at competitive costs, supporting their prioritization in Afghanistan's energy transition.

The findings support prioritization of renewable energy resources within Afghanistan's future generation expansion plans and provide a quantitative basis for policymaking, investment planning, and sustainable energy transition strategies.

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Cite this Article: Sayedi, S.L., Farhad, Z., Hashemi, S.H. (2026). Levelized Cost of Energy Analysis for Power Generation Technologies in Afghanistan: A Comparative Techno-Economic Assessment. International Journal of Current Science Research and Review, 9(7), pp. 3810-3818. DOI: https://doi.org/10.47191/ijcsrr/V9-i7-21