A Review on Diesel–Gaseous Fuel Dual-Fuel Generator Sets: Performance, Retrofitting, Emissions and Operational Challenges

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Abstract – *Diesel Generator sets are deployed in most of industries for power generation but due to rising fuel costs and stricter emission norms the focus is now shifting to dual fuel technologies. This paper consists review of 30 research papers focusing on dual fuel technology for diesel powered gensets using fuels like Natural Gas (CNG/LNG), Biogas, Liquified Petroleum Gas (LPG), syngas and producer gas in combination of diesel pilot fuel. The review is organized around five principal themes: retrofitting methodologies, emission analysis, performance, economic feasibility and operational challenges. The surveyed literature consistently demonstrates that gaseous fuel substitution of 50–95% is achievable without major engine modifications, with brake thermal efficiency improvements of up to 42% and significant reductions in smoke opacity (up to 95%), CO_2 (20–30%), and NOx (50–87%) under optimized conditions. Studies also highlighted role of exhaust gas recirculation (EGR), pilot fuel optimization, injection timing and air management techniques in improving overall generator performance. However recurring challenges include CO emission, Unburned hydrocarbon (UHC) emissions at low load conditions and methane slip in NG systems. The review identifies technically feasible and economical approach for cleaner and suitable power generation applications.*

Key Words: Dual fuel Generator, Diesel Generator sets, LPG, Producer Gas, Natural Gas, Brake Thermal efficiency, Emissions, Retrofitting, Power Generation

1. INTRODUCTION

Diesel Generator Sets are widely used for power generation, standby, and emergency conditions in industrial facilities, hospitals, telecommunication infrastructure, construction areas and also used in oil fields and remote locations where grid access is unstable. Diesel Generators are backbone for power backup and distributed power generation because of their robustness, reliability, ease of operations and ability to perform under varying load conditions. However rising fuel prices, environmental concerns, Greenhouse gas emissions and stricter norms calls for adoption of cleaner and economically feasible alternatives to diesel power generation systems.

Dual Fuel Technology has emerged as most practical solution which provides fuel flexibility without omitting high thermal efficiency and reliability provided by diesel fuel. Dual fuel technology uses gaseous fuels like Compressed Natural Gas (CNG), Liquified Petroleum Gas (LPG), Liquefied Natural Gas (LNG), Producer gas, Syngas or Biogas as primary fuels and diesel as pilot fuel. The gaseous fuel is inducted into the intake air charge and ignited by a small quantity of pilot diesel, preserving the fundamental compression-ignition mechanism while substantially reducing diesel dependency. This technology provides arrangement to partially replace diesel without extensive modifications to the base engine so it is a valuable option for both new installations and retrofitting of generator sets.

The research has reported diesel substitution up to 95% with brake thermal efficiency has been improved up to 43%under optimized operating conditions and significant reduction in NOx, CO_2 and particulate matter but there are challenges like methane slip in natural gas which leads to incomplete combustion and less power, increase in hydrocarbon and carbon monoxide emissions at part load conditions, ignition delay which requires advanced injection technologies to be implemented.

The growing availability of natural gas infrastructure, increasing interest in biomass derived fuels and need for cleaner fuels have accelerated research on dual fuel systems. Therefore, this review paper presents comprehensive assessment of dual fuel generator systems working on diesel-gaseous fuels. This literature review contains 31 research papers from 2006-2025 which evaluates current state of technology and categorized into five main categories namely retrofitting and conversion methods, performance characteristics, emission behaviors, economical feasibility and operational challenges. The main objective of this review paper is to identify research gaps by evaluating current trends in field of dual fuel generator technologies to provide base for future research and development.

2. REVIEW METHODOLOGY

This review was conducted through systematic research of articles available on academic databases Google Scholar, ResearchGate, Scopus, and Science Direct. Search terms used included combinations of keywords such as dual fuel engine, diesel generator dual fuel, natural gas diesel generator, LPG diesel engine, producer gas genset, biogas diesel dual fuel, retrofitting diesel genset, and dual fuel emissions. This research was limited to English language papers and ones which are translated to English by authors or publications covering experimental studies, simulation-based analysis, feasibility assessments, and technical reviews related to dual-fuel generator set operation.

From the initial pool of articles reviewed articles based on stationery generator sets operations, dual fuel emissions using gaseous fuels, challenges with using gaseous fuels in dual fuel systems and dual fuel economic analysis were chosen. Papers focused on automotive applications which can serve as strong base for emission and conversion analysis were also chosen. Based on this process 30 papers spanning from 2006-2025 were considered for detailed review.

The selected papers were systematically organized into a literature matrix capturing key attributes including author, year of publication, engine specifications, fuel combination, key findings, and identified limitations. This matrix served as the structural foundation for the thematic analysis presented in Sections 3 through 7 of this paper.

3. RETROFITTING

Retrofitting already existing diesel generator sets seems like cost effective pathway for decreasing diesel dependency without major modifications. This requires a system to introduce gaseous fuel in intake air stream of engine while retaining diesel injection as pilot fuel thereby preserving compression ignition method without major modifications to structure of diesel engine.

The reviewed literature shows that dual-fuel conversion of existing diesel generator sets is technically feasible across different engine sizes and scales. At the small-engine level, Tiwari **[4]** achieved 50–70% diesel substitution using CNG without major engine modifications, while Ismail et al. **[7]** developed an ECU-based CNG–diesel conversion kit that avoided engine disassembly. At the large-scale level, Kabeyi and Olanrewaju **[17]** demonstrated that converting a 120 MW diesel power plant to dual-fuel operation is technically and economically more viable than full replacement. Across all studies, reliable gaseous fuel supply and proper gas infrastructure emerged as key requirements for successful retrofitting.

4. COMBUSTION AND THERMAL PERFORMANCE

The combustion characteristics and Thermal performance of dual fuel operation depend on type of gaseous fuel used, proportion of diesel pilot fuel, engine speed, load conditions and air fuel ratio management. Understanding of these parameters are critical to optimize the dual fuel system.
The reviewed studies reveal that natural gas-diesel dual-fuel operation consistently achieves the highest brake thermal efficiency improvements, with papers **[13]** and **[21]** reporting BTE values of up to 42% and 43.1% respectively under optimized high-load conditions. Producer gas-diesel systems, while achieving significant diesel substitution of up to 52.7% **[6]**, show a notable decline in electrical efficiency due to the low calorific value of producer gas displacing intake air charge. Paper **[9]** identified an optimum pilot diesel quantity of 6–11 mg per cycle with an air excess ratio of 1.3–1.45 as critical for maximizing fuel economy in heavy-duty natural gas-diesel engines. A consistent observation across the literature is that dual-fuel performance improves significantly at high loads, while part-load operation remains a persistent challenge due to poor combustion of lean gaseous fuel-air mixtures.

TABLE 1- COMBUSTION AND THERMAL PERFORMANCE

Fuel Combination	BTE / Substitution	Challenge / Note
Natural Gas + Diesel [Refs 5,9,13,15,16,18,19,23,26,29]	BTE 38.6–43.1% (optimized high-load); pilot diesel 6–11 mg/cycle; air ratio 1.3–1.45; RCCI+LIVC cuts methane slip ≤80%.	Part-load poor; methane slip ↑ with NG fraction; NOx–BTE trade-off unresolved.
CNG + Diesel [Refs 4,7,12,14,17,18,25]	BTE up to 38.6% (with supercharger); 50–70% diesel substitution without major engine modification; stable at 30–45% CNG share.	CNG>45% causes ignition delay & HC rise; compression ratio is key control parameter.
LPG + Diesel [Refs 3,8,11]	BTE improved to 31%; BSFC ↓6–8%; efficiency ↑1.25% over diesel; moderate diesel savings.	Higher combustion temperature raises NOx; EGR required for NOx control.
Producer Gas + Diesel [Refs 6,10]	Max diesel substitution 52.7%; electrical efficiency ↑6.13–12.56% with increasing gas flow rate.	Electrical efficiency drops from ~19% to ~9.5% due to low calorific value; gasifier required.

Syngas + Diesel [Refs 22,27]	ITE ~39.3%; diesel substitution ~40%; NOx ↓75% with EGR optimization.	Very sensitive to syngas composition ; gasification & gas cleaning plant required.
Biogas / Biodiesel [Refs 21,30]	Power ↑16–22%; SFC ↓32–35%; liquid fuel savings 29–31%; off-grid feasibility shown.	Low calorific value limits substitution; emission data very limited in reviewed studies.

5. EMISSION CHARACTERISTICS

Emission reduction is one of the primary motives of adapting to dual fuel generator systems. The reviewed literature indicates that gaseous fuel substitution significantly reduces smoke opacity, particulate matter and carbon dioxide emissions. However, carbon monoxide and hydrocarbons tend to increase particularly under part load conditions due to unburnt gaseous charge. Compression ratio and pilot diesel quantity were identified as critical parameters influencing the emission-efficiency trade off, particularly in CNG-diesel systems **[26].**

As evident from Table 3, natural gas substitution consistently achieves the most significant reductions in smoke and CO_2 emissions, with Muhssen and Bereczky **[28]** reporting smoke opacity reductions of approximately 95% and Kabeyi and Olanrewaju **[17]** documenting NOx reductions of 50–87% at the large plant scale. Syngas-diesel operation demonstrated the strongest NOx reduction among alternative gaseous fuels, with Arslan et al. **[25]** reporting a 75% reduction alongside a 35% decrease in CO emissions through EGR optimization. LPG-diesel systems showed mixed NOx behavior Aydin et al. **[8]** reported a 4–6% increase in NOx attributed to higher in-cylinder combustion temperatures, while smoke and CO emissions were simultaneously reduced. The increase in CO and unburned hydrocarbons at low loads remains a recurring challenge across all gaseous fuel types, consistently linked to poor flame propagation in lean premixed gaseous fuel-air mixtures.

6. ECONOMICAL FEASIBILITY

The economic viability of dual-fuel conversion is a decisive factor in determining the practical adoption of this technology across different application scales. The reviewed literature evaluates economic feasibility primarily through parameters such as diesel fuel cost savings, payback period, return on investment, and specific fuel consumption reduction.

At the small-to-medium scale, Luna et al. **[26]** demonstrated a maximum fuel cost saving of 53% at 70 kW output on a turbocharged 4-cylinder diesel genset, with cost reductions observed across all tested power levels. Aydin et al. **[8]** reported a 6–8% reduction in brake specific fuel consumption on a single-cylinder diesel generator operating on LPG-diesel dual fuel, directly translating to lower operating costs. At the large industrial scale, Kabeyi and Olanrewaju **[17]** conducted a techno-economic assessment of converting a 120 MW diesel power plant to dual-fuel operation and estimated a payback period of approximately 4 months, establishing conversion as far more economically attractive than full plant replacement. Ismail et al. **[7]** further validated economic viability at the vehicle and genset level, reporting a return on investment period of 1.1–5.3 years depending on annual mileage and fuel consumption patterns.

Natural gas and CNG-based systems generally offer the greatest economic advantages due to their relatively low fuel cost and high diesel substitution potential. In addition, retrofitting existing diesel generators often requires significantly lower capital investment compared with purchasing new power generation equipment. Additional costs associated with fuel storage, gas supply infrastructure, safety systems, control units, and maintenance requirements must also be considered. Therefore, a comprehensive economic evaluation is necessary to determine the practical feasibility of dual-fuel generator implementation under specific operating conditions.

7. OPERATIONAL CHALLENGES AND RESEARCH GAPS

Dual fuel generator technology offers significant benefits in terms of fuel saving and emission reduction. However, there are several operational challenges that are limiting its implementation. The reviewed research indicates that performance of dual-fuel generator depends on combustion stability, fuel substitution ratio, engine load and control strategy so operational challenges occurs whenever gas substitution is increased beyond optimized limits and it hinders the performance of generator set.

Methane slip the escape of unburned natural gas through the exhaust emerges as the most critical and widely reported challenge in natural gas-diesel dual-fuel systems. Shouvik Dev, Hongsheng-Guo , Roya missaghian & Simon Lafrance **[19]** demonstrated that improved intake airflow management can reduce methane slip by approximately 28%, while Zarrinkolah and Hosseini **[22]** showed through CFD simulation that transitioning from conventional dual-fuel combustion to early injection RCCI mode can achieve reductions of up to 42.5%. However, these improvements consistently come at the cost of increased NOx emissions, highlighting a fundamental emission trade-off that remains unresolved in the current literature. Part-load operation represents another universal challenge. A.P. Carlucci, A. de Risi, D. Laforgia & F. Naccarato. **[2]** and Dimitriou et al. **[14]** both reported that lean premixed gaseous fuel-air mixtures at low loads result in poor flame propagation, increased CO and unburned hydrocarbons, and reduced thermal efficiency, with conventional remedies such as intake boosting and split injection proving largely ineffective. Pedrozo et al. **[15]** further identified natural gas composition variation as a significant practical challenge, as changes in methane number alter combustion characteristics and engine performance in ways that are difficult to control in field conditions. Across the reviewed literature, three overarching research gaps emerge: the absence of long-term durability and reliability studies on converted generator sets under real operating conditions, the limited investigation of transient load behavior in dual-fuel mode, and the insufficient translation of laboratory findings to commercially validated generator set applications.

8. CONCLUSION

Dual-fuel generator technology has emerged as a promising solution for reducing diesel consumption and improving the environmental performance of stationary power generation systems. The reviewed studies indicate that gaseous fuels such as natural gas, CNG, LPG, producer gas, syngas, and biogas can successfully replace a significant portion of diesel fuel while maintaining satisfactory generator performance. In addition to fuel savings, dual-fuel operation has been shown to reduce smoke emissions, particulate matter, and carbon dioxide emissions under optimized operating conditions. However, challenges such as increased carbon monoxide and hydrocarbon emissions, methane slip, ignition delay, and combustion instability at low loads continue to limit widespread adoption. The literature also highlights the importance of proper retrofitting, combustion control, and fuel management strategies for achieving reliable and efficient operation. Overall, dual-fuel generators represent a technically feasible and economically attractive alternative to conventional diesel generators, with considerable potential for supporting cleaner and more sustainable power generation in the future.

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ANNEXURE A

SR.NO	Author	Year	Engine	Fuel	Key Findings	Limitations
1	J. Patterson, A. Clarke, R. Chen	2006	Lister-Petter 4-cylinder DI Diesel Genset (2.29 L)	Methane-Diesel, Propane-Diesel, Butane-Diesel	Propane showed the best emission performance with significant reductions in NOx and smoke. Methane achieved the highest gas substitution levels (up to 95% at half load), while butane produced the highest NOx and smoke emissions. Dual-fuel operation reduced smoke emissions substantially compared to conventional diesel operation.	Study investigated only NOx and smoke emissions. CO, HC, brake thermal efficiency and long-term engine durability were not analysed. Tests were limited to fixed-speed genset operation (1500 rpm).
2	A.P. Carlucci, A. de Risi, D. Laforgia & F. Naccarato	2008	Single-Cylinder Common Rail DI Diesel Engine (CR 17.1:1)	Natural Gas (CNG) + Diesel Pilot Fuel	Dual-fuel operation significantly reduced particulate matter (PM) emissions compared to diesel-only operation. Combustion and emissions were strongly influenced by pilot diesel quantity and injection pressure. Proper pilot injection improved combustion stability and flame propagation.	CO and THC emissions increased under low-load conditions due to poor flame propagation of lean CNG-air mixtures. NOx formation remained sensitive to pilot fuel injection parameters.
3	A. Kumaraswamy & B. Durga Prasad	2012	Single Cylinder, 4-Stroke CI Engine (5 HP, 1500 rpm)	Diesel + LPG + EGR	Dual-fuel operation with LPG improved Brake Thermal Efficiency (BTE) up to 31% and significantly reduced smoke emissions. EGR effectively reduced NOx emissions. LPG substitution reduced diesel consumption while maintaining comparable engine performance.	EGR increased CO emissions, fuel consumption, and potential engine wear. HC emissions remained higher than diesel operation. Study limited to a small stationary engine and fixed operating conditions.
4	Abhay Tiwari	2015	Compression Ignition Diesel Engine Converted to Dual-Fuel Engine	CNG (Natural Gas) + Diesel	Diesel engines can be successfully converted into dual-fuel engines using CNG. Natural gas can replace 50–70% of diesel fuel while reducing CO_2, CO, HC, and NOx emissions. Dual-fuel engines retain diesel-like efficiency and can operate on 100% diesel if gas is unavailable.	Primarily a review/conceptual study; no experimental validation, performance testing, or detailed emission measurements were conducted.
5	Weifeng Li, Zhongchang Liu & Zhongshu Wang	2016	8.6 L, 6-Cylinder Turbocharged Diesel-NG Dual Fuel Engine	Natural Gas + Diesel	Three combustion modes (h, m, n) were identified. Advancing diesel injection timing, increasing EGR, and intake throttling improved brake thermal efficiency (BTE) and reduced HC emissions. The n-combustion mode provided the highest efficiency and lowest HC emissions.	Combustion became highly sensitive and unstable under n-mode operation if combustion boundaries were not carefully controlled. Study focused mainly on low-load conditions.
6	Monorom Rith, Jose Bienvenido M. Biona, H.W. Gitano-Briggs, Piseth Sok, Jeremias A. Gonzaga, Nechoh Arbon, Archie B. Maglaya	2016	ompression Ignition (CI) Diesel Gens	Diesel + Producer Gas	Producer gas successfully operated a diesel genset in dual-fuel mode. Maximum diesel replacement of 52.7% was achieved using Jatropha press cake-derived producer gas. Diesel consumption was significantly reduced compared to diesel-only operation. The technology demonstrated the feasibility of utilizing biomass-derived fuels for decentralized electricity generation. Biomass type had little effect on efficiency and energy consumption.	Electric-thermal efficiency dropped significantly from 19% (diesel mode) to approximately 9.5% (dual-fuel mode). Specific fuel consumption and specific energy consumption increased substantially because of the low calorific value of producer gas. CO and CO_2 emissions were higher than diesel-only operation. Producer gas displaced intake air, resulting in incomplete combustion. Mixed biomass feedstock caused unstable gasifier operation due to varying particle sizes. Results were limited to a small-scale generator system.
7	Muammar Mukhsin Ismail, Fathul Hakim Zulkifli, Mas Fawzi & Shahrul Azmir Osman	2016	Common-Rail Diesel Engine (Toyota Hilux Conversion)	CNG + Diesel	Successfully developed a CNG-diesel dual-fuel conversion kit without major engine modification. Diesel quantity was reduced using ECU-based fuel pressure emulation. Economic analysis showed ROI between 1.1–5.3 years depending on annual mileage and fuel consumption.	Focused mainly on conversion methodology and financial analysis. Detailed engine performance, combustion, efficiency, and emission measurements were not experimentally evaluated.
8	Aydin, M., Irgin, A., & Çelik, M. B.	2018	Single-cylinder diesel generator (2.4 kVA)	Diesel + LPG	BSFC ↓ 6–8%, Efficiency ↑ 1.25%, Smoke ↓ 80%, CO ↓ 30%, HC ↓ 20%	NOx ↑ 4–6%, additional injector and ECU required
9	Luksho, V.A. & Kozlov, Andrey & Terenchenko, A.s & Grinev, Vadim	2018	11 L Heavy-Duty Dual Fuel Engine	Diesel + Natural Gas	Fuel economy improved 20–30%, optimum pilot fuel 6–11 mg/cycle, optimum air ratio 1.3–1.45	NOx increases at high injection pressure and advanced timing
10	Sutheerasak, Pirompugd & Sanitjai	2018	John Deere 3029DF150, 3-Cylinder DI Diesel Engine Generator (2.9 L)	Supercharged Producer Gas + Diesel	Maximum diesel saving of **40%** achieved at 1200 rpm and 125 lpm producer gas flow rate. Electrical efficiency increased by **6.13–12.56%**, electrical power increased, and specific energy consumption decreased with increasing producer gas flow rate.	CO emissions, HC emissions, and smoke opacity increased significantly due to incomplete combustion and reduced oxygen availability. Study conducted only under full-load conditions and fixed diesel injection timing.
11	Alberto Boretti	2019	Compression Ignition Direct Injection (CI-DI) Diesel Engines	Diesel, CNG-Diesel, LNG-Diesel, LPG-Diesel	Dual-fuel engines reduce PM, NOx and CO_2 emissions while maintaining diesel-like efficiency. Natural gas-based dual-fuel operation offers better environmental performance than conventional diesel engines.	Methane slip can reduce environmental benefits. Dual-fuel systems require advanced fuel injection technology and optimization for maximum efficiency.
12	Arkadiusz Jamrozik, Wojciech Tutak & Karol Grab-Rogaliński	2019	Andoria 1CA90 Single-Cylinder Stationary CI Engine (573 cc)	CNG + Diesel	CNG share up to 45% improved combustion intensity, increased peak cylinder pressure and heat release rate. Most stable operation occurred at 30–45% CNG share. CO_2 emissions reduced by ~26% and CO emissions were nearly eliminated.	NO emissions increased with increasing CNG share. At CNG shares above 45%, ignition delay became excessive and HC emissions increased due to incomplete combustion.
13	Shouvik Dev, Hongsheng Guo & Brian Liko	2020	Caterpillar 3401 Single-Cylinder Heavy-Duty CI Engine (2.44 L)	Natural Gas + Diesel	Increasing NG fraction improved BTE up to ~42%, reduced soot and CO_2-equivalent emissions, and enabled significant diesel substitution at high loads. Optimized diesel injection timing improved combustion efficiency.	Higher NG fraction increased methane emissions, injector tip temperature, NOx emissions, and required careful optimization of diesel injection timing to avoid pressure-rise limitations.
14	Pavlos Dimitriou, Taku Tsujimura, Hirokazu Kojima, Kenji Aoyagi, Naoki Kurimoto & Yoshiaki Nishijima	2020	Single-Cylinder and Multi-Cylinder CI Engines	Natural Gas (CNG) + Diesel	Advanced diesel injection significantly improved combustion efficiency, reduced THC emissions, increased thermal efficiency, and reduced NOx at low loads. Hot EGR simultaneously reduced NOx, CO, and THC emissions while improving brake thermal efficiency. Split injection and intake boosting were ineffective at low-load operation.	Study mainly focused on low-load conditions. Intake boosting increased unburned emissions and reduced efficiency. Split injection caused excessive NOx formation and increased methane slip.

15	Vinícius B Pedrozo, Xinyan Wang, Wei Guan & Hua Zhao	2021	Single-Cylinder Heavy-Duty Dual-Fuel CI Engine	Natural Gas + Diesel	Natural gas composition significantly affected combustion behaviour, methane slip, NOx emissions, and thermal efficiency. Fuel-quality variation was identified as a major challenge because changes in methane number altered combustion characteristics and engine performance. Lower methane number reduced methane slip but increased NOx emissions, highlighting an emissions trade-off. RCCI combined with LIVC achieved up to 80% lower methane slip and NOx emissions while improving efficiency compared with conventional dual-fuel operation.	Single-cylinder laboratory study; no economic or durability analysis; limited gas compositions tested; no transient-load evaluation; applicability to commercial gensets requires further validation.
16	Enrico Mattarelli, Carlo Alberto Rinaldini, Tommaso Savioli, and Francesco Scrignoli	2021	Four-Cylinder, Four-Stroke, Turbocharged CRDI Dual-Fuel Engine (2.8 L, Gen-set Application)	Natural Gas + Diesel	Dual-fuel operation improved generator performance, increasing brake thermal efficiency from 35.8% to 39% while reducing NOx (32%), CO_2 (31%), and soot emissions (>50%) compared with diesel operation. However, CO and HC emissions increased significantly, and combustion quality deteriorated at low loads due to incomplete combustion of ultra-lean natural gas mixtures, creating operational challenges for stable low-load operation.	The study focused mainly on high-load operating conditions, with limited evaluation at transient conditions. Low-load dual-fuel operation remained challenging due to incomplete combustion. Long-term durability, economic feasibility, and catalyst performance for controlling increased CO and HC emissions were not investigated.
17	Moses J. B. Kabeyi & Oludolapo A. Olanrewaju	2022	Diesel Power Plant (Kipevu III, 120 MW)	Heavy Fuel Oil + Natural Gas (Dual Fuel)	Conversion to dual-fuel operation reduces fuel cost, specific fuel consumption, total emissions, and improves thermal efficiency. Payback period estimated at about 4 months, making conversion technically and economically feasible.	Natural gas infrastructure investment required. Methane leakage may reduce environmental benefits. Long-term dependence on gas may delay transition to zero-carbon energy systems.
18	Yuvenda, D., Sudarmanta, B., Jamaludin, J., Muraza, O., Putra, R. P., Lapisa, R., ... & Primandari, S. R. P.	2022	Single Cylinder DI Diesel Engine (411 cc, CR 18:1)	CNG + Diesel with Electric Supercharger	Optimizing air-fuel ratio (λ) improved thermal efficiency, cylinder pressure, HRR, combustion stability and reduced CO, HC and PM emissions. Maximum thermal efficiency reached 38.6% at high load with $\lambda = 1.69$.	Excessive air supply caused lean mixture formation, reduced combustion quality, lower cylinder pressure and lower thermal efficiency. Additional supercharger system increases complexity and cost.
19	Shouvik Dev, Hongsheng-GuQ , Roya missaghian , Simon Lafrance & honsheng guo	2022	Single-Cylinder Four-Stroke Heavy-Duty Dual-Fuel CI Engine	Natural Gas + Diesel	Methane slip due to incomplete combustion is a key challenge in dual-fuel engines. Improved intake airflow enhanced fuel-air mixing, reducing methane slip by ~28% and CO by 25%. However, this increased NOx and slightly reduced thermal efficiency, highlighting the trade-off between emission control and performance.	Conducted on a single-cylinder research engine under laboratory conditions; increased NOx emissions and slight efficiency loss were observed; fuel substitution ratio effects were not investigated; no economic, durability, or long-term operational analysis was performed; applicability to commercial gensets and oilfield power systems requires further validation.
20	Mostafa Soliman, Mohamed Elkelawy, Ahmed G. Olabi, and Mohamed M. Elsheikh	2022	V 4-Cyl DI Turbocharged Diesel Gen	ed Biogas (CH4 + CO2/N2) +	Dual-fuel operation improved fuel utilization and reduced smoke emissions compared with diesel operation. Engine performance and emissions were strongly influenced by operating conditions and gas substitution ratio. The study identified a trade-off between improving efficiency and controlling emissions, highlighting the need for combustion optimization for stable dual-fuel operation.	The study was conducted on a single-cylinder research engine and under limited operating conditions. Long-term durability, economic feasibility, transient-load behavior, and generator-specific performance were not evaluated
21	Hyunwook Park, Euijoon Shim, Junsun Lee, Seungmook Oh, Changup Kim, Yonggyu Lee, Kernyong Kang	2023	Heavy-duty 11.1 L Multi-cylinder Engine	Natural Gas + Diesel	RCCI mode achieved highest efficiency (41.4%) at low loads; E-Pilot achieved 43.1% BTE at medium loads; CDF achieved 42.8% BTE at high loads. Authors recommend E-Pilot for low-to-mid loads and CDF for high loads for optimal efficiency and emission reduction.	RCCI operation limited to low loads due to high pressure rise rate (MPRR). E-Pilot also unsuitable for very high loads. Multiple combustion modes and advanced control systems are required.
22	Zarrinkolah & Hosseini	2023	Single-Cylinder, Four-Stroke, Naturally Aspirated Natural Gas–Diesel Dual-Fuel Compression Ignition (CI) Engine (CFD-based engine model)	Natural Gas + Diesel	Methane slip is a key challenge in dual-fuel engines due to incomplete natural gas oxidation. Switching from CDF to EIRCCI combustion reduced methane slip by 33%, and optimized diesel spray geometry achieved up to 42.5% reduction. Injection timing, spray angle, and combustion-mode selection were identified as critical parameters for balancing efficiency and emissions.	The study was primarily CFD/simulation based and requires experimental validation. It was not conducted on a commercial generator set and did not evaluate electrical performance. Analysis was performed under limited operating conditions and did not assess transient loads. Economic feasibility, long-term durability, injector wear, and maintenance impacts were not investigated. Only natural gas–diesel operation was considered; associated gas and variable field-gas compositions were not evaluated.
23	Neeraj Kumar, Bharat Bhushan Arora, and Sagar Maji	2023	Single-Cylinder, Four-Stroke, Variable Compression Ratio (VCR) Dual-Fuel Engine	Diesel + CNG	increasing CNG substitution (up to ~80%) reduced CO_2, NOx, and smoke emissions, demonstrating the potential of gaseous-fuel operation. However, CO and HC emissions increased due to incomplete combustion. Compression ratio significantly affected combustion quality and emission performance, highlighting the challenge of balancing high fuel substitution with stable and efficient operation.	The study focused mainly on emissions and provided limited combustion and performance analysis. Experiments were conducted on a single-cylinder laboratory engine, with no evaluation of durability, transient operation, economic feasibility, or fuel-composition variation.
24	Ziyang Dai, Weikang Du, Jie Li, Yinmi Luo, Zhi Jia, and Binyang Wu	2023	Single-Cylinder, Four-Stroke, Compression Ignition Natural Gas Dual-Fuel Engine	Natural Gas + Diesel	Increasing intake pressure improved combustion activity and thermal efficiency, while EGR helped suppress knock and control emissions. Optimized intake conditions with suitable pilot injection timing achieved high thermal efficiency (~50%) with reduced THC, CO, and NOx emissions. The study highlighted the challenge of balancing combustion efficiency, knock suppression, and emission control under high-load dual-fuel operation.	The study was conducted under high-load operating conditions only, limiting applicability across the full operating range. Long-term durability, transient operation, economic feasibility, and generator-level performance were not evaluated. The effect of varying natural gas composition was also not investigated.
25	Arslan et al.Aysegul Arslan, Shouvik Dev, David Stevenson, James Butler, Hongsheng Guo, Madjid Birouk	2024	30 kW, 4-cylinder turbocharged generator	Diesel + Syngas	Diesel substitution 40%, ITE ≈ 39.3%, NOx ↓ 75%, CO ↓ 35%, PM reduced, HC increased at high EGR	High EGR increases HC and PM, optimization required
26	Francisco E. Tavares de Luna, Emerson F. Jaguaribe, Adriano S. Rumão & Jorge R. Henríquez	2024	Perkins 1104C-44TAG2 Turbocharged 4-Cyl Diesel Generator Set	Diesel + Natural Gas	Dual-fuel kit installed with minimal engine modification; fuel costs reduced across all power levels tested; maximum cost saving of 53% at 70 kW; soot and CO2 reduced at high loads; NOx reduced at low-medium loads; CO increased	Single engine model tested; no long-term durability analysis; results specific to Brazilian fuel pricing; transient load behaviour not evaluated
27	Shouvik Dev	2024	6-cylinder (Inline configuration) 4 stroke compression ignition retrofitted for dual fuel operation	Natural Gas + Diesel	The dual-fuel configuration successfully replaced up to 34% of diesel consumption during highway operation (Dev et al., 2024). Compared to a diesel-only baseline, the conversion yielded lower CO_2 and engine-out black carbon emissions, fulfilling the operating cost reduction and partial decarbonization goals typical of CNG retrofits	The primary drawback identified was "methane slip"—unburned methane escaping through the exhaust after-treatment system. This slip significantly increased total hydrocarbon emissions and negated some of the greenhouse gas advantages, while tail-pipe NOx emissions also saw an increase compared to pure diesel operation
28	Xiao Zhang, Jianqun Gao, Dawei Fan, Qizheng Yang, Fangjun Han, and Hongliang Yu	2024	MAN B&W 6S50ME-C-GI, Six-Cylinder, Two-Stroke, Low-Speed Marine Natural Gas–Diesel Dual-Fuel Engine	Natural Gas + Diesel	Advancing pilot diesel injection timing improved engine power, thermal efficiency, and natural-gas flame propagation, demonstrating better combustion performance. However, earlier injection also increased NO and methane emissions, highlighting the challenge of balancing efficiency improvement with emission control in dual-fuel operation. Injection timing significantly affected ignition delay and rapid combustion stages.	The study focused mainly on pilot diesel injection timing while keeping other operating parameters constant. Results were obtained under controlled marine operating conditions and may not directly represent generator applications. Long-term durability, transient operation, economic feasibility, and fuel-composition variation were not evaluated.
29	Hassan Sadah Muhssen & Ákos Bereczky	2025	IVECO AIFO 8031, 24 kW diesel engine coupled with generator	Diesel + Natural Gas	Diesel consumption reduced, NOx reduced, CO_2 reduced, smoke reduced by ~95%	CO and THC emissions increased, BTE reduced
30	Dhairiyasamy & Gabiriel	2025	5 kVA Single Cylinder 4-Stroke Diesel Generator	Biogas + Biodiesel (B8, B20, B50, B80, B100)	Power Output ↑ 16.06–21.77%, SFC ↓ 31.53–34.97%, Liquid Fuel Savings 28.74–31.08%, Dual-fuel operation feasible for off-grid applications	No emission analysis, no durability testing, limited biogas supply, no economic analysis, small-scale setup only