Production of hydrogen gas from water via electrolysis for community power generation

Wichien Hermharn[1], Sittichot Kradang-nga[1], Pongsakorn Kachapongkun[1], Sirichai Jirawongnuson[2]
[1]Department of Rattanakosin College for Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin, Nakhon Pathom, Thailand
[2]Faculty of Engineering, Rajamangala University of Technology Rattanakosin, Nakhon Pathom, Thailand

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ABSTRACT

Rural and remote communities often rely on diesel generators, which are costly, inefficient, and emit greenhouse gas and particulate pollutants. This study combines real-time hydrogen production via electrolytic water separation with a conventional 5,871-cc diesel backup generator to enhance combustion performance and reduce environmental impacts. A self-built electrolyzer was powered by a direct current (DC) battery and precisely controlled by an electronic control unit (ECU) to provide hydrogen output based on engine load conditions. The results of testing co-fueling improved fuel efficiency by 20-25%, with a peak 24.9% reduction in fuel consumption at 50% load. Emission measurements revealed significant reductions in black smoke, $PM_{2.5}$, PM_{10}, and CO_2, with the maximum CO_2 reduction of 23.4 kg CO_2-e/hr. The system operates without the need for a hydrogen storage tank, thus improving safety and reliability. These findings demonstrate that this low-cost and low-emission approach represents a practical alternative for backup power in remote areas. Future work will focus on long-term stability and monitoring hydrogen flow rates for varying load conditions.

Corresponding Author:

Sirichai Jirawongnuson
Faculty of Engineering, Rajamangala University of Technology Rattanakosin
Nakhon Pathom, Thailand
Email: sirichai.jir@rmutr.ac.th

1. INTRODUCTION

Due to population growth, industrialization, and the increasing use of energy-consuming technologies, the global demand for energy continues to rise [1]. Presently, this demand is mainly met by the increasing consumption of fossil fuels, which considerably contribute to greenhouse gas (GHG) emissions and air pollution, especially through combustion in internal combustion engines [2]–[4]. Airborne pollutants, such as carbon dioxide (CO_2), toxic dust, and $PM_{2.5}$-related smog, significantly accelerate climate change and give rise to severe health and environmental hazards [3], [4]. Additionally, the increasing use of fossil fuels has contributed to energy shortages and the rising prices of fuel [4], [5]. These adverse effects indicate the immediate need for new, cleaner, and more sustainable energy sources [5], [6]. Hydrogen energy is recognized as clean, versatile, and renewable energy. So, it has become a primary alternative in the efforts to reduce pollution and greenhouse gas emissions [7], [8]. Recently, hydrogen has demonstrated its potential to replace common fossil fuels in various industry sectors: power generation, transportation, and industrial processes. Although renewable energy sources like solar and wind are increasingly used in our society, many facilities still count on diesel-powered backup generators, particularly during main power supply outages [9], [10]. This clearly indicates an opportunity for hydrogen to serve as a supplementary fuel in existing diesel-based power systems [11]–[13], which will require further improvements in efficiency to become a renewable energy source.

Among the various hydrogen-producing techniques, water electrolysis has attracted substantial attention due to its environmental sustainability and operational flexibility, as it does not require any fossil fuel input [14], [15]. This technique allows for real-time production of hydrogen gas without the need for a hydrogen gas storage tank and large installation space. When combined with the internal combustion engine system, separated hydrogen obtained from water electrolysis can be used as a supplementary fuel to enhance combustion efficiency, decrease emissions, and lower diesel consumption without the requirement of critical modifications to existing engine setups. Current developments in electrolysis techniques aim to improve efficiency, scalability, and integration with renewable energy systems, such as solar and wind power sources, for hydrogen production. Polymer membrane electrolysis (PEM) has gained significant attention due to improved catalyst efficiency and its flexibility for integration with renewable energy sources for hydrogen production. For example, Kradang-nga and Kachapongkun [16] applied PEM to split hydrogen gas from water and used it as additional fuel with the diesel fuel of the pickup truck. Their modified system showed significant fuel saving and emission reductions. Arat [17] evaluated hydrogen-supplemented internal combustion engines in hybrid electric vehicle applications. They found that the hydrogen addition can improve engine performance and enhance emission reductions. Similarly, Sun *et al.* [18] and Zhang *et al.* [19] found that hydrogen direct injection improved combustion stability and flame speed.

Alkaline electrolysis (ALK) has been regarded as a cost-effective technique for hydrogen production. Gu *et al.* [20] evaluated ALK and found that improving the efficiency of this electrochemical method potentially makes it more appropriate for large-scale hydrogen production. Solid oxide electrolysis (SOE) has also received attention because of its usefulness. Hauch *et al.* [21] reported that SOE can be applied to be used for decentralized hydrogen production. In parallel, Tang *et al.* [22], Raviteja and Kumar [23], and Castro *et al.* [24] presented that the use of hydrogen as a co-fuel to the diesel engine and reported that the use of dual fuels can improve the engine performance and reduce emissions.

Despite these valuable findings, present studies mostly focus on laboratory-scale setups. Limited attention has been paid to practical challenges such as real-time hydrogen production without storage tanks, system automation, and direct integration into stationary diesel generators under practical operating conditions. Moreover, small-scale or community power generation systems are increasingly important, particularly in remote areas where access to centralized power systems is limited and unreliable. These conditions clearly indicate the need for cost-effective, clean, and adaptable power generation technologies suitable for rural and remote areas.

In addition to the theoretical aspects of hydrogen production via electrolysis, we benchmark our system against recent green hydrogen initiatives and microgrid integration models. Projects have focused on large-scale hydrogen production using renewable energy sources such as wind and solar [25]. These studies emphasize hydrogen storage and its integration into microgrids to enhance energy reliability in remote areas. However, the system presented in this study combines hydrogen production via electrolysis with diesel backup generators to offer a small-scale and cost-effective solution that can be integrated into microgrid configurations, promoting energy security and supporting clean energy transitions in rural communities. This approach is agreeable to ongoing efforts to reduce fossil fuel dependency and support local energy resilience.

This study aims to investigate the gap by developing and evaluating an on-site hydrogen production and co-fueling system produced for auxiliary diesel-electric generators. The system is designed for real-time hydrogen production via electrolysis and allows precise fuel mixing without the need for hydrogen storage tanks or engine redesign. The novelty of this work involves a real-time, storage-free hydrogen production system designed for direct integration into stationary diesel generators. In addition, this novel system is specially designed for remote and off-grid areas. In contrast to the traditional systems that often depend on large storage tanks and engine modifications, this innovative system facilitates on-site hydrogen production through electrolysis and allows for precise fuel mixing with diesel. This newly modified system can therefore be a cost-effective solution for areas where the electricity supply is not reliable. Without the need for significant modification, this system provides a sustainable energy solution that enhances energy reliability and supports the transition to clean energy in remote regions.

Furthermore, the real-time fuel mixing enhances fuel management by maintaining engine performance and supporting emission reductions. This novel approach can thus provide a useful contribution to the need for energy, particularly in remote areas and small-scale energy applications. The objectives of this work are to determine the optimal hydrogen-to-diesel ratio for maximum engine performance, to evaluate the impact of hydrogen-diesel dual-fuel operation on emissions, including black smoke, $PM_{2.5}$, PM_{10}, and CO_2, and to assess the potential of cost reduction in electricity generation compared to using pure diesel fuel. The paper is organized as follows: section 2 describes the system and methods; section 3 presents results and discussion; and section 4 provides conclusions and practical insights.

2. METHOD

2.1. The hydrogen-producing electrolysis process

This study employed a self-developed electrolysis system to produce hydrogen gas in real time for use as a supplementary fuel. The electrochemical process uses a direct current (DC) power supply to initiate reactions at the electrodes. At the same time, the electrolyte facilitates ion transport throughout the process. The reactions in the hydrogen-producing electrolysis process can be given as in (1)-(3) [6], [24], [26].

$$\textit{At the cathode}\ \ 2H^+(aq) + 2e^- \rightarrow\ H_2(g) \tag{1}$$

$$\textit{At the anode}\ \ 2H_2O \rightarrow O_2(g) + 2H^+(aq) + 4e \tag{2}$$

$$\textit{Overall reaction}\ \ 2H_2O \rightarrow 2H_2O(g) + O_2(g) \tag{3}$$

2.2. A self-designed power generation system using hydrogen from electrolysis

A self-made electrolysis system was developed to generate hydrogen in real time as a supplementary fuel. The electrolyzer consisted of 65 stainless steel (SUS 316L) plates arranged as 5 cells connected in series, each containing 13 plates (7 cathodes and 6 anodes). The plate dimensions were 105 mm×80 mm× 1.3 mm with 5 mm spacing between each plate. Figure 1 shows the self-made electrolysis system.

The electrolyte was distilled water mixed with 5% KOH by weight, functioning as the ionic conductor. The electrolyte reservoir had a capacity of 4 liters (3 liters in the reactor and 1 liter in the reservoir tank). Hydrogen and oxygen gases produced at the electrodes were separated in a gas-liquid separator. Hydrogen was then sent to the intake manifold. A 12 V battery system was utilized to power the electrolyzer. During operation, the input voltage and current ranged from 12.0-14.5 V and 10.0-13.0 A, respectively. Hydrogen production rate was not measured directly in liters per minute, but it was obtained from the rate of water loss per minute for a three-hour period. Estimated hydrogen production was determined from water mass loss (grams) by using the ratio: one gram of H_2O produces 1/9 gram of hydrogen. The theoretical efficiency of the self-made electrolyzer (η) was then calculated by (4) [15]–[17].

$$\eta\ = \frac{(\textit{Energy from produced } H^2)}{(\textit{Input Electrical Energy})} \times 100\% \tag{4}$$

2.3. A self-designed power generation system

To evaluate the possibility of hydrogen-diesel dual fuel operation, a diesel-powered backup generator was modified to integrate the electrolysis system. The original engine used in this experiment was a Hino EH100 diesel engine with a capacity of 5,871-cc connected to a 60-60-kilowatt alternator as the load generator operated at a constant speed of 1,500 rpm, as shown in Figure 2. The generator was tested under five load conditions (0, 25,50, 75, and 100%). The load application was precisely controlled by resistive heaters. Each test operated for 30 minutes per load condition. The fuel consumption was measured using the precision graduated cylinder (±1 mL) and a stopwatch.

Figure 1. The self-made electrolysis system: five units are arranged in a series circuit

Figure 2. A Hino EH100 diesel engine with a capacity of 5,871-cc coupled to a 60-kW alternator

2.4. The design of electronic control unit

Electronic control unit (ECU) is used to control the production and distribution of hydrogen to the engine. In this test, the ECU is designed to adjust signals to delay the injection timing. This design aims to decrease the supply of the main fuel and, simultaneously, allow the engine to use the generated hydrogen as a supplementary fuel. ECU also plays a role in controlling the hydrogen-producing process in the reactor. This precise control in the reactor is used to make sure that the electrical power supply can effectively correspond to the load of the engine. The ECU is shown in Figure 3, and the interface of the program for the hydrogen production adjustment as per the engine's load is given in Figure 4.

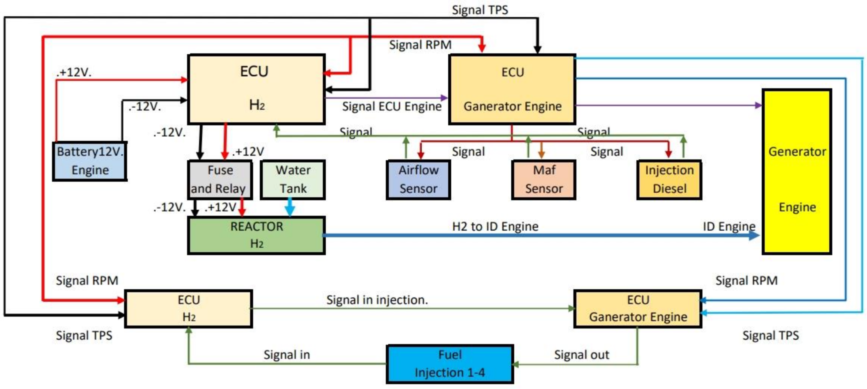

Figure 3. Control system design diagram of ECU

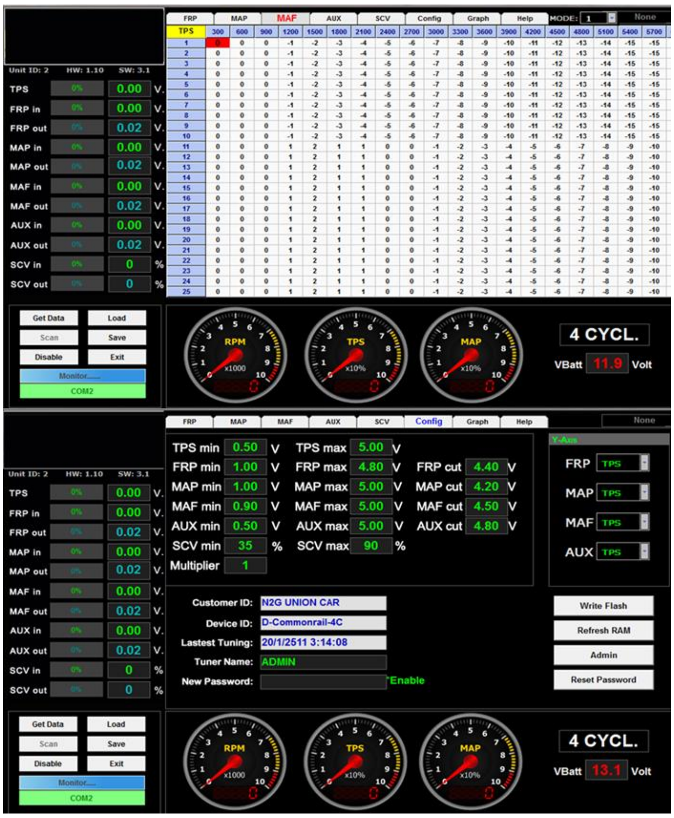

Figure 4. The program interfaces for the hydrogen production tuning

2.5. Self-designed hydrogen-assisted backup generator system

The self-designed hydrogen production-assisted power backup generator was constructed by integrating the real-time hydrogen production system and ECU with various control and safety components, as shown in Figure 5. This design distinguishes itself from prior systems by regulating hydrogen gas production to respond to the engine's load requirements. ECU controls all processes, including fuel mixing and system safety. A safety backfire is also installed to maintain operational safety. The ECU monitors engine load and then adjusts hydrogen production. When the engine shuts down, hydrogen production is immediately stopped, and any residual gas is directed into the water tank to prevent accumulation. The source of energy for this system includes diesel fuel and hydrogen generated through electrolysis. The mixing of hydrogen and diesel for use in the diesel power backup allows the system to operate with improved fuel efficiency and reduced emissions. The 12-14.5 V DC battery supplies power to the PEM electrolyzer reactor, which contains an electrolyte to facilitate the electrolysis process. This electrolyzer operates with a voltage range of 2.0-2.5 V and a current density of 0.5-1.0 A/cm², with an efficiency ranging from 65-75% under common operating conditions. The water employed for electrolysis is treated by a filtration process to remove impurities, followed by demineralization to obtain high-quality water for the electrolysis process. Regarding safety, a pressure relief valve, automatic shut-off mechanism, and a gas detector are installed with the system to mitigate the risks of hydrogen leaks or overpressure conditions. These precautions ensure that hydrogen produced during electrolysis is well handled and safely stored. A fuse is also included in the circuit to protect against electrical overloads. With this design, the system can function safely and effectively under different load conditions, making it suitable for backup power applications used in rural and remote areas.

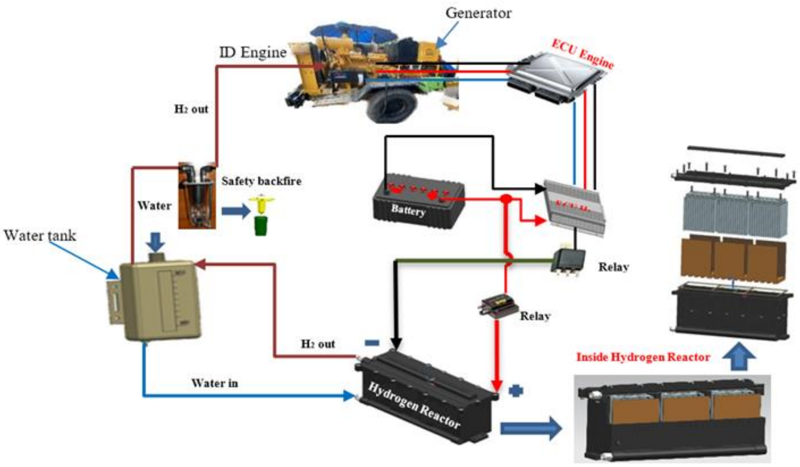

Figure 5. Schematic diagram of self-designed power generation system

2.6. Fuel consumption and emissions measurements

The fuel consumption rate is measured in liters per hour using a flow meter and manually validated with time and measured fuel volume. Break-specific fuel consumption (BSFC) is an essential parameter to evaluate the effectiveness of a hydrogen-assisted power backup generator [27]–[30]. This parameter technically represents the amount of fuel consumed per unit of power produced. In this study, BSFC in liters per kilowatt-h can be calculated using (5) [15]–[17].

$$BSFC = \frac{(Fuel\ Consumption\ in\ L/h)}{(Electrical\ Output\ in\ kW)} \tag{5}$$

The emissions monitoring was also monitored. A smoke meter (OIML R99 Class 0, ISO-3930 compliant) was used to measure the black smoke emission. A certified laser scattering particle counter was utilized to measure $PM_{2.5}$ and PM_{10}. CO_2 emission was monitored using a non-dispersive infrared (NDIR) CO_2 sensor. Each measurement was repeated three times and then averaged. Ambient temperature was controlled at 25±2 °C.

3. RESULTS AND DISCUSSION

3.1. The electrical power consumption and the efficiency of the self-made hydrogen-producing system

The hydrogen-producing system was examined using measurement devices connected to the electrolyzer unit. In this experiment setup, the positive terminal of the battery was connected to that of the electrolyzer, whereas the negative terminal of the battery was connected to that of the electrolyzer. Obtained data, including electric current, voltage, and the weight of water lost, were recorded every minute for a period of three hours. The electrical power supplied to the hydrogen-producing system was calculated as the product of the recorded voltage and current during the testing period, as detailed in Figure 6.

Figure 6 shows the examination results for the electrical power consumption of the hydrogen-producing unit during the electrolysis process. The maximum and minimum consumption for hydrogen separation were recorded as 167.60 and 150.18 W, respectively. The average power consumption for hydrogen separation was obtained at 156.78 W. The average voltage and current were measured at 14.00 V and 11.50 A. Naturally, the hydrogen-producing process from the electrolyzer causes a reduction in water volume [27]. Technically, the reduction of water volume can be used to indicate the efficiency of the power consumed by the hydrogen-producing unit [28]–[31]. The experiment set up for measuring the loss of water initially contained three liters of water in the electrolyzer with an extra one liter in the backup water tank. The water level in the backup tank was recorded every minute for the three-hour investigation period.

Figure 7 illustrates the reduction in water weight during the hydrogen gas separation process. Over the investigation period, the total water weight decreased by 50.88 grams. The energy efficiency of the electrolyzer was obtained by considering that one gram of water contains 1/9 gram of hydrogen. Then, the total water loss of 50.88 grams can be regarded as 50.88/9 grams of hydrogen generated in 3 hours. As exhibited in Figure 5, the average electrical power consumption during the process was 156.78 W. Consequently, the theoretical efficiency of the self-made hydrogen-producing unit based on hydrogen separation theory from water was estimated at 45.97%.

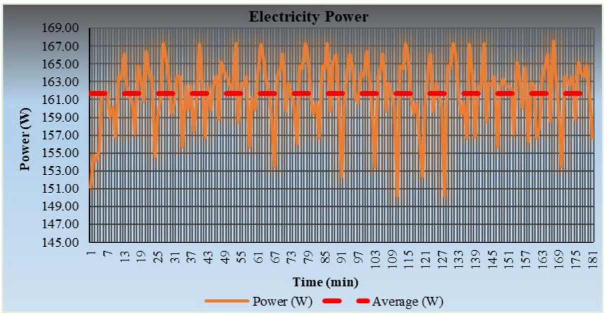

Figure 6. The electrical power used by hydrogen-producing unit during the electrolysis process

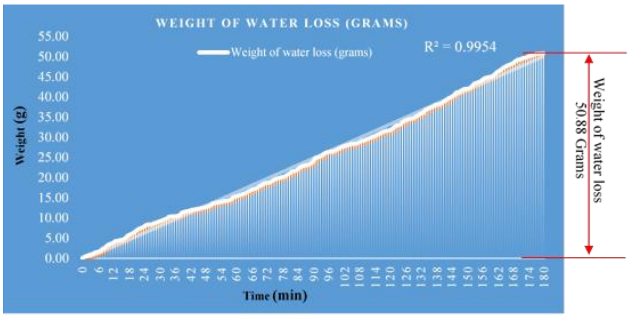

Figure 7. The reduction of water weight during the electrolysis process

The results show that the self-made hydrogen production system used an average of 156.78 W of power and resulted in a water loss of 50.88 grams for a three-hour period, corresponding to a theoretical efficiency of about 45.97%. In comparison to the system reported by Kradang-nga and Kachapongkun [16], this system utilized less power (125.74 W) and had a lower water loss (40.02 grams). Nevertheless, both systems achieved almost the same efficiency. This difference can be attributed to the engine sizes used in the two studies. The present study employed a larger 5,871-cc engine, which is larger than a 2,500-cc engine used by Kradang-nga and Kachapongkun [16]. Technically, a larger engine requires a higher volume of hydrogen to support combustion, leading to increased power consumption during hydrogen production. Besides, both systems gained nearly similar efficiency, reflecting that the hydrogen production process performs consistently with the small and large engines. This finding suggests that the self-made system developed in this study is suitable for high-displacement engines used in larger stationary power systems, particularly in rural areas where demand is potentially higher.

3.2. Analysis of fuel consumption rate and brake specific fuel consumption

In this present test, the production of electricity was performed with a diesel-powered backup generator equipped with a hydrogen-producing electrolysis system operating at a constant speed of 1,500 rpm (in accordance with the standard of the generator). The self-modified backup generator was operated under two conditions. The first one used pure diesel, and the second one employed hydrogen as a co-fuel to the diesel engine. The electricity production was examined under no load and loads at 25, 50, 75, and 100% corresponding to power outputs of 15, 30, 45, 60 kW, respectively.

Figure 8 displays the fuel consumption rate with various load conditions using a direct current supply of 12-14.5 V and an electric current range of 10-13 A. It is clear from Figure 7 that at a constant speed of 1,500 rpm, the co-fuel system achieved an average fuel saving of 2.3 liters per hour under load conditions of 50-75 %, corresponding to an electricity output of 37.5 kWh. This result indicates that the produced hydrogen gas was effectively blended with diesel fuel at a constant speed of 1,500 rpm. At the same time, ECU precisely adjusted the diesel fuel supply, allowing the produced hydrogen gas to be used as a supplementary fuel source. The results also exhibit that using a co-fuel system resulted in a fuel saving of 24.9% as compared to the pure diesel condition. At a 50% load, the fuel consumption rate achieved the lowest, recorded at 0.58 liters per minute, with respect to 0.77 liters per minute gained from the pure diesel use.

The BSFC of 100% diesel and co-fuel under various power output conditions is illustrated in Figure 9. Results show that both systems displayed an increasing BSFC trend as the load increased, meaning that at the constant speed, the higher loads require more fuel for energy production. In addition, at all power output conditions, BSFC of the co-fuel system is consistently lower than that of pure diesel, indicating the improved fuel efficiency in the co-fuel system. The most efficient BSFC was found at a load of 30 kW (50% load) with a value of 3.45 liters/kWh.

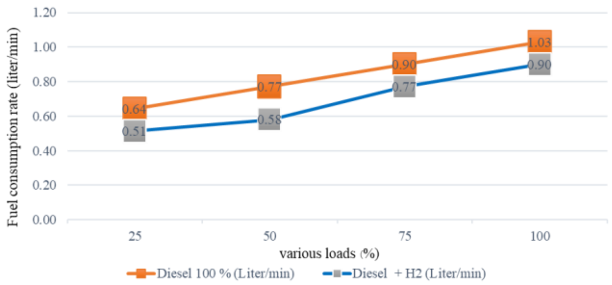

Figure 8. Fuel consumption rate test with loads at 25, 50, 75, and 100%

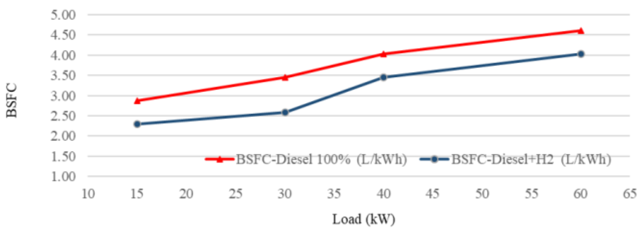

Figure 9. The comparison of the BSFC with various load conditions of 15, 30, 45, and 60 kW at a constant engine speed of 1,500 rpm

The results of this study confirm that hydrogen-diesel co-fueling can reduce fuel consumption and improve combustion efficiency in stationary generators, particularly at medium load conditions. This system achieved a fuel saving of 24.9%, which is agreeable to the results from Kradang-nga and Kachapongkun [16], who reported fuel savings of 27.8 and 16.7% under different load conditions in a vehicle. On one hand, the steady engine speed and fixed loads in the generator enhanced consistent hydrogen blending. On the other hand, changing road conditions in the vehicle study may result in the efficiency reduction. In addition, using a larger 5,871-cc engine in this study also demonstrates that the system can work effectively in high-displacement stationary engines. Although both fuel consumption and BSFC increased with load, the hydrogen-diesel system consistently showed lower values compared to diesel-only operation, indicating improved fuel efficiency. These findings are also consistent with those of prior studies. Sun *et al*. [18] and Zhang *et al*. [19] reported that adding hydrogen enhanced the combustion stability, resulting in improved combustion efficiency. Tang *et al*. [22] and Raviteja *et al*. [23] presented that using hydrogen with diesel can reduce fuel use. Castro *et al*. [24] showed that hydrogen-diesel systems can improve overall engine performance. Therefore, the results of all investigations indicate that hydrogen co-fueling can reduce diesel use and lower fuel costs, particularly in backup power systems for rural or remote areas.

3.3. Analysis of level of black smoke, $PM_{2.5}$, PM_{10}, and CO_2

The comparison study of the percentage reduction of black smoke was conducted by employing a smoke detector conforming to OIML R99 Class 0, ISO-3930, and BAR97 standards to measure the exhaust smoke occurring during combustion. In addition, $PM_{2.5}$ and PM_{10} levels were measured at different engine speeds using a certified fine particle measurement device. The studies were performed on two systems- pure diesel and co-fuel system-under load conditions at 25, 50, 75, and 100% during the electrolysis process.

Figure 10 illustrates that using a co-fuel system with the produced hydrogen gas can reduce emissions of black smoke, $PM_{2.5}$, and PM_{10} at all load conditions as compared to using the pure diesel system. At a 50% load, emissions of black smoke were reduced more effectively than at other load conditions. Nevertheless, $PM_{2.5}$ emissions exhibited a smaller reduction with respect to those at a 25% load. This finding implies that lower engine loads result in less combustion, thereby minimizing the generation of fine particulate pollution, but leading to higher PM_{10} levels. In addition, black smoke emissions at a 25% load were found to be higher than those at a 50% load. This suggests that load conditions of 50-70% represent the most suitable working range for the combined use of diesel and produced hydrogen for electricity generation. Furthermore, this present study found that at a 37.5 kW load or 50% load, using a co-fuel system with the produced hydrogen gas achieved a fuel saving of 24.9% in comparison to using 100% diesel fuel.

Figure 11 further emphasizes that CO_2 emissions decreased for all load conditions. A maximum CO_2 emissions reduction was 14.1%, equivalent to 23.4 kg CO_2-e/hr, at a condition of 50% load. This indicates the usefulness of hydrogen-diesel co-fueling in greenhouse gas emission reduction during power production. These results are consistent with the findings of Kradang-nga and Kachapongkun [16], Sun *et al*. [19], Zhang *et al*. [19], Tang *et al.* [22], Raviteja *et al.* [23], and Castro *et al*. [24]. All found that hydrogen-diesel dual-fuel engines can improve combustion performance, resulting in the reduction of black smoke and emissions. Thus, the present study supports previous works that using hydrogen as a co-fuel with a diesel engine is an efficient method to decrease black smoke, fine particles, and CO_2 emissions. The study also shows that this method works effectively in stationary power systems, particularly for backup generators in rural or remote areas where clean and affordable energy is required. From this test, important details were found in comparing the use of diesel-only and H_2–diesel co-fuel systems to obtain performance and environmental impact metrics, as shown in Table 1. The quantitative performance (fuel consumption and BSFC) from Table 1 indicates that the hydrogen-diesel co-fuel system provides significant fuel savings (up to 24.9%) with improved engine efficiency. Additionally, the environmental impact metrics in Table 1 show significant CO_2 reduction (23.4 kg CO_2-e/hr) and improvements in air quality with considerable reductions in black smoke, $PM_{2.5}$, and PM_{10} emissions. These results confirm that the proposed system offers a cost-effective, environmentally sustainable alternative for backup power generation, particularly in remote and off-grid areas where access to reliable, clean energy is limited. Clearly, the novel on-site hydrogen system not only indicates technical possibilities but also presents significant feasibility for reducing the need for external energy sources and providing power to regions where electricity is not reliable. The integration of hydrogen production via electrolysis with diesel backup generators obviously offers a cost-effective choice for remote areas. This newly modified system also reduces the use of fossil fuels and significantly decreases harmful emissions: CO_2, $PM_{2.5}$, and black smoke. In addition, this innovative system could potentially be developed to use fuel cells, small-scale energy, and energy storage systems to increase energy reliability in remote areas, where it is difficult to access conventional power systems.

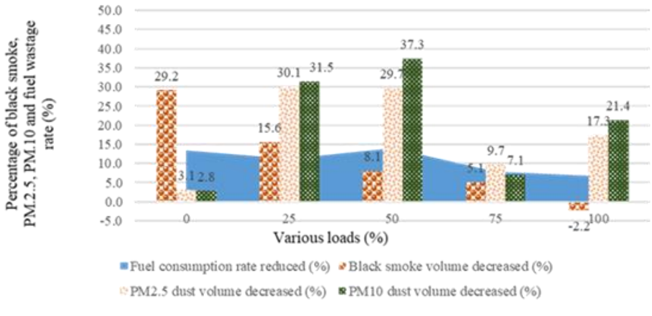

Figure 10. The percentage reductions in black smoke, $PM_{2.5}$, and PM_{10} emissions, along with the fuel consumption rate at various load conditions (%)

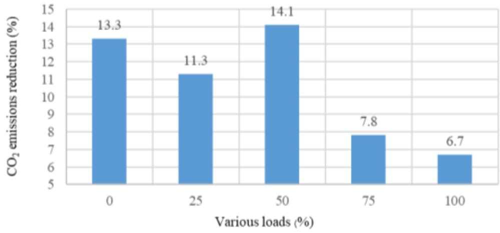

Figure 11. The reduction of CO_2 emissions (%) at different load conditions

Table 1. Obtained performance and environmental impact metrics

Parameter	Diesel only	H_2–diesel co-fuel	Change
Fuel consumption @50% load	0.77 L/h	0.58 L/h	-24.9 saving
CO_2 emissions @50% load	Baseline	–23.4 kg CO_2-e/hr	-14.1
BSFC (all loads)	Higher	Lower	Improved efficiency
$PM_{2.5}$/PM_{10}/black smoke	Baseline	Reduced	Significant reduction
Electrolyzer power use	N/A	156.78 W avg	
Electrolyzer efficiency	N/A	45.97%	Comparable to vehicles

4. CONCLUSION

This study proposes an effective approach to reducing electricity production cost and pollution emission by using real-time hydrogen gas, produced from a self-developed electrolysis system, as a supplementary fuel in diesel-powered backup generators. Engine performance, fuel efficiency, emissions, and the cost of electricity production were evaluated under various load conditions and compared with a conventional diesel system, showing that the modified generator significantly improved fuel efficiency, with the highest fuel saving of 24.9% at a 50% load and notable savings at other loads. Emission analysis indicated considerable reductions in black smoke, $PM_{2.5}$, PM_{10}, and CO_2, including a CO_2 reduction of 23.4 kgCO_2-e/hr, highlighting the contribution of the system to greenhouse gas mitigation. These findings demonstrate that the proposed hydrogen–diesel co-fueling system offers a cost-effective and environmentally sustainable alternative for backup power generation, particularly in rural or remote areas where access to reliable, clean energy is limited, and provide a foundation for future development toward integrated systems with energy storage, smart control, and supportive policy frameworks.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Wichien Hermharn						✓	✓	✓	✓	✓				
Sittichot Kradang-nga	✓		✓	✓		✓		✓	✓		✓			
Pongsakorn Kachapongkun	✓	✓			✓					✓		✓	✓	✓
Sirichai Jirawongnuson	✓	✓		✓						✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

INFORMED CONSENT

Not applicable. This study did not involve human participants or patient data, and therefore, informed consent was not required.

ETHICAL APPROVAL

Not applicable. This article does not contain any studies with human participants or animals performed by any of the authors. No ethical approval was required for the experimental setup described in this work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SJ], upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Wichien Hermharn is an experienced Mechanical Maintenance Superintendent at the Star Petroleum Refining Co., th. Skill in cost management, manpower management, preventive maintenance, and corrective maintenance in rotating equipment such as pumps, compressors, gas turbines, steam turbines, fin fan, mixer, loading arm, static equipment such as tank, vessel, column, valve, and PSV in refinery and chemical plant. He can be contacted at email: wichienh@sprc.co.th.

Sittichot Kradang-nga has a Ph.D. degree in Energy and Environmental Management from the Rattanakosin College of Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin. He has over 20 years of experience as an engineer and production manager in the manufacturing industry. His main research interests are renewable energy and energy storage. He can be contacted at email: sittichot.kra@rmutr.ac.th.

Pongsakorn Kachapongkun is an experienced Assistant Professor at the Rattanakosin College of Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin. Skilled in energy conservation, heating and cooling, cold storage, renewable energy, and corporate carbon footprint assessment. He holds a Ph.D. in Energy Technology from King Mongkut's University of Technology Thonburi. He can be contacted at email: pongsakorn.kerd@rmutr.ac.th.

Sirichai Jirawongnuson is an experienced Assistant Professor and Vice President at the Rattanakosin College of Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin. Skilled in mechanical engineering, energy conservation, renewable energy, and logistics systems. He holds a Ph.D. in Mechanical Engineering from Kasetsart University. He can be contacted at email: sirichai.jir@rmutr.ac.th.