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Comparative Analysis of Turbine Performance using the Conventional and Alternative Energy Sources

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Abstract

With an emphasis on important metrics like thermal/aerodynamic efficiency, power output, reliability, environmental impact, and cost-effectiveness, this study compares turbine performance across conventional (natural gas) and alternative (biogas) energy sources. Data from previous studies, operational reports, and performance models for several types of gas turbines are combined in the analysis. Methane content, lower heating value (LHV), combustion efficiency, fuel consumption, Nox and CO emissions, net efficiency, and environmental impact are examples of key performance indicators (KPIs). Natural gas has a higher heating value per cubic meter than raw biogas. This means that more biogas is needed to produce the same amount of energy, and system modifications (such as specific input manifolds and higher flow rates) are necessary for efficient operation. Standard gas turbines frequently show higher intrinsic combustion efficiency when using natural gas, but research has shown that biogas can achieve combustion performance and efficiency comparable to natural gas with the correct fuel injection and combustion systems. Therefore, when choosing between conventional and alternative energy sources for turbine operation, a multi-criteria analysis that takes into account variables including complexity, cost, reliability, and environmental objectives is required in addition to energy performance.

Keywords: Turbine Performance, Conventional Energy, Alternative Energy, Biogas, Efficiency

Introduction

Due to the region's great potential for renewable energy, the need to electrify rural regions, and the advantages of wind and hydropower for the environment, turbine utilization is rising across Sub-Saharan Africa [1-5]. They may be applied on both big and small stages, provide a sustainable substitute for fossil fuels, and save money over time by using free water and wind resources [6, 7]. In Sub-Saharan Africa (SSA), where there are major obstacles to energy access, assessing turbine performance is essential to guaranteeing the sustainability, dependability, and economic viability of energy projects [8]. Effective policy and investment decisions are informed by performance evaluation, which also aids in optimizing energy generation and matching technology to site-specific conditions [9, 10]. The main causes of the notable changes in turbine performance between conventional and alternative energy sources are variations in the working fluid characteristics and energy conversion processes [11-13]. Turbine performance, which is sometimes represented as a ratio of actual power output to ideal power output, quantifies how well a turbine transforms fluid energy (such as water, steam, or wind) into mechanical energy [14, 15]. Isentropic efficiency, which contrasts real and ideal energy conversion and is impacted by heat, friction, and design constraints, is one of the key performance measures [16, 17]. While alternative sources like wind or solar thermal involve special designs and efficiency linked to resource availability, conventional sources that use combustion (fossil fuels) typically yield higher, more consistent power generation [18, 19]. High isentropic and thermal efficiency are displayed by modern conventional steam turbines, especially in ultra-supercritical power plants (up to about 42% for the Rankine cycle, with overall plant efficiencies possibly approaching 58% in combined cycles) [20, 21]. Because of a steady, regulated fuel supply, the performance is steady and predictable. These are frequently big, intricate devices made to enhance energy extraction from steam or hot combustion gasses at high temperatures and pressures. They often use reheat cycles and multi-stage designs (high-pressure, intermediate-pressure, and low-pressure). Certain gas turbines are designed to run on a certain fuel, but they can alternate between natural gas and diesel [22-26]. Natural gas is more efficient and produces fewer emissions in the combustion chamber [27-29].

One of the most effective ways to reduce carbon dioxide emissions (CO2) is to replace conventional fossil fuels with alternative gases [30-33]. Technologies for the production of new energy resources facilitate the development of renewable energy, which reduces the use of conventional energy sources like oil and natural gas [34, 35]. The need to develop renewable energy sources, such as solar radiation, hydropower, wind energy, biomass, marine and oceanic currents, tides and castings, geothermal energy is growing due to the limited supply of energy. The growth of rural areas and the generation of new jobs can both benefit from alternative technology. Innovative system installation necessitates the participation of experts and financial resources, which promotes regional economic growth. However, a number of obstacles must be removed before new technologies can be successfully implemented, including high upfront costs, challenges in securing funding, and a lack of public awareness of the benefits of these technologies. In addition to the aforementioned, using alternative gas as fuel for energy complexes can improve the nation's energy security and lessen reliance on energy imports [36, 37]. The region's energy needs can be satisfied by using gas from nearby sources, which lowers the possibility of supply disruptions and improves the stability of the energy infrastructure [38]. Over the past ten years, there has been a global increase in the production and burning of biogas to produce heat and power. In Europe, biogas technologies have evolved into pilot projects that showcase alternative energy's potential [39-45]. Concurrently, the Russian Federation's substantial biomass potential for the development of new energy sources creates good conditions for the biogas bioenergy industry's successful growth. The organic component of livestock and poultry farms, solid municipal waste, and bottom silt deposits can all be utilized as a consistent source of biomass for biogas production. Because the sources of coal, natural gas, and oil are limited and the daily accumulation of organic waste requires the creation of creative disposal techniques, the usage of biogas is relevant in the modern era [46-51].

Although biogas is a renewable energy source that may power turbines, it frequently needs to be pre-treated, and the efficiency of the turbine may be lower than that of natural gas. The anaerobic digestion of organic waste produces biogas [52-58], a mixture of carbon dioxide and methane [59-62] that can be compressed and purified to power gas turbines to produce electricity. Performance can be enhanced by using upgraded biogas, or "biomethane," although raw biogas can also be utilized with the right cleaning and engine modifications. According to evaluations, biogas can be utilized in gas turbines to produce electricity, which frequently results in higher power output but is less efficient than natural gas. Although biogas's increased flow rate can increase turbine power and its strong knock resistance is advantageous, its lower methane concentration (lower heating value) results in decreased performance. However, using biogas can result in turbine overheating and a reduction in compressor surge margin. These issues can be addressed by techniques such compressor air bleeding or under-firing, however they can lower net power and efficiency. There are several applications for biogas as an energy source. First, biogas can be directly burned in boiler rooms and thermal power plants to produce heat and electricity. Second, biogas can be utilized as fuel in fuel components and gas turbines to generate energy. Furthermore, biogas can be burned to produce energy for its own purposes in a variety of technological processes, as well as utilized to heat water and the building. receiving biogas from a variety of source materials by anaerobic fermentation. Its physical properties are comparable to those of natural gas, which is made up of 90–99% $CH4$. Biogas may also be transported easily because its physical properties are similar to those of natural gas. However, biogas has a low heat capacity when compared to other conventional fuels.

2. Benefits of using Biogas in Turbines

By extracting powerful methane from organic waste, biogas in turbines offers a dependable, renewable energy source that lowers greenhouse gas emissions. Effective waste management, the creation of nutrient-rich biofertilizer, and increased energy independence are further advantages. Because biogas has a faster flow rate than natural gas, burning it can boost the power output of the gas turbine. Because biogas has a high knock resistance, it can be used with high-compression engines to increase power density. Biogas is a sustainable substitute for fossil fuels like natural gas since it is a renewable energy source made from biological waste. According to some research, burning biogas can produce lower emissions of Nox than burning natural gas, but it may also raise emissions of CO.

2.1 Environmental Benefits

The captures methane, a potent greenhouse gas that decomposing waste would otherwise release into the environment. helps manage waste and lessen odors by diverting organic waste from landfills. Digestate, the residue from the manufacture of biogas, is an organic fertilizer rich in nutrients that can lessen the demand for synthetic fertilizers.

2.1 Energy and Economic Benefits

Compared to solar or wind, biogas is a more dependable energy source that can deliver electricity fast during periods of high demand. reduces dependency on fossil fuels and outside energy markets by producing a local, independent energy supply. It can be produced at a reasonable cost, particularly on a smaller scale, and makes money from the sale of electricity. Local jobs are produced by the construction and upkeep of biogas facilities.

3. Drawbacks and Performance Challenges

High dependability and consistency are characteristics of turbine performance using conventional energy sources (such as coal, natural gas, and oil), but they are hampered by substantial resource depletion and environmental degradation. On the other hand, clean operation and limitless fuel supplies are provided by alternative (renewable) energy sources including biogas, wind, sun, and hydro, but they have significant performance issues with intermittency, energy storage, and location-specific generation. The main disadvantage is that during burning, greenhouse gases (CO_2, N_2O) and pollutants (SOx, NOx, particulates) are released, contributing to acid rain, climate change, and public health problems. Toxic radioactive waste from nuclear power plants needs to be stored safely for a long time. Due to their limited supply, conventional sources cause price swings and raise questions about long-term energy security. Drilling and mining are examples of extraction operations that pose health and environmental dangers (such as oil leaks and black lung disease in miners). Thermal pollution in adjacent water bodies can result from thermal power facilities that utilize a lot of cooling water. Natural disasters and geopolitical events can cause interruptions to centralized power plants that depend on fuel supply lines.

This is a major performance challenge because energy generation from sources like wind and solar is completely dependent on weather conditions (wind speed, sunlight availability), making them unreliable as a sole "baseload" power source. Effective energy storage is required to counteract intermittency, but current battery technology is often expensive, has limited capacity, and can deteriorate over time. Although operating costs are low, the initial capital investment for building renewable energy farms and associated infrastructure (like transmission lines from remote sites) is high. Centralized, reliable electricity flow was the goal of traditional power grids. Grid stability and management are complicated by the fluctuating, decentralized character of renewable energy sources. There are worries about visual effects, noise pollution, and possible effects on wildlife (such as bird deaths). Large dams can force communities to relocate, disturb local ecosystems, and change river flow. can release some subterranean gasses during excavation and cause small seismic activity (earthquakes). Under some circumstances, some renewable technologies, such as some varieties of vertical axis wind turbines, may be less energy efficient than their horizontal axis counterparts. However, because biogas contains less methane than natural gas, it has a lower heating value, which might reduce overall efficiency. Utilizing biogas may result in turbine overheating and a decrease in the compressor's surge buffer. Higher ambient temperatures and simple cycle gas turbines are especially vulnerable to this. Because of the fuel's reduced energy content and the power required to compress it, overall efficiency frequently declines even though net power may rise.

4. Key Performance Variances in Conventional and Alternative Energy Sources

Biogas's lower methane content and substantial carbon dioxide ($CO2$) content are the main reasons why a gas turbine utilizing biogas performs differently from one using natural gas. This leads to a lower heating value (LHV), decreased efficiency, and changed emissions. Because biogas has a far LHV than natural gas, it usually results in decreased power production and efficiency in gas turbines. One study found that using biogas instead of natural gas reduced gas turbine efficiency by 8.5%. However, by adjusting combustion characteristics like the swirl number and fuel injector diameter, performance can be equivalent; however, this may result in higher CO emissions and necessitates a certain biogas composition. Biogas is a feasible alternative fuel when performance and emission trade-offs are controlled through optimization or by combining it with natural gas. It also has environmental advantages, such as lower CO_2 emissions. Furthermore, in a specially built or adapted gas turbine combustor, biogas can achieve combustion performance comparable to natural gas; however, because of its lower heating value and methane concentration, it often has a lower overall efficiency. The biogas composition and the system's engineering modifications have a significant impact on the performance.

Furthermore, because biogas has a substantially LHV than natural gas, biogas-fueled gas turbines consume a lot more fuel by volume or mass. However, biogas can match natural gas in terms of performance and thermal efficiency with the right fuel upgrades or combustion chamber changes. The composition of natural gas (NG) and biogas (BG) is the main factor that affects how well they work in gas turbines. While raw biogas usually comprises around 60% methane and 40% carbon dioxide (CO_2), which results in a much LHV, NG is primarily composed of methane (90–99% CH_4) and has a high LHV. Additionally, the primary effect of biogas' LHV is that a lot more fuel needs to be pumped into the combustion chamber in order to produce the same amount of power as natural gas. Additionally, because of its almost carbon-neutral lifecycle and waste management role, biogas provides significant environmental benefits over natural gas when used in turbine performance. However, biogas combustion might cause problems with increased carbon monoxide (CO) emissions if the system is not specially adjusted, whereas natural gas gives superior combustion efficiency in typical turbines. Compared to raw biogas (45–75% methane with considerable CO_2), natural gas has a higher heating value per cubic meter due to its higher methane concentration (85–95%). This implies that more biogas is required to generate the same amount of energy, and system adjustments (such as particular input manifolds and increased flow rates) are required for effective functioning. When using natural gas, standard gas turbines often exhibit higher intrinsic combustion efficiency. However, research has demonstrated that biogas can attain combustion performance and efficiency comparable to natural gas with the right adjustments made to the fuel injection and combustion systems. Existing natural gas power plants will find the transition easier because biomethane (upgraded biogas) may be put straight into natural gas pipes and used interchangeably without requiring infrastructure upgrades. Table 1 shows the summary of key performance variances in comparative analysis of conventional and alternative energy sources.

Table 1. Summary of Key Performance Variances in Comparative Analysis of Conventional and Alternative Energy Sources

S/N	Feature	Natural Gas	Biogas
1	Methane Content	85-95% CH_4	45-75% CH_4 (raw)
2	Lower Heating Value (LHV)	Higher	Much Lower (due to high CO2 content)
3	Combustion Efficiency	Generally higher	Can be comparable with specific adjustments, but often lower
4	Fuel Consumption	Lower flow rate needed	Significantly higher flow rate needed for the same power output
5	Nox Emissions	Higher	Markedly lower
6	CO Emissions	Lower	Higher
7	Net Efficiency	Generally higher exergy efficiency	Lower net efficiency, especially in simple cycle engines
8	Environmental Impact	High greenhouse gas contributor (fossil fuel)	Near carbon-neutral (renewable fuel)

5. Comparative Analysis of Conventional and Alternative Energy Sources Usage in Turbine Performance

Although conventional energy sources (fossil fuels) have substantial detrimental effects on the environment and unstable fuel prices, they typically provide higher instantaneous power output and thermal efficiency when utilized in turbines. Although their performance can be reliant on fluctuating natural conditions, alternative energy sources mainly renewables like wind and hydro—use turbines with reduced operating costs and fewer emissions.

5.1 Efficiency and Power Output

Although raw biogas can result in a slight increase in gross power due to a higher overall mass flow through the turbine (as more fuel volume is required), the net power output is usually lower, especially when accounting for the energy required for fuel compression. Raw biogas generally results in a decrease in the overall net electrical efficiency of the turbine compared to natural gas because of its high carbon dioxide (CO_2) content and hence lower LHV. To achieve the same power output, a much larger mass flow of biogas, which can cause aerodynamic problems and possibly reduce the compressor surge margin in machines designed for natural gas. Biogas has a lower LHV, meaning it has less energy per unit mass or volume compared to natural gas. This often results in lower efficiency and power output. For example, one study found an 8.5% lower gas turbine efficiency when running on biogas versus natural gas.

5.2 Emissions

Emissions are the main environmental trade-off. One key benefit of using biogas is that it produces far reduced Nox emissions. Nevertheless, it results in increased CO emissions, a problem that needs to be addressed with particular combustor design changes or post-combustion treatment techniques.

i. **CO2:** Using biogas significantly reduces CO_2 emissions, a major benefit for environmental goals,
ii. **NOx:** Optimized biogas combustion can lead to lower NOx emissions compared to natural gas, and
iii. **CO:** The trade-off for achieving comparable performance and lower NOx with biogas can be an increase in CO emissions.

5.3 Fuel Compatibility and Upgrading

Natural gas-powered turbines can run on a mixture of natural gas and biogas, with performance variations based on the percentage of biogas. Biogas upgrading (removing CO_2 and contaminants) to biomethane is very effective for performance closer to design specifications, producing a fuel with almost natural gas-like qualities.

5.4 Modifications

Because biogas has various combustion characteristics, achieving maximum combustion performance may require particular modifications to the fuel injector design and swirl number within the combustion chamber to maintain flame stability and adequate mixing.

5.5 Feasibility & Mitigation

Particularly in applications involving combined heat and power (CHP), biogas is a practical substitute. Biogas upgrading (removing CO2 and other contaminants like H2S) and small adjustments to the fuel injection system and combustor design are frequently required to attain performance comparable to natural gas. The performance of enhanced biogas (biomethane) is almost the same as that of natural gas.

5.6 Fuel Consumption and Efficiency

To make up for the decreased LHV brought on by the inert CO2 content, a gas turbine running on raw biogas needs a much higher mass flow rate of fuel. When compared to natural gas, this results in a reduction in overall electrical and thermal efficiency.

5.7 Combustion

Low burning velocities, lean extinction limits, and flame stability present problems for raw biogas in conventional NG combustors. However, combustion performance comparable to natural gas can be achieved with specialized combustor designs that use modified fuel injectors and swirl numbers. Studies reveal that by tailoring the fuel-air mixture, the combustion performance may be made similar to natural gas despite the reduced energy content.
i. Comparable combustion performance can be achieved by using a certain biogas composition with the appr opriate swirl number and fuel injector diameter.
ii. Blending biogas with natural gas can preserve efficiency while lowering the total carbon footprint, which i s one way to lessen performance loss.
However, removing CO2 from raw biogas and turning it into biomethane, which contains 95% methane, prod uces a fuel that can almost exactly match the performance of natural gas in current turbines without requirin g major changes.

5.8 Overall Turbine Performance

While raw biogas results in higher fuel consumption, its use in optimized systems, like combined heat and power (CHP) plants, can result in high overall energy and economic efficiency, especially when heat sales are taken into account. The presence of non-combustible components (CO2 and NO2) in biogas acts as a diluent, reducing the adiabatic flame temperature and overall energy yield per mole of fuel, which generally leads to a decrease in net electrical efficiency and power output in standard micro gas turbines compared to natural gas.

5.9. Operational Flexibility

Because of its fluctuating composition, the usage of biogas necessitates a careful assessment of combustion factors like stability and lean blow-out limits. Dual-fuel systems, which employ mixtures of natural gas and biogas, can provide significant operational flexibility and efficiency.

6. Greenhouse Gas (GHG) Emissions

6.1 Natural Gas

When a fossil fuel is burned, old, stored carbon dioxide (CO_2) is released into the atmosphere, greatly accelerating climate change. Because methane is a very powerful greenhouse gas, methane leaks during extraction and transportation (midstream and upstream emissions) further increase its climate impact.

6.2 Biogas

Anaerobic digestion of organic waste, such as manure, food scraps, and sewage, yields a renewable energy source. The lifespan of biogas is almost carbon neutral since the CO2 produced after combustion is about equal to the CO2 absorbed by the source organic matter throughout its growth. Additionally, a significant source of greenhouse gas emissions is directly reduced by trapping the methane from organic waste that would otherwise leak into the atmosphere in farms or landfills.

6.3 Other Pollutants (NOx, CO):

Nitrogen Oxides (NOx): An important benefit for air quality is that burning biogas typically results in much lower NOx levels than burning natural gas.
Carbon Monoxide (CO): Compared to natural gas, biogas combustion in unmodified gas turbines has a greater rate of CO emissions and a poorer initial combustion efficiency. This problem can be lessened and comparable performance can be attained with specialized combustor designs and operating characteristics (such as higher swirl numbers).
Land and Water: Drilling and hydraulic fracturing are two methods of extracting natural gas that can harm local ecosystems, including water and land resources. On the other hand, biogas generation is an effective way to manage waste and generates digestate, a nutrient-rich byproduct that can substitute synthetic fertilizers, establish a circular economy model, and lessen the environmental impact of fertilizer manufacturing.

Conclusion

According to the review of the literature, biogas is a superior and essential alternative for global decarbonization efforts because of its overall lifecycle environmental benefits, especially the significant reduction in GHG emissions and waste utilization. Although, it presents some technical challenges in achieving optimal combustion efficiency in standard turbines when compared to the energy-dense natural gas. Because biogas has a lower methane content and heating value than natural gas, biogas-fueled turbines have lower electrical efficiency and net power production. However, with the right adjustments, they provide equivalent combustion performance and substantial environmental benefits. Additionally, biogas offers substantial environmental benefits as a renewable and nearly carbon-neutral fuel, making it a viable and significant alternative with the right engineering solutions, even though using it in gas turbines presents technical challenges due to its lower energy density and higher CO emissions. Although biogas's lower LHV poses performance issues, gas turbines can use it successfully. Careful engineering and a particular biogas composition can preserve performance, although doing so may result in increased CO emissions. As an alternative, combining biogas and natural gas is a workable strategy to preserve efficiency while reaping environmental advantages including lower CO_2 emissions.

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