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Performance Evaluation and Cost–Benefit Analysis of Solar and Combustion-Based Power Generation Using Energy Audit Techniques: A Case Study of Jalgaon City

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ABSTRACT
The increasing need for energy and environmental issues have exacerbated the need for effective and ecologically friendly methods for power generation. The need for power generation has initiated a trend of increased use of both combustion and solar methods to meet the growing demand for power. The energy audit methodology is a systematic approach for analyzing the efficiency and cost-effectiveness of power generation. The current study aims to conduct a comprehensive analysis of the efficiency and cost-effectiveness of power generation using the solar and combustion methods of power generation. The study will be focused on the Jalgaon City area. The study will investigate the efficiency and associated costs of using environmental resources for power generation. The study will employ computational analysis to determine the input and output ratio for both power generation methods. The study will show that solar power generation is more viable and eco-friendly when compared to the combustion method of power generation.

KEYWORDS
Energy Audit, Solar Power, Combustion-Based Power Generation, Cost–Benefit Analysis, Sustainability, Jalgaon City.

1. Introduction

Energy is considered to be the backbone of present-day economic development and enhancement of living standards. With the increased pace of industrial development in developing countries, it is safe to say that there has been an exponential rise in demands for energy. The present world energy scenario marks an important turning point, as indicated in an International Energy Agency publication [1], that is, the future world energy scenario is highly dependent on present-day decisions. In relation to this concern in the Indian context, increased urban development has put tremendous strain on present energy infrastructure, leading to a re-evaluation in energy production strategies as indicated in annual reports from the Ministry of New and Renewable Energy [2]. Conventionally, energy conversion systems due to combustion, depending on fossil fuels like coal, diesel, and natural gas, have remained predominant in the energy sector. Although these energy conversion systems provide high reliability as well as grid inertia, they are faced with a lot of challenges. On the economic front, they are prone to fluctuating fuel prices in the global market, in addition to rising O&M costs. Moreover, they are major sources of ghg emission, particulate matter, as well as thermal pollution, due to which climate change and pollution have become serious concerns. Recently, researchers have highlighted the need for a sophisticated protection system to protect electrical components in high-power energy conversion systems [3].

On the other hand, solar energy is a potential green alternative that has appeared on the horizon. The geographical location of the Indian sub-continent falls under the tropical zone, thereby receiving adequate solar radiation. It becomes a preferred option for large-scale solar photovoltaic installations [4]. Jalgaon City, also known as the new Phoenix of the East, is a favorable location within the Khandesh area of Maharashtra to produce solar power due to its high yearly intensity of solar radiation and ample daylight. Nevertheless, to overcome the barriers between conventional and green energy, proper futuristic evaluation is necessary in the form of financial and technical justification of the start-up costs,

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facilitated by energy efficiency action plans at the state level [5]. Contemporary optimization methods, such as Chameleon Swarm Optimization, have foundอวse to promote energy management in such power generation systems [6].

The energy audit is an important tool for making decisions in this process. Energy audit is described as the systematic method for achieving a sufficient understanding of the existing energy use pattern, the means for understanding the factors influencing energy consumption patterns, and the practical method for calculating the cost-effectiveness of energy saving opportunities. It differs from the inspection process because it combines technical information with financial information to estimate long-term feasibility. This research paper will highlight a comparative performance analysis of solar-powered systems in comparison to combustion-based power-generation systems in Jalgaon City. Using energy audit processes, it will attempt to balance out the increased operating costs of combustion-based systems, in comparison to increased investment costs of solar energy-based systems.

2. Objectives

The principal goals of this study are:

- To assess the efficiency of solar and combustion-based power generation systems using energy audit methods.
- To analyze and compare the cost structures associated with both energy sources.
- To determine the economic feasibility and payback period of solar power installations.
- The study aims to assess the effects of combustion-based power generation.
- To develop policy-oriented suggestions for sustainable urban energy planning for Jalgaon city.

3. Literature Review

Energy audit and integration with renewable resources have received significant attention as a subject matter for study. The underlying fundamental works, as discussed in the writings of Hodge [7], tend to identify the general principles which govern the use and implementation of alternative energy resources, providing a base normative scenario to judge current practices and developments by.

A. Importance of Energy Audits

Energy audit was found to be the primary means through which the extent of the energy performance can be estimated. As per the Bureau of Energy Efficiency (BEE), Energy audit 'is a method of observation and analysis of use of energy.' The significance of periodical energy audits being helpful for the concerned industries as well as institutions to detect energy wastage and implement conservation has been well established from the earlier research conducted. The relevance of implementing energy audit related to thermal power stations has highlighted the significance of the process with respect to Heat Rate Variability & Auxiliary Consumption of Power. Further, the adoption of solar PV stations has been encouraged through detailed processes of energy audits conducted by Chisale & Mangani [8].

B. Economic Comparison of Power Systems

In reality, most papers are focused on the economic trade-off between solar and combustion-based power. Bhattacharyya examines a wide framework of energy economic concepts. Lifecycle costing has been recognized as a key role-player in both governance as well as market activities. The traditional methods of power generation using diesel-powered generators are normally less costly to install but entail extremely high operating expenses related to consumption. On the other hand, Kumar & Sharma indicate that though it initially needs higher investment costs, the solar PV power system incurs very low operating costs amounting to a substantial savings of funds. A comparative study undertaken by Nawaz & Tiwari for applications in Indian village power needs indicates that renewable resources are cost-effective in their mode of application. Similarly, another study by Singh & Singh supported the same concept by stating that the solar PV power system connected to the electric power grid has started outperforming the use of diesel-powered electric power generation due to lower LCOE over a period of

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20 years. Recent economic studies by Devi indicate the wide advantages of solar power applications in the domestic sector from a cost standpoint.

C. Technological Optimizations

There have been some advancements in recent times with the aim of maximizing the efficiency of the solar systems. For example, in cases involving partial shading of the PV cells, the efficiency may be greatly reduced. However, the efficiency of the total cross-tied layout of 6 6 design has been found to enhance the power produced in such a scenario [14]. Including these efficiencies within the cost model would give a better estimate of the viability of using solar power.

D. Environmental Considerations

Sustainability in the environment is one of the main drivers in energy transition. Combustion-based power generation is well-known to cause air and greenhouse gas pollution in urban areas. Studies conducted in the context of India [15] reveal that switching to solar power brings down carbon footprints. Not much has been explored in this area related to Tier-2 cities, who face different challenges in this aspect. Solar rooftops have been explored in different countries for saving electricity bills. According to a study conducted in India, it is clear that additional expenditure on electricity consumption in each category is brought down by using solar rooftops.

E. The Research Gap

The pros associated with solar power have been figured out globally, however, there is limited knowledge about case studies pertaining to individual Tier-2 cities corresponding to countries like India, namely Jalgaon, as far as localized climate and norms are concerned, and it may have a significant impact on the financial feasibility associated with the power setup. The aim associated with the current study is to bridge the gap.

4. Research Methodology

For conducting a comparative analysis, this research follows a quantitative research paradigm and focuses on a standard energy audit process prescribed by the Bureau of Energy Efficiency (BEE), India. The research method aims at obtaining operational data and anticipating long-term financial outcomes.

A. Research Design

It applies a descriptive and analytical case study approach with the focal point being Jalgaon City (21.0077°N, 75.5626°E). Jalgaon was chosen as it represents the climatic conditions of the Khandesh area with high irradiation of 5.5–6.0 kWh/m2/day. This makes the area an ideal test site for the feasibility of the proposed solar PV technology when compared with the conventional backup power source.

B. Data Collection Strategy

To ensure data accuracy, a two-layered method was utilized to collect data:

- Primary Data: The primary data was gathered after carrying out field measurements for a period of 12 months. This takes into consideration the seasonal changes, such as summer, monsoon,
  - Solar System: Data on real-time power generation in kiloWatt hours, inverter efficiency, and degradation rates on solar panels in a 100 kW solar system mounted on a rooftop.
  - Combustion System: Data were taken for the fuel consumption rates (liters/hour), the load loading factors, and the flue gas temperatures of a similar 100 kVA diesel generator.
- Secondary Data Sources: Historical electricity bills, MSEDCL tariff rates, and OEM technical data were collected and sourced from Maharashtra State Electricity Distribution Company Limited (MSEDCL) and OEM technical datasheets.

C. Energy Audit Framework

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The audit execution followed a three-phase protocol:

- Phase I: Preliminary Audit (Walk-through): The visual survey was performed to diagram the electricity distribution network, locate principal load centers, and evaluate the condition of existing combustion-powered generators on site. The past electricity consumption data was examined to identify the 'energy use index' (EUI).
- Phase II: Detailed Investigation: Advanced instruments were used in the experiment for accurate measurements:
  - Power Analyzers: For analyzing voltage, current, power factor, and harmonics.
  - Pyranometers: in support of comparison of local solar irradiance with satellite -derived irradiance.
  - Flue Gas Analyzers: To measure emissions (CO, NOx) from combustion sources.
- Phase III: Post-Audit Analysis: For synthesizing the data in the report to calculate the performance criteria of Specific Energy Consumption (SEC) and Plant Load Factor (PLF).

D. Computational Modeling & Analytical Tools

All of the quantitative analysis was conducted using computer simulation tools. They were used to conduct a simulation of the lifecycle cost analysis (LCCA) and sensitivity testing.

- Financial Modeling: The Payback Period is calculated using Discounted Cash Flow Approach:

$$\boldsymbol{Payback} = \frac{\textbf{Initial Investment}}{\textbf{Annual Savings} - \textbf{Annual O\&M}}$$

- Environmental Modeling: The carbon footprints were estimated using the standard grid emission factor for India (0.82 kg CO_2/kWh) as opposed to direct carbon calculations from the fuels for combustion systems.

5. Simulation Result and Discussion

The computational modeling enables a thorough techno-economic analysis. The outcomes are evaluated in four significant aspects: dynamics of generation, cost structure, financial viability, and market sensitivity.

A. Comparative Energy Generation Dynamics

The results of the simulations (Table I, Fig. 1) bring to the fore the existence of a basic difference in the operation mode, which is random for solar power while deterministic for combustion power.

- Plant Load Factor (PLF): The PLF of the combustion system is extremely high, producing 330,000 kWh every year as against 180,000 kWh produced by the solar system. This is because of the inherent property of power generation systems like combustion, which have the capability to produce power whenever needed without any dependencies regarding climatic conditions.
- Efficiency Gap: Although the lower gross energy output of solar systems results in a greater efficiency, the net usable energy efficiency of solar systems is 85% instead of 70% for the combustion system. The efficiencies lowered by heating losses and parasitic losses, which are absent in solar cells, impact the overall efficiency of the combustion equipment.

Table 1: Installed Capacity & Energy Generation

Parameter	*Solar Power*	*Combustion Power*
Installed Capacity (kW)	100 kW	100 kW
Avg. Operating Hours/Day	6 hours	10 hours
Annual Operating Days	300	330
Annual Energy (kWh)	180,000	330,000

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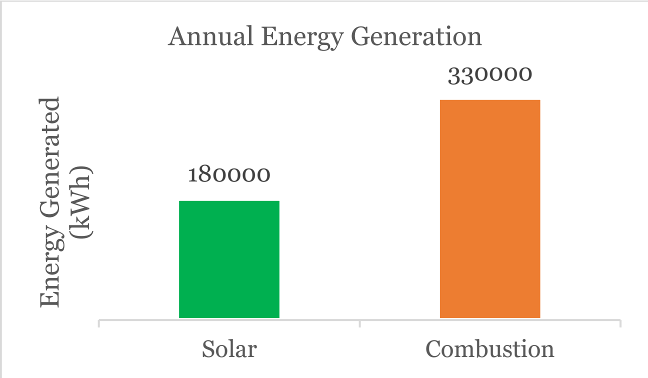

Fig. 1.Annual Energy Generation Comparison

B. Cost Structure and Levelized Cost Analysis

The economic analysis shows a sharp contrast in the cost profiles of the two technologies, as depicted by Table II.

- OPEX Difference: The Combustion system follows a ”low CAPEX, high OPEX” model. In a relative sense, the installation cost is 40% cheaper at Rs. 30 Lakhs compared to solar systems. However, the recurring annual expenditure is at Rs. 24 Lakhs. This is largely contributed by fuel consumption at 75% of the OPEX and mechanical maintenance.
- Cost Stability: The solar system, on the other hand follows a "high CAPEX, near-zero OPEX" model. The only annual maintenance cost is cleaning of the panels and checking the invertors, which aggregates to just Rs. 1 Lakh.
- Unit Cost Differential: As shown in Fig. 2, the Cost per Unit (CPU) for solar is Rs. 0.56/kWh, while it is Rs. 7.27/kWh for combustion. This 12-fold differential signifies that solar energy offers protection against fuel price volatility.

Table 2: Cost Components (Rs. per year)

Cost Component	*Solar (Rs.)*	*Combustion (Rs.)*
Capital Cost (One-time)	50,00,000	30,00,000
Fuel Cost (Annual)	Nil	18,00,000
O & M (Annual)	1,00,000	4,00,000
Emission Control (Annual)	Nil	2,00,000
Total Annual Operational	1,00,000	24,00,000

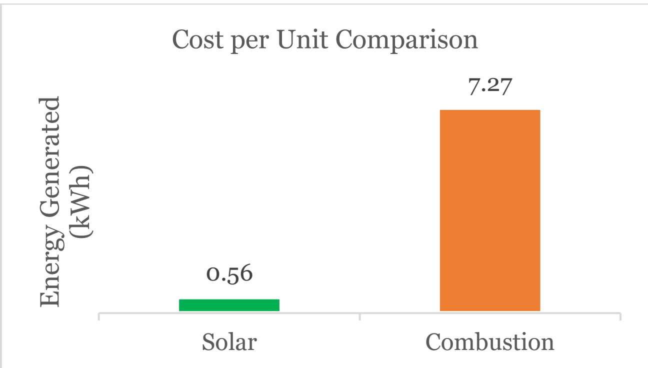

Fig. 2. Cost per Unit Comparison: Solar (Green) vs. Combustion (Orange)

C. Financial Viability and Payback Projections

The cumulative cash flow analysis (Fig. 3) provides a roadmap for Return on Investment (ROI).

- Liquidity Recovery: The operational savings of a whooping amount of Rs. 12.07 Lakhs per annum bridges the gap between the initial capital gap of Rs. 20 Lakh.
- Break-Even Analysis: The project reaches its break-even point in approximately 4.14 years.

With the remaining 20+ years out of the standard 25-year performance warranty of the solar modules, the system will operate at a minimal marginal cost.

- Depreciation of Assets: This is where it needs to be incredibly underlined that the solar assets in India are many a times covered under accelerated depreciation policies of the government, which would theoretically bring down the payback period much lower than 4.14 years calculated above, although the same was not considered in the base case to maintain conservatism.

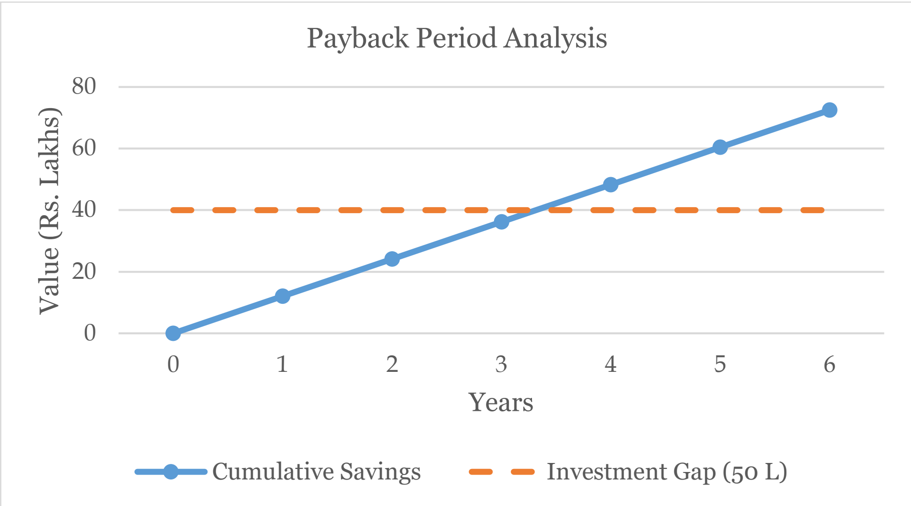

Fig. 3. Payback Period Analysis showing break-even around year 4

D. Sensitivity and Risk Assessment

To ensure the robustness of the financial model, a sensitivity analysis was conducted (Table III). This examines the viability of the project in light of market risks.

- Tariff Fluctuations: Even assuming a pessimistic situation where electricity tariffs fall by 10% (which means that the "savings" factor of solar is decreased), the payback period is not more than 4.63 years. This is well within the 5-year investment requirement.
- Fuel Inflation Risk: On the other hand, any rise in fossil fuel prices (represented by "Tariff +10%" equivalent) quickens payback to 3.75 years. This simply means that while fuel-based systems have a natural risk of volatility in prices, solar systems protect against future increases in energy prices.

6. Environment Impact Assessment

The implications of power generation decisions have both short- and long-run implications that transcend into the environmental arena. This section presents the value of the green transformation that has occurred at the Jalgaon thermal power plant regarding the reduction of Green House Gases, improvement of air quality, and value of the attributes.

Table 3: Sensitivity Analysis (Tariff Fluctuation)

Scenario	*Tariff (Rs.)*	*Savings (Rs.)*	*Payback (Yrs)*
Base Case	7.27	12,07,800	4.14
Tariff +10%	8.00	13,35,600	3.75
Tariff -10%	6.50	10,80,000	4.63

A. Greenhouse Gas (GHG) Abatement

Combustion-based power plants are a major causative of human-made climate change. Energy audit analysis shows that the 100 kW combustion-based power plant, which uses fossil fuel, releases a total of 290,000 kg (290 tons) of CO_2 every year. This is estimated in view of a specific emission coefficient of diesel (2:68 kg CO_2 = liter). In contrast, a solar PV power plant does not release any CO_2. In a span of 25 years, it avoids 7,250 tons of CO_2 in the atmosphere.

B. Local Air Quality and Health Impact

In addition to GWP, combustion-based generators contribute to the emission of localized air pollutants such as Nitrogen Oxides (NOx), Sulfur Oxides (SOx), & Particulate Matter (PM2:5). In an urban area like Jalgaon, these contribute to airborne diseases & Smog. The difference between the emission types is reflected in table IV. The advantage of using solar energy is that it bypasses point source pollution altogether, thereby contributing to a favorable Air Quality Index in the surroundings of the setup.

Table 4: Emission Comparison and Carbon Credit

Parameter	*Solar*	*Combustion*
CO2 Emissions (kg/year)	0	290,000
Air Pollutants	Nil	High
Noise Pollution	Nil	Moderate

C. Economic Value of Carbon Mitigation

The carbon reduction has some possible monetary value under different carbon trading systems like Clean Development Mechanism (CDM) or other voluntary carbon markets.

- Quantifiable reductions: Based on what is stated above, it reduces 290 tCO2e per year.
- Potential Value: On the basis of a conservative carbon credit price of Rs. 2,000/tons (notified due to the trend prevailing for voluntary trade of renewable energy certificates), the environmental advantage could unlock an additional streams of value.

Estimated Potential Revenue:

$$\boldsymbol{Value = 290\ tons \times Rs.2,000/ton}$$
$$\boldsymbol{= Rs.5,80,000\ per\ year}$$

This economic estimation further enhances the financial viability of the solar project, suggesting an additional benefit beyond the traditional CAPEX-OPEX savings.

7. Conclusion

This comparative study explicitly verifies that solar energy is a far better alternate to the burning method among the solar and burning method configurations for the case study, namely Jalgaon City. Even though burning method configurations provide dispatch ability, they have higher operating and penalty costs, whereas solar configurations have a lower levelized cost and a shorter payback period. Using the concept of energy audit, it is proven by this study that not only does solar energy ensure financial benefits, it also reduces carbon emissions to a significant extent.

A. Policy Recommendations

On the empirical observations of the present study, the following recommendations are offered to speed up the energy transition in the case of Jalgaon City:

- Incentivized Rooftop Adoption: Encourage rooftop adoption through incentives such as the offering of property tax rebates for residential and commercial buildings that implement grid-connected solar photovoltaic cells.
- Mandatory Energy Audits: Industries having a connected load of more than 100 kVA should be made mandatory to undergo energy audits every year. Thus, inefficiencies can be identified and outdated combustion generators can be phased out.

Scheduled Retiring of Combustion-Based Systems: A policy must be developed to progressively restrict the use of diesel power generators to only emergency peaking reserves, with the eventual aim of retiring them entirely in favor of BESS by 2030.

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