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Impact of Biogas Substitution on the Performance of a Diesel Engine: A Dual-fuel Approach toward Clean Energy

Vinod Kumar T
Department of Mechanical Engineering, Vels Institute of Science, Technology and Advanced Studies
Pallavaram, Chennai, Tamil Nadu, India
vinodkmrmech@gmail.com

John Presin Kumar A
Department of Mechanical Engineering, Hindustan Institute of Technology and Science
Padur, Chennai, Tamil Nadu, India
johnpk@gmail.com

Jacob S
Department of Mechanical Engineering, Vels Institute of Science, Technology and Advanced Studies,
Pallavaram, Chennai, Tamil Nadu, India
jacobthermal@gmail.com

Senbagan M
Department of Aeronautical Engineering, Dhanalakshmi Srinivasan College of Engineering and Technology,
Chennai, Tamil Nadu, India
senbagam@gmail.com

Sathish S
Department of Aerospace Engineering Hindustan Insititute of Technology and Science,
Padur, Kelambakkam, Tamilnadu, India
sathishamg88@gmail.com

Seralathan S
Department of Aeronautical Engineering, Hindustan Institute of Technology and Science
Padur, Kelambakkam, Tamilnadu, India
siva.seralathan@gmail.com

***Abstract*—This study examines the working parameters of a transformed compression ignition engine to operate on the biogas-diesel blended fuels as dual-fuel combustion engine. This is achieved through coupling the dynamometer operated at constant speed, compression ratio and constant rated engine speed. Variable loads at 20%, 40%, 60%, 80% and 100 percent of full load are tested. Three fuel configurations namely, pure diesel, 10% biogas and diesel mixture, and 30% biogas and diesel mixture. The 30% biogas with diesel mixture offer a higher brake thermal efficiency and mechanical efficiency at medium to high load thereby suggesting a high energy conversion as a percentage of biogas applied. Conversely, the 10% biogas with diesel blend has a smoother part-load transients, but its typical performance is lower than that of the one provided at pure diesel operation. The brake power output is in correlation of loads across each of the fuel types and the 30 percent mix of biogas and diesel emerge as a most favorable performance profile. Overall, these results prove the feasibility of biogas with diesel dual-fuel configuration in fueling the CI engine output to the broader operating scope.**

Keywords—Diesel mixture, brake power, CI Engine, Dual fuel, Energy conversion, Biogas.

I. INTRODUCTION

Burning of fossil fuel to run the machineries and vehicles remains one of the primary sources of emissions, a fact long observed by the energy systems researchers. According to Subramanian et al. [1], diesel fuel contributes to a higher percentage of the total volume of fuel consumed in these sectors. Although one can applaud the efficiency and mechanical durability of the diesel technology, on which much of the current transport, agricultural and power generation systems rely upon, it can be said that such utilization may be described as the gradual, accelerated consumption of the fossil fuel that not only encourage the high volume of greenhouse-gas emissions, but the accelerated pace of resource extinction and the ultimate increase in operations costs. According to Subramanian et al. [2], scientists are devoting much attention to the launching of working platforms using the dual fuel types of and the structured introduction of the alternative energy sources which are considered the key means of controlling the ecological damage and the establishment of development on the basis of sustainable use. B. B. Sahoo et al. [3] had mentioned in the context of renewable options that biogas is one of the potential fuels that can be used in compression ignition engines. Biogas refers to a green energy product that is produced through anaerobic breakdown of organic wastes like agricultural inputs, food wastes, and animal manure. The bio-gas is mainly composed of methane (CH_4) and carbon dioxide (CO_2) that can be allowed to enter the intake manifold of a diesel engine simultaneously with a small amount of diesel thus acting as a surrogate for the ignition. A dual-fuel system would allow partial replacement of diesel without much alteration in the current engine design. S. Sathish et al [4] as well as. S. Dahlgren et al. [5] in their scholarly articles had mentioned about the use of the dual fuel CI engine whereby biogas and diesel are introduced simultaneously.

M. Feroskhan et al. [6] highlighted the improvements in the brake thermal efficiency (BTE) and the consumption of diesel reduction when biogas was added to the engine at high loads. Similarly, performance tests indicated the conversion of energy which became more effective when the biogas content was increased mostly at full-load operations. According to S. Kumar et al. [7], similar results were obtained viz., biogas biodiesel blends exhibited better performance under medium and high load conditions despite extended ignition delays caused by the higher CO_2 content of biogas. A detailed examination of literature sources showed that many researches were conducted on the aspect of emissions and combustion mechanisms, but fewer on the full-spectrum behavior under the restricted ways of loading viz., uncontrolled loading. V. Pandey et al. [8] highlighted that low levels of biogas substitution (i.e., 10%) were sufficient to provide a more stable engine behavior at the cost of reduced overall efficiency compared with normal diesel operation, under partial-load regimes. On the other hand, S. Subramanian et al. [9] described on the substitution of higher rate (30 percent or higher) offering a better efficiency over a range of 80 to 100 percent loading. Describing the tendencies of modern CI engines, it is necessary to refer to the behavior accompanying the loads on the CI engines when operating in dual fuel engine mode. The research work carried out by S. Sivasubramaniyan et al. [10] showed that effectiveness of fuel-air mixing, duration of the delay during the ignition, and burning time were the decisive factors for the brake power and thermal power efficiency. These can be imperfect in layer mixing at lower loads or the ignition at lower loads can be further retarded which will result in incomplete combustion and mechanical efficiency will be decreased. This is not true at increased loads where optimized biogas proportions do not just boost the output power, but also cut down on the fuel use and maintain the stability of operation. M. F. Al-Dawody et al. [11] studied on the field-installed diesel engines that were rarely operated at one full-load point. Instead, these were often requested and often tasked to serve the various demand driven loads, which alters not only the power output of the engine but also the associated thermal signature. Empirical evaluation therefore must be comprehensive and it must include, at least, several load conditions such as 20%, 40%, 60%, 80%, and 100% loads. On this same aspect, G. Saravanan et al. [12] revealed the significance of taking dual fuel mappings using a load-dependent parameter in the formation of adaptive fuel-injection schemes.

Hence, the purpose of this study is to investigate the performance characteristics of a CI engine running on biogas and diesel blends. Five load regimes namely, 20%, 40%, 60%, 80% and 100% of the rated torque are applied to the compression ignition (CI) engine that is only fueled with diesel and with 10/80 and 30/70 mixtures of biogas and diesel. The main performance characteristics such as brake power, brake thermal efficiency and mechanical efficiency are investigated to understand the most appropriate mix that gives better performances over different load conditions.

II. Experiments and Methods

In this study, a four-stroke, single-cylinder, water-cooled compression-ignition (CI) engine is used and it is connected directly onto an eddy current dynamometer. The test rig of the experimental setup as shown in Fig. 1. Consists of CI engine test rig (combined with an eddy-current dynamometer), biogas mixing set-up, biogas sensors, and data acquisition system. The schematic arrangement shows the combination of the dual-fuel injector system that allows mixing of biogas and diesel for different loading conditions. The turbocharged engine consists of 80mm bore, 110mm stroke, and a compression ratio of 16.5:1. The engine is operated at 1500 rpm giving an output of 4.4 kW. A generator coupled to an adjustable electrical resistance is used in order to simulate varied load conditions whereby the load could be dynamically increased allowing load to be progressively increased using generator up to a full load of 100 % and 20 % of full load respectively. A thorough check is carried out on the engine before the start of the experimentation in order to ensure that it is ready to operate. The listed inspection are completed before the operation: check the lubrication oil level in the sump, check the circulation of cooling water and check the presence of an adequate amount of diesel in the tank. After the initial operations are carried out, the engine is started and allowed to attain the operating temperature. The generated power obtained is recorded by monitoring the electrical current and voltage. A thermocouple is mounted into the cooling water circuit and its signal is connected to the digital temperature gauge in order to measure the temperature of the circulating fluid at regular intervals during the experimentation.

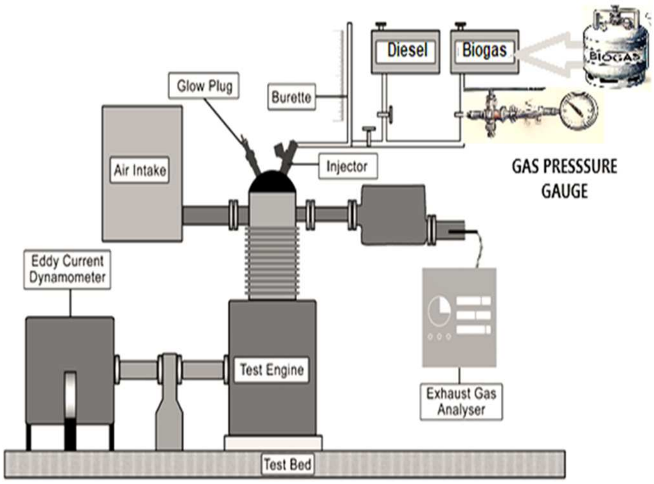

Fig. 1. Experimental setup

To assess the in-cylinder behaviour, piezoelectric pressure sensor is used to measure the combustion pressure [13]. A dual fuel layout is used and a gas regulator controls the flow of biogas which is pre-mixed with the air and introduced into the flowing air through the intake manifold. In the present study, fueling method entailed is injecting the conventional diesel into an unmodified injector in the course of power stroke. This is simultaneously accompanied by the sudden influx of pre-chamber rich charge of biogas air into the cylinder just prior to the suction stroke and hence leading to a complete blend and the consequent combustion process. This is achieved by a set of valves that permits the controlled variable mixture between biogas and air by a wide variety of load situations. In the present study, three different fuel blends are tested and these includes a basic blend of pure diesel (100% diesel), 10% of biogas-diesel (blend 1) and a mixture of 30% of biogas-diesel (blend 2). The biogas which is contained in a storage cylinder is withdrawn through a metered outlet using a pressure-regulated model and volume ratios are ensured by manipulation of the volumetric flow rate.

TABLE I. Fuel Properties of Diesel and Biogas [13]

S.NO	Particulars	Biogas	Diesel
1	Cetane number	--	50
2	Heating Value (MJ/Kg)	24.50	24.50
3	Viscosity level @ 40ºc	--	3.32
4	Flame temperature, 0ºC	875	2056
5	Self-ignition temperature, 0ºC	551	356

Table I lists the properties of fuels whose characteristics includes flame temperature of 875˚C and a very high self-ignition temperature of 551˚C. These two factors influence the combustion retardation and the ignition quality. The testing of a fuel composition must be extensive at a variety of engine loads when it is assessed.

The performance assessment entails five different operating load conditions i.e., 20%, 40 %, 60 %, 80 % and 100 % of total load). The initial readings are taken with diesel fuel to make this as the reference for comparative analysis. Equations used to assess the engine performance parameters are as follows. Brake thermal efficiency is given in equation (1),

$$\eta_{bth} = \frac{BP}{m_f \times CV} \times 100 \quad (1)$$

where BP is the brake power (kW), m_f is the fuel mass flow rate (kg/s), and CV is the calorific value of fuel (kJ/kg). Brake specific fuel consumption (BSFC) and mechanical efficiency, n_m is given in equations (2) and (3) respectively, wherein IP is the indicated power (kW).

$$BSFC = \frac{m_f}{BP}[kg\ /\ kwh] \quad (2)$$

$$n_m = \frac{BP}{IP} \times 100 \quad (3)$$

Later, the tests are performed using dual-fuel whereby the biogas is introduced along with air through the intake manifold as a pilot fuel. Using this setup, the fuel flow rate of the diesel is continually monitored using a burette and a manometer and the mass flow rate is calculated. The performance parameters such as brake power, brake thermal efficiency, and mechanical efficiency is calculated using the equations shown above after the end of every test run. Exhaust gas analyzer named QROTECH is used in this study to analyze the exhaust gases at steady-state conditions. Every readings in this experimentation is repeated thrice to ensure reliability of results.

III. Results and Discussion

Fig. 2. depicts the variation of brake power (BP) as a function of engine load for the varied fuel mixtures considered in this investigation. The BP increases at higher loads, which is as expected since larger quantities of fuel are burned at high engine loads thereby producing the resulting high-power output.

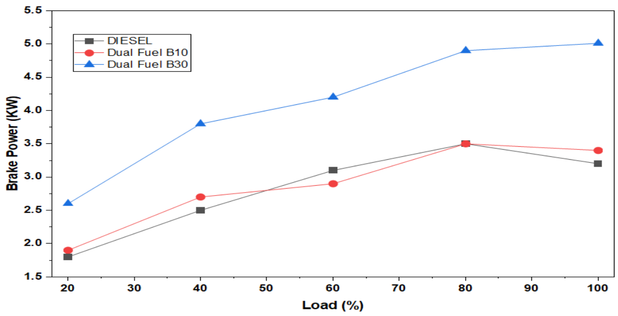

Fig. 2. Brake power with respect to engine loads

In the earlier published literature by K. Ridhuan et al. [14], it is mentioned that diesel fuel always has the best brake power which is often seen as a consequential of the high cetane number, calorific value and combustion characteristics of diesel.

TABLE II. Brake Thermal Efficiency (BTE) at Different Load Conditions

S. No	Load (%)	Diesel (%)	10% Biogas-Diesel	30% Biogas-Diesel
1	20	24.5	23.1	22.8
2	40	28.2	26.9	27.5
3	60	31.4	29.6	32.1
4	80	33.8	31.5	35.0
5	100	34.6	32.0	36.2

Table II shows the brake thermal efficiency of the engine with different loads. It is noteworthy that although the B30 blend exhibits reduced amounts of brake power during the low load condition, it is equally efficacious as unblended diesel during the full load condition. Therefore, the increased levels of biogas substitution would portray a highly effective influence under the circumstances of greater engine strain. B10 blend gives the midway performance between the two and gives an average performance and outperforming B30 blend under low or mid load conditions but trailing behind that of diesel with respect to performance.

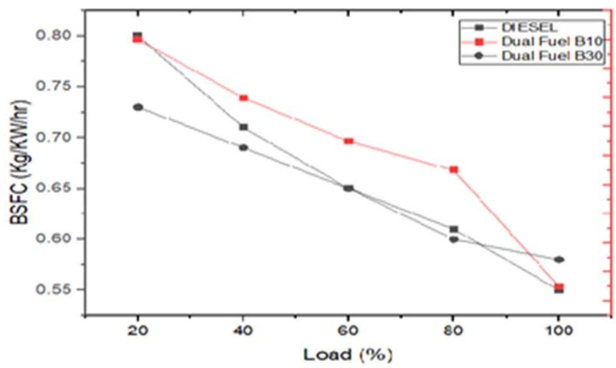

Fig. 3. BSFC with respect to load

The results for BSFC with respect to load is shown in Fig. 3. It also indicate that diesel continues to show the lowest BSFC at all engine loads, which can be mostly due to its high energy density and extremely fine combustion control.

TABLE III. Brake Specific Fuel Consumption (BSFC) at Different Load Conditions

S.NO	Load (%)	Diesel (%)	10% Biogas-Diesel	30% Biogas-Diesel
1	20	0.38	0.42	0.40
2	40	0.34	0.36	0.35
3	60	0.31	0.34	0.32
4	80	0.29	0.31	0.28
5	100	0.28	0.30	0.27

Table III represents the brake specific fuel consumption with different loads. On the other hand, the determined dual-fuel blends show an increasingly greater BSFC values, especially at low-to-medium loads that signify poor utilization of the fuels.

These two blends of biogas used as diesel fuel B30 records the most pronounced rise in BSFC both in full-load and mostly in partial-load operations due to the low calorific value of the biogas and the delay in combustion caused by the high level of CO_2 in the gas and also due to low temperature of the resulting flames. However, increases in load show a statistically significant decreasing trend in the BSFC for the B30 blend with diesel indicating that combustion is more efficient in areas where the cylinder temperature is higher. Hence, it is able to create an effective ignition of biogas. B10 blend takes a middle ground as it shows an increment of BSFC that is smaller but maintains a better gas mileage when compared to B30 blend at lower loads.

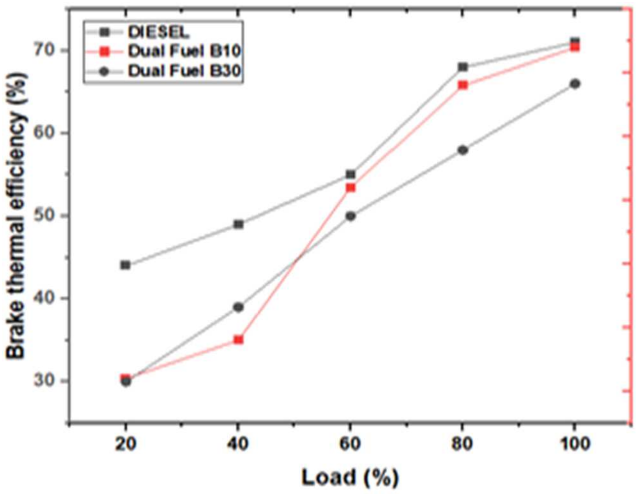

Fig. 4. Effect of Load on Brake thermal Efficiency

The effect of load on brake thermal efficiency is illustrated in Fig.4. Most importantly, BTE increases with load in all types of fuels because of increasing engine power requirements, the impact of frictional and parasitic loss decreases.

TABLE IV. Mechanical Efficiency at Different Load Conditions

S.NO	Load (%)	Diesel (%)	10% Biogas-Diesel	30% Biogas-Diesel
1	20	72.0	70.5	71.2
2	40	76.3	74.8	77.1
3	60	80.5	78.0	82.0
4	80	83.7	81.5	85.4
5	100	85.2	82.8	87.0

Table IV illustrates the mechanical efficiency of the engine with operating at different loads. Diesel again records to bring out the best BTE due its excellent ignition nature. Similar observations are evident for bio-diesel: Blend B10 demonstrates greater thermodynamic efficiency than B30 blend at every load points, especially within the midrange (40–80%), thereby confirming that partial substitution of diesel with biogas can yield a superior thermal performance under controlled blending conditions. B30, though visibly less effective above 50 percent engine load, actually it had a marked increase in BTE at both 80 percent and 100 percent operating levels that clearly defines it as being suitable to the heavy-duty applications.

Mechanical efficiency also droops as the load increases as shown in Fig. 5. Among the three tested fuel samples, B10 blend displays maximum efficiency throughout all the loads as compared to those of diesel and B30 blend. This condition is presumably associated with better burning characteristics of biogas-diesel mixtures with low runs of substitute and with lesser conduction to the engine yesteryear system. B30 blend achieve higher mechanical efficiency than diesel only at very large loads, but even then, still at a lower value as compared to B10; the decrease is most likely due to higher viscosity and ignition delay inherent to biogas-rich blends. Although diesel produced a sturdy thermal output, it still had the worst mechanical efficiency, and that is largely because of the high degree of frictional and pumping losses.

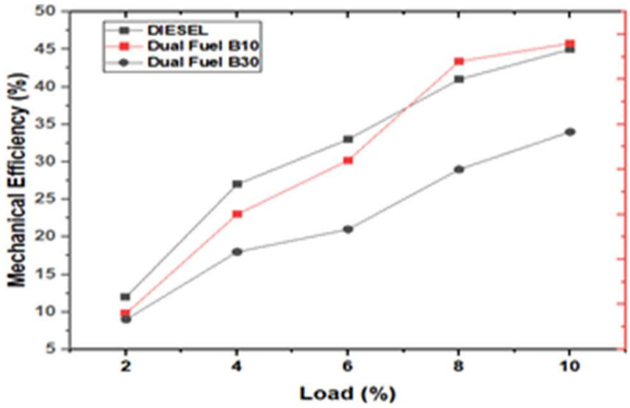

Fig. 5. Effect of Load on Mechanical Efficiency

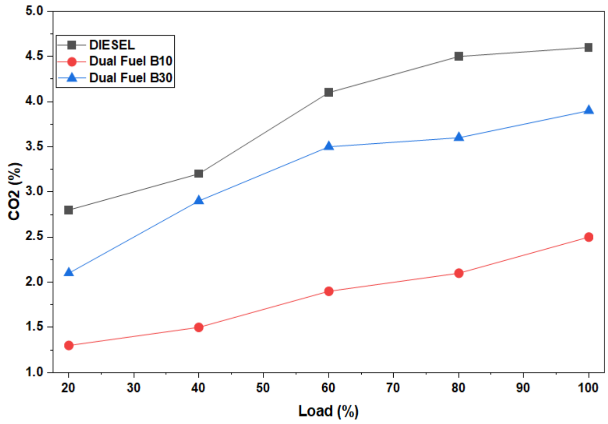

Fig. 6. CO2 concentration with respect to load

Fig. 6. Elucidate the changes in carbon dioxide (CO_2) emissions in terms of percentage as a function of engine load, varying from 10 % to 100 % for three fuel options namely pure diesel, dual-fuel B10 (10 % biogas + diesel), and dual-fuel B30 (30 % biogas + diesel). There is a similar trend throughout the fuels that are tested, whereby at a higher load, the amount of CO_2 emitted increases. Such action may be attributed to the interaction of the higher combustion efficiency and the increasing fuel consumption at higher loads, which have the effect of increasing CO_2 production. Among all tested loads, diesel resulted in the highest levels of CO_2 emissions, which is attributable to its high levels of carbon, combined with full combustibility. Diesel recorded about 4.8 % CO_2 at 100 % load indicating that it has high energy release and efficiency of combustion.

In this study, the dual-fuel operation is investigated with the use of both B10 and B30 blends and it shows that low CO_2 emissions are experienced with higher concentrations of biogas use. Namely, the B10 blend produces moderate values of emissions, having around 2.0% at 10% load, 4.0% at full load condition. In comparison, B30 blend had the least amount of CO_2 emission at all loads, and this shows how high levels of biogas-substitution lead to carbon intensive emissions. Its further reduction can be explained by a lower carbon to hydrogen ratio of biogas and occurrence of non-reactive CO_2 in biogas which limits ignition temperatures and CO_2 production. These are consistent with findings that, biogas-diesel parallel mode of operation has recognizably lesser emission of CO_2, especially when the blend rates are high. As diesel has high combustion output, B30 blend is more environmentally friendly, thus supporting the adaptability of the dual-fuel CI engines as a cleaner and sustainable alternative of the traditional diesel engines. Biogas and diesel use in dual-fuel mode shows an observable increase in brake thermal efficiency, especially at medium to high engine loads, over the conventional operation using diesel. In addition to fuel efficiency, this mode also suggests less reliance on fossil diesel, and it promotes diversification of energy. S. Taneja et al. [15] results suggest that biogas substitution correlates with a decrease in CO_2 and particulate matter emissions, and therefore it has a contribution to play in cleaner combustion. These results show that biogas-diesel dual-fuel systems could be viewed as a viable opportunity in its use for the internal combustion engines with an overall benefit to the environment.

IV. Conclusions

These experimental investigations examined the performance parameters of a single-cylinder compression-ignition (CI) engine in dual-fuel mode when fueled by mixtures of biogas and diesel. Five load points are tested, three fuel conditions, such as pure diesel, 10% biogas + diesel (B10) and 30% biogas + diesel (B30) and parameters such as mechanical efficiency, brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) are analyzed. B10 blend result in slightly higher BSFC and BTE throughout the entire extent of the loading condition, although BTE is practically the same as the diesel-only reference base. B10 blend at all loads took the lowest level; a relatively close value is observed in B30 blend and the diesel only fuel, which suggests that there is no significant difference in the delay at ignition timing. Finally, it is found that the mean luminance intensity is maximum with B30 fuel blend, which implies a large portion of fuel combustion capacity. The results reveal that there is an increase in brake power, brake thermal efficiency and mechanical efficiency with the increase in load during all tested fuels. Diesel maintained continuous high performance and the reason is that it has greater calorific value and inherently stable combustion. Dual-fuel configuration had part-load performance and mechanical efficiency superior to B10 blend and full-load B30 thermal efficiency and brake power. Such observation shows that biogas-diesel dual-fuel operation is a thermodynamically viable and energy-efficient substitute diesel operation, especially it can be made to be optimized with reference to specific loads, and as such to be a sustainable and renewable substitute. All these observations indicate that biogas fuel can be used in a dual fuel-operating mode along with the diesel fuel to provide a significant efficiency improvement primarily at the medium-high engine power levels.

V. Future Work

The replacement rates of biogas can be accelerated further beyond 30% in the future to ascertain the stability of the engines, the combustion traits and performance under higher penetration rate of renewable fuels. This dual-fuel configuration will be complemented by enhancing control measures to enhance sustainability and reduce the emissions such as exhaust gas recirculation (EGR) and catalytic after-treatment systems. In addition, the endurance testing with real driving cycles on the field is to be conducted in the long-period to test the strength and survivability of the system. Upgraded biogas (biomethane) will also be considered so that high substitution ratios can be enabled without being affected by operation stability. Lastly, the implementation of this dual-fuel setup in rural decentralised power generation and farm implements will be discussed, with reference to its capability to become a feasible and alternative to the traditional use of diesel, which is both practical and environmentally safe.

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