

Article

Review of natural gas vs diesel in gas turbines: Efficiency enhancement, emissions reduction, and technological adaptation

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Abstract

This paper presents a comparative analysis of natural gas and diesel as fuels for gas turbine power generation, focusing on efficiency, emissions, and sustainability. The findings indicate that natural gas, owing to its higher hydrogen-to-carbon ratio, achieves significantly lower NO_x and greenhouse gas emissions compared to diesel. However, diesel exhibits slightly superior thermal efficiency and lower specific fuel consumption under similar operational conditions. Overall, the study concludes that natural gas represents a more sustainable and environmentally favorable option, offering a balanced trade-off between performance, cost, and emission reduction in modern energy systems.

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Keywords

Gas turbines; natural gas; diesel fuel; thermal efficiency; emissions reduction

Introduction

Fuel composition critically governs gas turbine performance, directly influencing power output, operational stability, and emission profiles (Burnes & Camou, 2019). Fuels with higher hydrogen-to-carbon (H/C) ratios such as natural gas enhance thermal efficiency and reduce pollutant formation, while key parameters such as heating value, dew point, Joule-Thompson coefficient, and Wobbe index determine operational suitability (Sefiddashti et al., 2021).

Recent research prioritizes dual-fuel systems (natural gas/diesel) to achieve operational flexibility, reduce NO_x and particulate emissions, and overcome efficiency constraints at low loads (Karagöz et al., 2016). This study provides a

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comparative assessment of natural gas and diesel in gas turbine power generation, evaluating critical factors including fuel economy, operating costs, thermodynamic efficiency, emission footprints, and environmental sustainability (Molière, 2023).

Key research areas include the dynamics of fuel-switching between diesel and natural gas in gas turbines to optimize combustion performance and minimize emissions (Pourhedayat et al., 2024). Advances in dual-fuel turbine technologies allow operation on both fuels interchangeably, enhancing flexibility and reliability (Haque et al., 2020). Efforts are also being made to mitigate emissions and performance degradation at low loads, where dual-fuel engines often suffer efficiency drops and increased CO₂ output (Nemitallah et al., 2019).

Recent literature increasingly emphasizes reducing dependence on diesel fuel by promoting cleaner energy sources such as natural gas and hydrogen blends, aligned with sustainability goals (Stefan et al., 2022). The purpose of this study is to compare and evaluate the effectiveness of natural gas and diesel fuels in gas turbine power generation, highlighting differences in efficiency, operating cost, emissions, and environmental impact (Elwardany et al., 2023).

The basic gas turbine cycle

A gas turbine is a type of heat engine that transforms some of the chemical energy of fuel into mechanical energy that can be used. Though the work is done sporadically, it functions similarly to an internal combustion engine running on four strokes (Burnes & Camou, 2019).

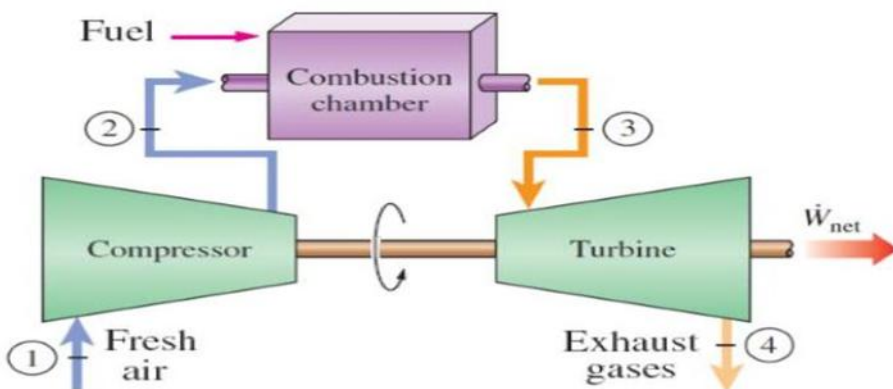


Figure 1. Gas turbine cycle (Burnes & Camou, 2019)

In the gas turbine cycle, air is compressed, mixed with fuel in the combustion system, and ignited—heating it to 1371–1760°C (2500–3200°F). Secondary air

moderates temperatures before the high-energy gas expands through the turbine, driving the compressor and external loads (Elwardany et al., 2023). Exhaust gases are repurposed for heating/drying applications or released via chimneys, with residual heat recovery boosting overall efficiency.

Gas turbines dominate distributed power generation due to their Brayton-cycle operation, offering:

- Higher waste heat utilization
- Dual-fuel flexibility
- Compact design with low emissions
- Lower operating costs than diesel/steam alternatives

System configurations include open cycles (air expelled post-turbine), closed cycles (working fluid recycled), and combined cycles (optimized for large-scale efficiency despite complexity) (Molière, 2023).

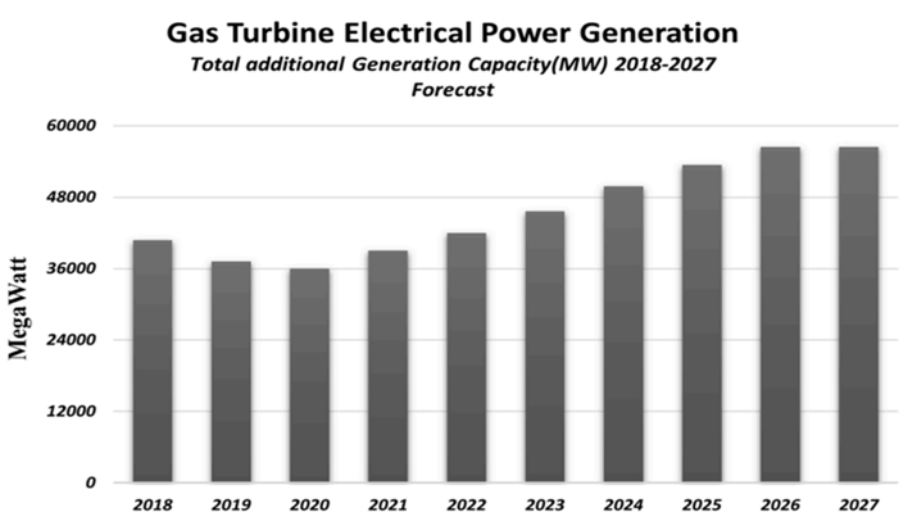


Figure 2. The evolution of gas turbines' contribution to the production of electricity (Imteyaz et al., 2018)

Figure 2 forecasts additional gas turbine power generation capacity (MW) from 2018–2027. Key trends show 2018–2023 stable growth (~36,000–40,000 MW/year), followed by 2024–2027 accelerated expansion, rising from ~48,000 MW (2025) to 54,000 MW (2027) (Imteyaz et al., 2018). This indicates a significant increase in gas turbine adoption for electricity generation post-2023, reflecting their growing importance in the energy sector.

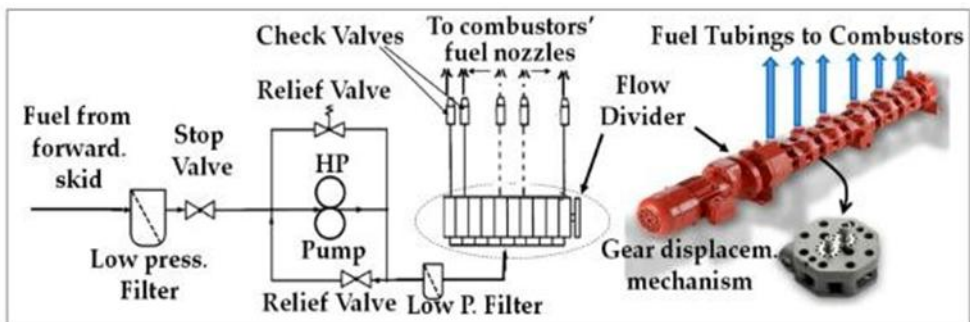


Figure 3. Simplified schematic of the liquid fuel delivery system for a gas turbine (Elwardany et al., 2023)

Figure 3 illustrates the essential components and flow path of the liquid fuel system used in gas turbines. The system typically includes a fuel tank, low-pressure filter, stop valve, high-pressure (HP) pump, relief valves, flow divider, and injectors that distribute fuel evenly to the combustors' nozzles. The configuration ensures a stable and continuous fuel supply under controlled pressure, which is crucial for maintaining efficient combustion and turbine performance (Elwardany et al., 2023).

Diesel fuel

Diesel power generators come in a range of sizes and are used for off-grid, decentralized, and centralized power generation. The power plants can be used for a variety of tasks, such as peak load generation, central power generation, standby power generation, emergency power generation, black start generation, and mobile power generation in different field applications.

A diesel engine power plant's performance is affected by a number of variables, such as its size, load profile, engine condition, mode of operation, and maintenance schedule. It is advisable to select various generator sets of varying sizes because demand is dynamic and the ideal design plan is to have a generator with a rating equivalent to the current demand. In diesel power plants, diesel engines are mostly employed as prime movers, turning electric generators and alternators to produce energy. The engine, fuel storage supply system, engine charge air intake system, engine exhaust system, engine cooling system, lubricating system, engine starting system, speed governing and control system, instrument, and control air system are the main parts of a diesel power plant. Inline, V-, four-, and two-stroke engines are examples of dynamic engines.

Engines with four strokes are better because they are more balanced and efficient. Before atomized fuel is introduced to start combustion, air in diesel engines is

compressed adiabatically, raising the air temperature. Warm temperatures cause the diesel to ignite on its own, moving the pistons and rotating the crankshaft (Elwardany et al., 2023).

Natural gas fuel

Composition and properties

Natural gas, primarily methane (CH₄, ~90%), is a fossil fuel formed from ancient biomass under heat/pressure (Speight, 2007). Found in deep reservoirs, shale, and coal beds, it is extracted via vertical wells (>1,000m depth) (Speight, 2007). Impurities (CO₂, H₂S, mercury) are removed during processing (Animah & Shafiee, 2020). When cooled to -162°C, it becomes LNG for storage (Arefin et al., 2020). Three engine types utilize it for power: gas-fired turbine, dual-fuel engines, and spark-ignition engines. Natural gas offers cost efficiency, lower emissions, fuel flexibility, and reduced operating costs (Karagöz et al., 2016).

Table 1. Typical composition of compressed natural Gas (Arefin et al., 2020)

No.	Element	Symbol/Formulae	Volumetric %
1	Methane	CH ₄	94.42
2	Ethane	C ₂ H ₆	2.27
3	Propane	C ₃ H ₈	0.03
4	Butane	C ₄ H ₁₀	0.25
5	Nitrogen	N ₂	0.44
6	Carbon dioxide	CO ₂	0.57
7	Others	-	2
	Total		100%

Thermodynamic characteristics

Compressed natural gas (CNG) exhibits distinct thermodynamic properties compared to diesel and gasoline (Table 2) (Arefin et al., 2020). While diesel has higher density (837 kg/m³) and molecular weight (186 kg/kmol), CNG possesses superior combustibility with a higher auto-ignition point (900K), wider flammability range (15.6 vol%), and the highest octane number (120-130) (Karagöz et al., 2016), making it ideal for spark-ignition engines. CNG composition (Table 1) is predominantly methane (90-94%), with minor constituents including ethane, propane, butane, nitrogen, and carbon dioxide (Arefin et al., 2020).

Notably, natural gas has significantly higher volumetric energy density (40.9 MJ/m³) than hydrogen (12.7 MJ/m³) (Table 2). A 20% hydrogen blend yields only 2.54 MJ/m³ from hydrogen against 35.26 MJ/m³ from natural gas, resulting

in total energy content of 37.8 MJ/m^3 —7.2% lower than pure CNG (Imteyaz et al., 2018). Consequently, 7.2% more blended fuel must be burned for equivalent heat output, while carbon emission reduction remains proportionally limited to 7.2% (not 20%) (Nemitallah et al., 2019).

Table 2. Thermodynamic properties of compressed natural gas (Arefin et al., 2020)

	Property	Unit	Gasoline	Diesel	CNG
1	Stoichiometric Ratio	Ratio	14.2	15	15.7
2	Cetane number	Unit	N/A	40-55	N/A
3	Octane number	Unit	96	N/A	120-130
4	Lower calorific value	Mj/kg	42.2	43.5	45.9
5	Higher calorific value	Mj/kg	45	45.6	50.3
6	Density at 25°C (DIN 51757)	Kg/m ³	749	837	2.52
7	Molecular weight	Kg/kmol	106.2	186	16
8	Minimum ignition energy	Mj	0.33	0.5	0.26
9	Lamilar flame speed	cm/sec	30	-	37.5
10	Flammability unit	Vol% in air	5.2	1	15.6
11	Adiabatic flame temp	K	2227	-	2266
12	Vaporization energy	Mj/m ²	293	192	215-276
13	Flash point	K	266	325	124
14	Combustion Energy	Kj/m ³	32.6	36	24.6
15	Auto ignition point	K	505-755	477-533	900

Economics and life cycle of LNG

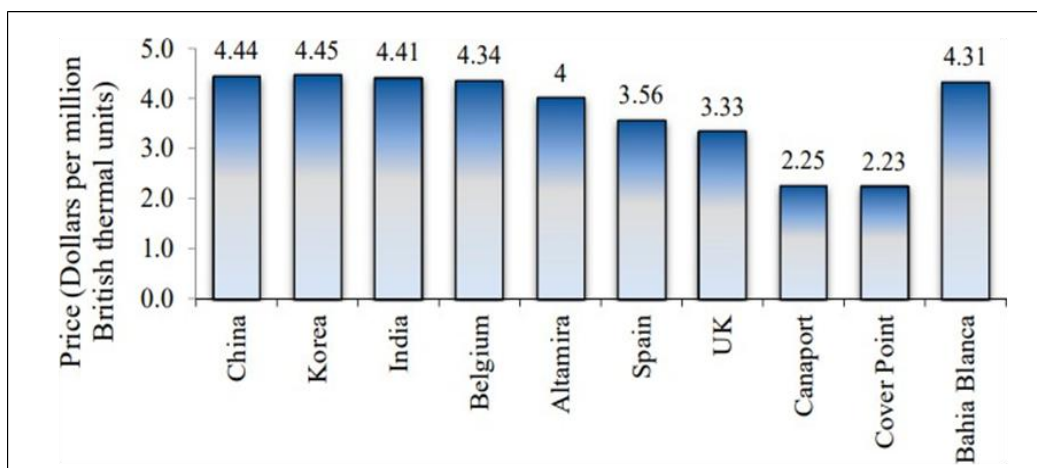


Figure 4. Global landing price of natural gas (LNG) (Dudley, 2019)

Figure 4 shows the worldwide LNG price as of June 2019 (Dudley, 2019). South Korea and China had the highest landed price of LNG in the world (Dudley, 2019). The price received at the regasification plant is referred to as the landed price. Netback price is taken into consideration for the determination of these prices, which is based on the effective price for a seller and producer at a definite location (Animah & Shafiee, 2020).

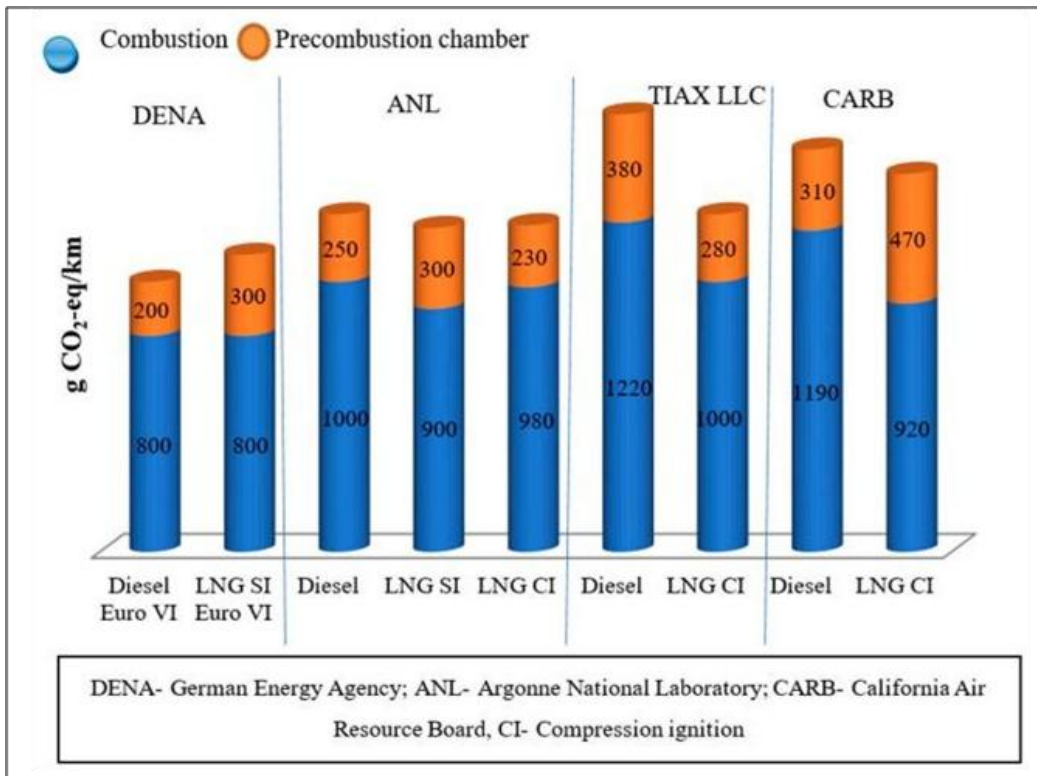


Figure 5. Comparison of the life cycle greenhouse gas emissions of heavy-duty diesel and LNG vehicles (Arefin et al., 2020)

Figure 5 compares the life cycle greenhouse gas emissions of heavy-duty vehicles powered by diesel and LNG across four different studies (Arefin et al., 2020). Overall, diesel vehicles tend to have lower greenhouse gas emissions during the combustion phase compared to LNG vehicles (Elgohary & Seddiek, 2012). However, LNG vehicles may have higher emissions during the pre-combustion phase, depending on the study. The analysis suggests that, in general, diesel engines demonstrate superior performance in terms of overall life cycle emissions when compared to LNG, particularly in the combustion stage.

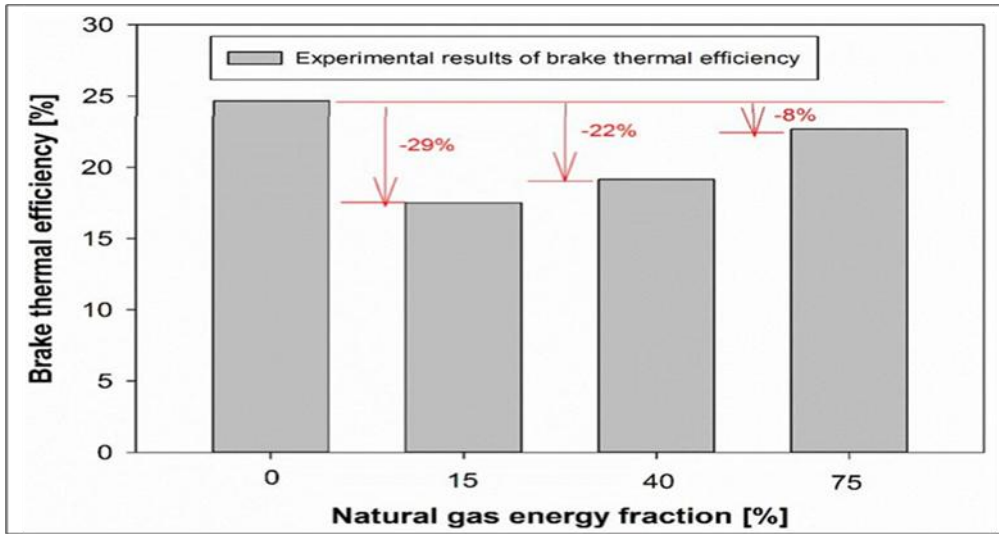


Figure 6. Impact of varying natural gas injection amounts on brake thermal efficiency (Karagöz et al., 2016)

Figure 6 shows the effect of varying amounts of natural gas addition on brake thermal efficiency (BTE) in an engine (Karagöz et al., 2016). Brake thermal efficiency measures how effectively an engine converts fuel into mechanical energy.

Key findings:

- Natural Gas Energy Fraction (0%): When the engine runs on 100% diesel, the brake thermal efficiency is at its highest, around 25%.
- Natural Gas Energy Fraction (15%): Adding 15% natural gas reduces the brake thermal efficiency by 29%, indicating a significant drop in efficiency.
- Natural Gas Energy Fraction (40%): At 40% natural gas, the efficiency drop is less severe, at 22%, showing some recovery in efficiency compared to the 15% fraction.
- Natural Gas Energy Fraction (75%): When the natural gas fraction is increased to 75%, the brake thermal efficiency shows a smaller reduction of 8%, indicating that at higher natural gas fractions, the efficiency loss is minimized (Karagöz et al., 2016).

The initial addition of natural gas (up to 15%) significantly reduces engine efficiency. However, as the proportion of natural gas increases to 75%, the efficiency loss becomes less pronounced, potentially indicating a stabilization or adaptation in the engine's performance with higher natural gas use (Arefin et al., 2020; Karagöz et al., 2016).

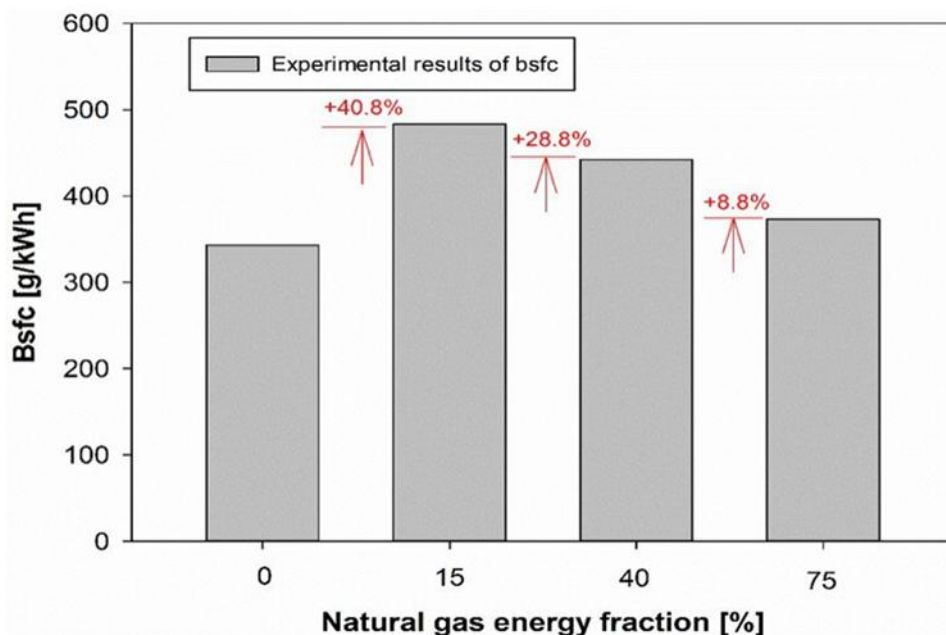


Figure 7. Effect of varied amount of natural gas addition on BSFC (Karagöz et al., 2016)

Gaseous fuels (e.g., natural gas) exhibit a higher stoichiometric air-to-fuel ratio than diesel, necessitating greater air mass for complete combustion. As demonstrated in Figure 7:

- Airflow rates increase significantly with gaseous fuels to meet stoichiometric requirements ($\approx 15.7:1$ for NG vs. $\approx 15:1$ for diesel).
- The excess air factor ($\lambda > 1$) further rises to ensure combustion completeness and temperature control, intensifying heat dissipation.
- Consequence: Excess air absorbs combustion heat, lowering peak temperatures and reducing thermal efficiency versus diesel engines.

Thus, while gaseous fuels enable cleaner combustion, their inherent air demand imposes an efficiency trade-off via heat loss (Karagöz et al., 2016).

The experimental results of brake specific fuel consumption (BSFC), measured in grams per kilowatt-hour (g/kWh), at different fractions of natural gas energy (Figure 7). BSFC is a measure of the fuel efficiency of an engine in terms of the fuel amount consumed per unit of power generated.

As the fraction of natural gas in the fuel mix increases, there is a trend of increased BSFC. This indicates that higher amounts of natural gas lead to higher fuel

consumption per unit power, which might imply lower efficiency under these specific conditions (Karagöz et al., 2016). Here is a breakdown:

- At 0% natural gas (pure diesel or another base fuel), the BSFC is the lowest among the tested configurations.
- At 15% natural gas, BSFC increases by 40.8% compared to the base level.
- At 40% natural gas, there is a further increase in BSFC, totaling 28.8% from the previous level.
- At 75% natural gas, the increase in BSFC slows down to 8.8% from the previous level.

This pattern suggests that while increasing natural gas fraction may be beneficial for reducing emissions or other factors, it decreases the thermal efficiency of the engine as observed through the rising BSFC values. This can be influenced by factors such as engine design, the calorific value of the fuel mix, and how well the engine processes different fuel types (Karagöz et al., 2016).

Performance comparison

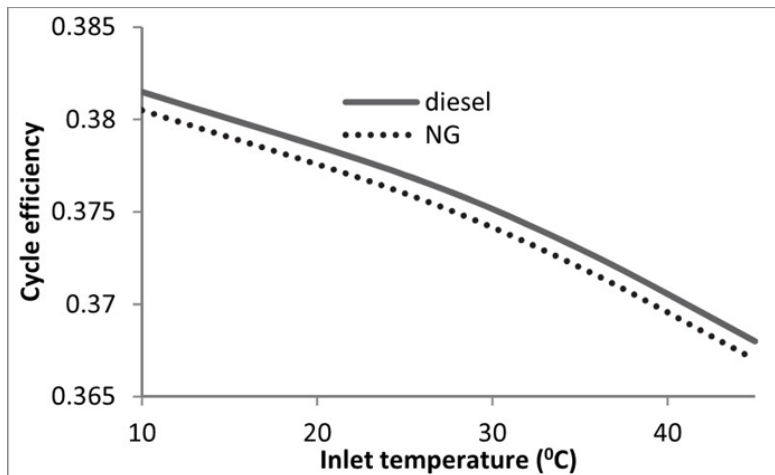


Figure 8. Shows the various fuels' cycle efficiency (Elgohary & Seddiek, 2012)

To compare in Figure 8 the cycle efficiency between diesel and natural gas as fuels, we can look at various factors:

Diesel Fuel:

- Higher Compression Ratio: Diesel engines generally have higher compression ratios than natural gas engines, which leads to higher thermal efficiency.

- **Energy Density:** Diesel has a higher energy density than natural gas, meaning more energy per unit volume, which contributes to its overall efficiency.
- **Efficiency Range:** Diesel engines typically operate with cycle efficiencies ranging from 30% to 40%.

Natural Gas:

- **Lower Compression Ratio:** Natural gas engines usually have lower compression ratios, resulting in lower thermal efficiency compared to diesel.
- **Clean Combustion:** Natural gas burns cleaner than diesel, reducing energy losses associated with incomplete combustion.
- **Efficiency Range:** Natural gas engines generally have cycle efficiencies ranging from 25% to 35%.

Diesel Engines: Generally more efficient due to higher compression ratios and energy density. **Natural Gas Engines:** Slightly less efficient but cleaner and potentially more sustainable.

This comparison highlights the trade-offs between efficiency and environmental impact when choosing between diesel and natural gas as fuels (Elgohary & Seddiek, 2012).

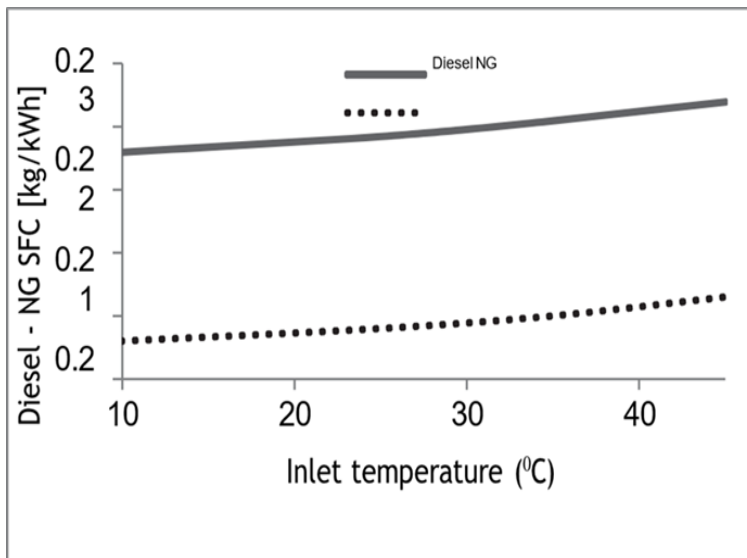


Figure 9. Comparison of the various fuels' specific fuel usage (Sefiddashti et al., 2021)

Figure 9 compares the specific fuel consumption (SFC) of diesel and natural gas (NG) as a function of inlet temperature. Specific fuel consumption, measured in kilograms per kilowatt-hour (kg/kWh), is plotted on the vertical axis, while the inlet temperature, in degrees Celsius, is on the horizontal axis.

- Diesel (represented by the solid line) consistently shows a higher specific fuel consumption (SFC) than natural gas (NG) (represented by the dotted line) across all inlet temperatures.
- Both fuels exhibit a slight increase in specific fuel consumption as the inlet temperature rises. However, the rate of increase for diesel is more gradual, indicating it is less sensitive to changes in inlet temperature compared to natural gas.
- The gap between the SFC values for diesel and NG remains fairly consistent across the temperature range, suggesting that natural gas is more fuel-efficient in converting energy into power.

The graph shows that natural gas (NG) has a lower specific fuel consumption compared to diesel, making it the more fuel-efficient option, especially as the inlet temperature increases. This could imply that using natural gas may lead to better energy efficiency and lower operating costs in applications where fuel efficiency is critical (Sefiddashti et al., 2021).

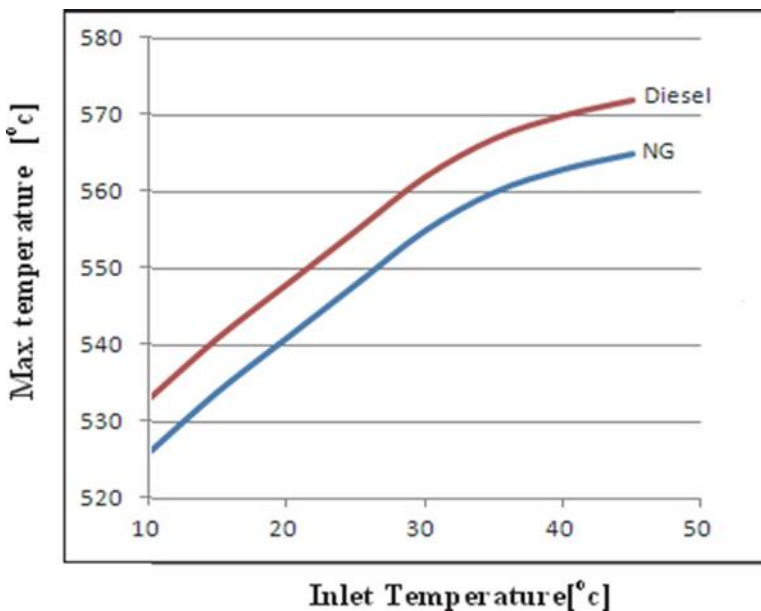


Figure 10. Shows a comparison of the fuels' peak temperatures (Yang et al., 2024)

From Figure 10, we can observe the following:

- Diesel (represented by the red line) consistently achieves higher maximum temperatures than natural gas (NG) (represented by the blue line) across the entire range of inlet temperatures.
- As the inlet temperature increases from 10°C to 50°C, the maximum temperature for both fuels rises. However, the rate of increase appears slightly steeper for diesel, indicating that it is more sensitive to changes in inlet temperature.
- The gap between the maximum temperatures for diesel and NG widens as the inlet temperature increases, suggesting that diesel's thermal performance outpaces that of natural gas under higher inlet temperature conditions.

Diesel is shown to reach higher peak temperatures compared to natural gas (NG), particularly as the inlet temperature increases. This could imply that diesel fuel is better suited for applications requiring higher thermal outputs, though this may come with different considerations regarding efficiency and emissions (Yang et al., 2024).

Performance assessment

Gas turbine performance is critically governed by fuel composition and quality, where combustible components (methane, hydrogen, carbon monoxide) and inert constituents (nitrogen, CO₂, water vapor) interact with contaminants like hydrogen sulfide, siloxanes, or particulates to impact combustion stability, component longevity, and emission profiles. Key fuel parameters including Wobbe index, heating value, dew point, and Joule-Thompson coefficient must be optimized to prevent operational hazards such as hydrate formation, injector clogging, or uncontrolled combustion dynamics arising from impurities or liquid hydrocarbons. Natural gas remains the predominant fuel due to its cost-effectiveness and lower emissions, though its variable composition necessitates rigorous fuel system evaluation encompassing storage, conditioning, and seasonal adaptability (Imteyaz et al., 2018).

Advanced combustion technologies significantly enhance performance: Enhanced-vortex (EV) burners extend flammability limits while reducing NO_x, while oxy-combustion systems employing membrane-based oxygen separation (replacing cryogenic ASUs) achieve 0.5–17.5% energy/cost savings (Portillo et al., 2019). Premixed oxy-fuel combustion outperforms lean premixed (LPM) designs

in flame stability and emissions control, particularly with hydrogen enrichment boosting efficiency. Burner innovations like the micromixer (MM, stable near blowout limits) and Advanced Enhanced-vortex (AEV, widest stability range) further optimize combustion. System-level improvements are realized through the Allam Cycle (oxy-combustion), delivering ~50% efficiency gains via exhaust gas recirculation, staged combustion reducing recirculation demands, and higher operating pressures—albeit with increased pressure drop trade-offs. Operational flexibility is augmented by variable geometry systems that dynamically adjust to load and ambient condition fluctuations (Nemitallah et al., 2019).

Conclusion

The study provides an analytical comparison between natural gas and diesel as fuel options for gas turbines, emphasizing the various aspects that influence their performance, operational costs, and environmental impact. Natural gas emerges as the superior choice due to its enhanced fuel economy and efficiency in combustion, which translates into reduced operational costs and lower emissions. These attributes make natural gas a more environmentally sustainable option, as it emits significantly fewer nitrogen oxides and greenhouse gases compared to diesel. The evaluation also highlights the adaptability of gas turbines to different fuel types, underscoring the importance of the hydrogen-carbon ratio in fuel compositions, which directly affects efficiency and emission levels. Moreover, the document discusses the specialized handling and storage requirements of natural gas, which, despite posing some logistical challenges, do not overshadow its benefits. With the growing emphasis on environmental sustainability and cost efficiency in power generation, natural gas is recommended as the optimal fuel choice for gas turbines, balancing economic benefits with environmental considerations. This comprehensive analysis serves as a guide for power plant operators in making informed decisions regarding fuel selection, aiming to optimize both operational performance and environmental impact.

Competing interests

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References

- Animah, I., & Shafiee, M. (2020). Application of risk analysis in the liquefied natural gas (LNG) sector: An overview. *Journal of Loss Prevention in the Process Industries*, 63, Article 103980. <https://doi.org/10.1016/j.jlp.2019.103980>
- Arefin, M. A., Nabi, M. N., Akram, M. W., Islam, M. T., & Chowdhury, M. W. (2020). A review on liquefied natural gas as fuels for dual fuel engines: Opportunities, challenges and responses. *Energies*, 13(22), Article 6127. <https://doi.org/10.3390/en13226127>
- Burnes, D., & Camou, A. (2019). Impact of fuel composition on gas turbine engine performance. *Journal of Engineering for Gas Turbines and Power*, 141(10), 1–10. <https://doi.org/10.1115/1.4044238>
- Dudley, B. (2019). *BP statistical review of world energy 2016*. Pureprint Group Limited.
- Elgohary, M. M., & Seddiek, I. S. (2012). Comparison between natural gas and diesel fuel oil onboard gas turbine powered ships. *Journal of King Abdulaziz University: Marine Sciences*, 23(2), 109–127. <https://doi.org/10.4197/Mar.23-2.7>
- Elwardany, M., Nassib, A. E. M. M., & Mohamed, H. A. (2023). Comparative evaluation for selected gas turbine cycles. *International Journal of Thermodynamics*, 26(4), 57–67. <https://doi.org/10.5541/ijot.1268823>
- Haque, M. A., Nemitallah, M. A., Abdelhafez, A., Mansir, I. B., & Habib, M. A. (2020). Review of fuel/oxidizer-flexible combustion in gas turbines. *Energy and Fuels*, 34(9), 10459–10485. <https://doi.org/10.1021/acs.energyfuels.0c02097>
- Imteyaz, B. A., Nemitallah, M. A., Abdelhafez, A. A., & Habib, M. A. (2018). Combustion behavior and stability map of hydrogen-enriched oxy-methane premixed flames in a model gas turbine combustor. *International Journal of Hydrogen Energy*, 43(34), 16652–16666. <https://doi.org/10.1016/j.ijhydene.2018.07.087>
- Karagöz, Y., Sandalci, T., Koylu, U. O., Dalkiliç, A. S., & Wongwises, S. (2016). Effect of the use of natural gas–diesel fuel mixture on performance, emissions, and combustion characteristics of a compression ignition engine. *Advances in Mechanical Engineering*, 8(4), 1–13. <https://doi.org/10.1177/1687814016643228>
- Molière, M. (2023). The fuel flexibility of gas turbines: A review and retrospective outlook. *Energies*, 16(9), Article 3962. <https://doi.org/10.3390/en16093962>
- Nemitallah, M. A., Abdelhafez, A. A., Ali, A., Mansir, I., & Habib, M. A. (2019). Frontiers in combustion techniques and burner designs for emissions control and CO₂ capture: A review. *International Journal of Energy Research*, 43(14), 7790–7822. <https://doi.org/10.1002/er.4730>
- Portillo, E., Alonso-Fariñas, B., Vega, F., Cano, M., & Navarrete, B. (2019). Alternatives for oxygen-selective membrane systems and their integration into the oxy-fuel combustion process: A review. *Separation and Purification Technology*, 229, Article 115708. <https://doi.org/10.1016/j.seppur.2019.115708>

- Pourhedayat, S., Hu, E., & Chen, L. (2024). Yearly hour-by-hour performance evaluation of a SIEMENS gas turbine power plant for Australia's climate condition with and without a novel intake air pre-cooling strategy. *Energy Conversion and Management X*, 21, Article 100501. <https://doi.org/10.1016/j.ecmx.2023.100501>
- Sefiddashti, A. R., Shirmohammadi, R., & Petrakopoulou, F. (2021). Efficiency enhancement of gas turbine systems with air injection driven by natural gas turboexpanders. *Sustainability*, 13(19), 1–17. <https://doi.org/10.3390/su131910994>
- Speight, J. G. (2007). Recovery, storage, and transportation. In *Natural gas* (pp. 87–111). Elsevier. <https://doi.org/10.1016/B978-1-933762-14-2.50009-1>
- Stefan, E., Talic, B., Larring, Y., Gruber, A., & Peters, T. A. (2022). Materials challenges in hydrogen-fuelled gas turbines. *International Materials Reviews*, 67(5), 461–486. <https://doi.org/10.1080/09506608.2021.1981706>
- Yang, Y., Nikolaidis, T., Jafari, S., & Pilidis, P. (2024). Gas turbine engine transient performance and heat transfer effect modelling: A comprehensive review, research challenges, and exploring the future. *Applied Thermal Engineering*, 236, Article 121523. <https://doi.org/10.1016/j.applthermaleng.2023.121523>