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Experimental Underperformance Detection of a Fixed-Speed Diesel–Electric Generator Based on Exhaust Gas Emissions

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Abstract: Low load is one of the most challenging combustion stages for a fixed-speed diesel electric generator. Due to incomplete combustion during this phase, a significant proportion of contaminants form inside the cylinder. This can lead to numerous chemical and mechanical harms to the diesel engine, resulting in friction, efficiency reduction, increased fuel consumption, and prematurely ending the generator's life. These phenomena are qualified as underperformance, possibly due to a misfire and/or a low-efficiency value (air fuel–fuel ratio). Therefore, detecting and preventing underperformance and reducing its extended operation is crucial. This paper deals with the performance and emission analysis of a multicylinder fixed-speed diesel engine driving an electric generator (300 kW) fueled with ultra-low sulfur diesel (≤15 mg/kg) to provide energy in an isolated Canadian community. The tests were carried out according to ISO 3046-1:2002 standard in a remote site to identify clues that can prevent prolonged operation in underperformance. Among the tests conducted, emissions such as sulfur (S), carbon dioxide (CO_2), nitrogen oxide (NOx), and exhaust gas temperature are considered the best indices for detecting the underperformance of a fixed-speed diesel–electric generator under very-low and low load (0–30%) with the following registered values: 18 ppm for S, 4% for CO_2, 150 ppm for NOx, and 210 °C for the temperature.

Keywords: low load; exhaust gas temperature; underperformance; brake-specific fuel consumption; diesel generator; sulfur emission; nitrogen oxide emission; carbon dioxide emission

Citation: Ghorbanzadeh, M.; Issa, M.; Ilinca, A. Experimental Underperformance Detection of a Fixed-Speed Diesel–Electric Generator Based on Exhaust Gas Emissions. *Energies* **2023**, *16*, 3537. https://doi.org/10.3390/en16083537

Academic Editors: Adonios Karpetis and Constantine D. Rakopoulos

Received: 9 March 2023
Revised: 13 April 2023
Accepted: 18 April 2023
Published: 19 April 2023

1. Introduction

Underperformance is when an engine is not producing the expected or desired level of power output, regardless of its operating speed [1–3]. The low regime, on the other hand, refers specifically to low engine speeds or revolutions per minute (RPM) [4]. While underperformance and the low regime are often associated, they are not necessarily the same. An engine can be underperforming at any RPM, including high RPMs. For example, an engine may produce less power than expected due to a mechanical issue, such as a worn piston ring, regardless of operating speed [5]. Conversely, an engine may be operating at low RPMs without necessarily underperforming. This could be intentional during a time of load transition, for example, onboard ships or in rail transport, when the diesel–electric generators operate under low load (≤30%) but for a determined time (less than 30 min) [6–9]. According to the Caterpillar manufacturer, underperformance occurs when the diesel generator operates under low load (≤30%) for an extended period (over 30 min) and frequently. Furthermore, if the engine is not producing enough power to meet the output demands, it may be considered underperforming even at low RPMs.

According to [10], the underperformance of diesel engines at low regime operation is due to a few factors. First, diesel engines operate by compressing air to a high temperature and pressure before injecting fuel, igniting, and driving the piston. At low engine speeds, the air compression is not as effective and the fuel may not ignite as efficiently, leading to incomplete combustion and reduced power output. Additionally, at low engine speeds, the engine's turbocharger may not be spinning fast enough to provide sufficient airflow to the engine, resulting in a lack of power [11]. This is because turbochargers rely on the engine's exhaust gas flow to drive a turbine that compresses incoming air. As a result, the exhaust gas flow is reduced at low engine speeds, resulting in less boost pressure and reduced power output.

Furthermore, diesel engines often have a narrow power band, meaning their optimal operating range is relatively narrow [12]. Therefore, the engine may not operate within this optimal range at low speeds, reducing power output and efficiency [13]. Table 1 describes the causes and consequences of the prolonged low-load operation on a fixed-speed diesel–electric generator performance.

Today, there are a few ways to detect the underperformance of an engine. According to [14], the most apparent sign of underperformance is a decrease in power output. Additionally, fuel consumption, engine noise, and/or vibration can be signs of underperformance. Regular maintenance and inspection can also help prevent underperformance by identifying and fixing issues before they become significant problems [15].

Table 1. Effects of fixed-speed diesel–electric generator light load running [16–18].

Phenomena	Signs of Occurrence	Causes/Consequences
Wet stacking	- Black liquid similar to engine oil flowing from the turbocharger or the exhaust pipe. - Wet or dark fluid around the right side of the engine at the exhaust manifold	Prolonged engine operation at a low load prevents the temperature from reaching its required value for the complete combustion of all the injected fuel.
Polishing cylinder	- Increasing oil consumption - Power loss	Local mechanical friction is probably due to carbon deposits around the rings caused by poor combustion from running the engine at a low load.
Glazing cylinder	- Increasing oil consumption - Power loss - Engine smoke	- Engine cold start - Highly additive oil (extended oil change interval) - Underloaded operating condition
Effects	- Cost: The excessive occurrence of these phenomena reduces the remaining life of the engine and its main components by several years. These phenomena also increase fuel consumption and, consequently, costs. - Pollution: increases engine smoke and greenhouse gases. - Power: reduction of the maximum power produced by the engine compared to its nominal power. - Maintenance: a fixed-speed engine experiencing these problems requires more frequent maintenance than an engine operating with an adequate load.	

To the best of the author's knowledge, experimental or research studies have yet to be done on the detection of underperformance of a fixed-speed diesel–electric generator based on exhaust gas emissions or attempted to address this issue when running under a low load in isolated communities during an extended period. However, the solutions being discussed today to address the issue of underperformance [16–22] may be an attractive approach for these communities. Still, they cannot be implemented shortly due to their outdated infrastructure and lack of access to clean fuels at these locations. Therefore, this study addresses the issue of preventing diesel generator underperformance by investigating diesel engine emissions and fuel consumption under three different load levels (i.e., very low, low, and regular). The paper contains six sections. After the introduction, Section 2 presents the case of remote communities' electrification in northern Canada and the technical challenges affecting diesel–electric generators. Section 3, entitled Experimental Apparatus, presents the equipment used in the experiments, followed by Section 4 "Methodology", which describes the methodology and applied tools. Section 5, Results and Discussion, gives the results obtained and the analysis performed. Finally, Section 6, Conclusion, synthesizes this work's findings and gives a perspective for future work.

2. Case of Remote Communities in Northern Canada

Remote communities in Canada, where most of the population is indigenous, rely on diesel fuel for heating and energy generation [23–27]. More precisely, to be self-sufficient in electrical energy, 79% of these remote communities favored fossil fuel generators, mainly diesel [28,29], as shown in Figure 1, due to their reliability and familiarity of the local utilities with the technology. We analyzed 213 remote Canadian communities for diesel use for electricity generation. Most diesel–electric generators in these isolated communities are oversized to meet peak demand. As a result, they can be five times greater than the average electrical load [5,30,31]. In addition, these generators typically are fixed-speed and run mostly at low loads (Table 2), leading to higher oil consumption and, consequently, a more significant deposit of carbonized oil or oil residue in the engine and its suction and exhaust system [32].

Table 2. Load levels as a percentage of rated power.

Power Percentage	Load Level
0–25%	Very low load
26–39%	Low load
40–80%	Regular load
81–90%	High load
91–100%	Very high load

The appearance and persistence of residue have a detrimental effect on the engine's lifespan and functioning behavior. Consequently, the number of maintenance activities tends to rise [33–35]. Additionally, an engine running in low-load mode cools down, which results in only partial fuel combustion and can produce white smoke with significant hydrocarbon emissions [36–38]. Furthermore, the proportion of incomplete combustion in the oil increases due to the low fuel temperature. Due to these issues, the oil leaks and is released through the exhaust valves because the piston rings, the piston itself, and the cylinder do not dilate enough to ensure a reliable seal. This indicates that the quality and characteristics of the lubricant are diminished as the diesel oil enters the crankcase [39]. One technique to address this issue and eliminate these deposits is to increase the engine speed until the operating temperature is attained. In the industry sector, especially in the USA, using a load bank is a standard technique to lessen these adverse effects [40]. On the other hand, combining small, new fixed-speed diesel–electric generators whose combined power energy output is equivalent to a single large, fixed diesel–electric generator can prevent the large engine from functioning under a low load [41].

In this study, we compare a diesel generator's exhaust emissions, exhaust temperature, and fuel consumption under two conditions: in the first scenario, the diesel generator will be subjected to low loads for a brief period (15 min) before being subjected to a load greater than 40%; while in the second scenario, the diesel generator will be subjected to low loads for a lengthy period (up to 2 h of operation) before being subjected to a load greater than 40% again. The final objective is to analyze the impact of short-term low-load operation versus long-term low-load operation on engine combustion and fuel consumption and to see if there is a possibility of preventing the deterioration of diesel engine efficiency from the results obtained.

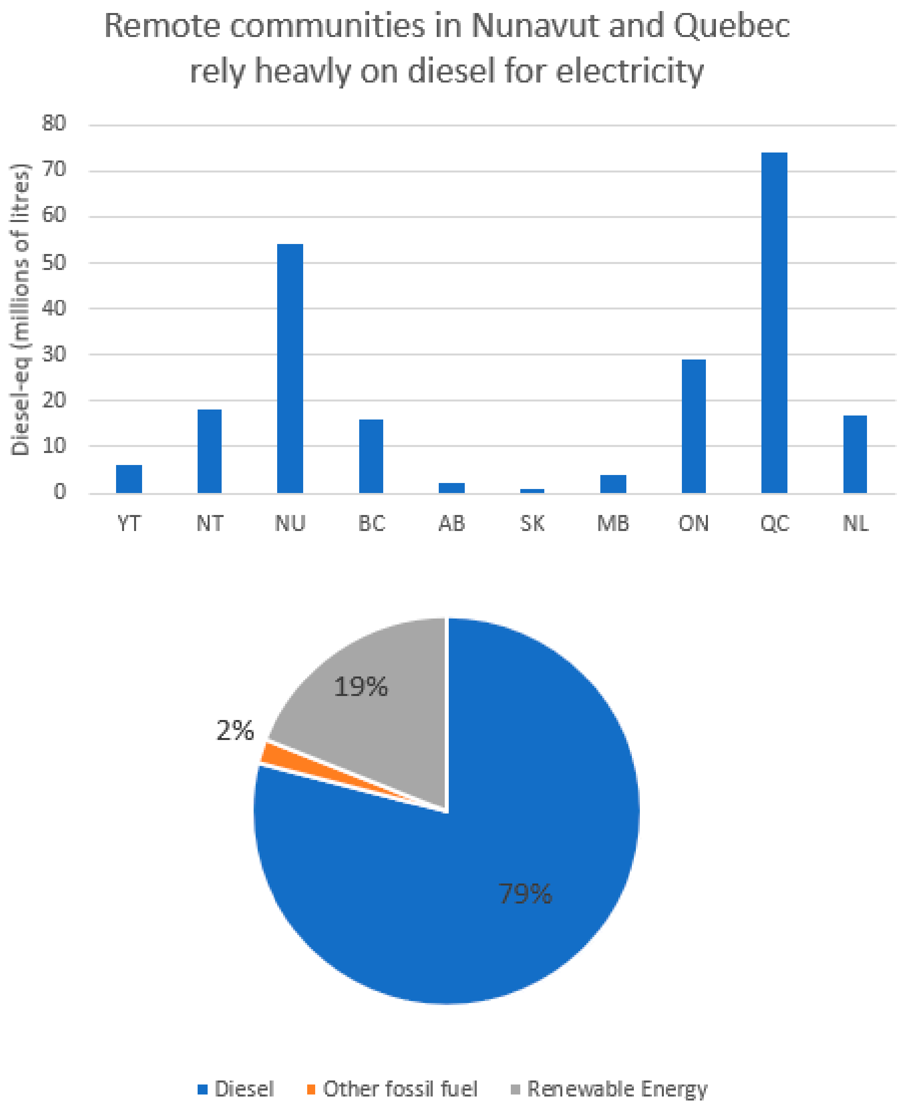
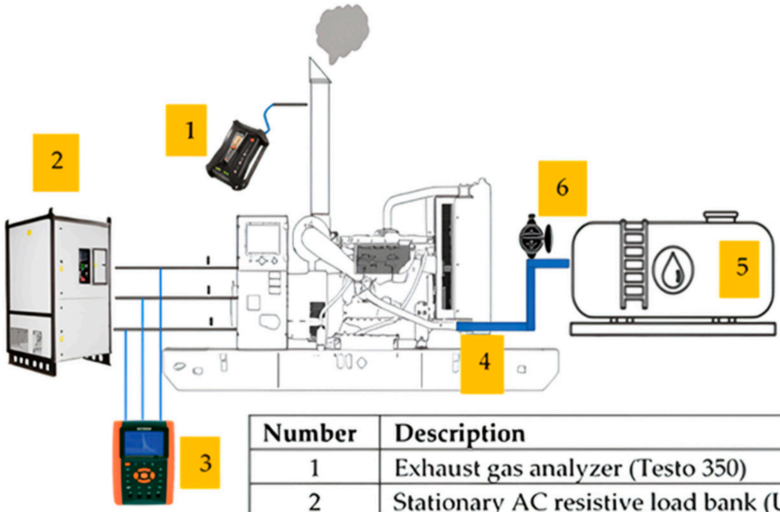


Figure 1. Remote communities in Canada, mainly Nunavut and Quebec, rely on diesel fuel for heating and electricity generation [42].

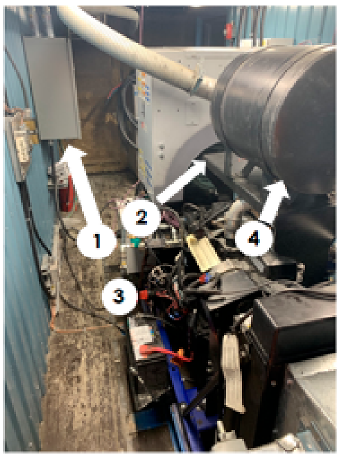
3. Experimental Apparatus

This study used an 8.8 L heavy-duty fuel compression ignition engine to drive a 300 kW alternator for the experiments. The engine has an efficiency of 36%. The test bench components and an overview of the layout are shown in Figures 2 and 3. The engine features advanced combustion emission reduction technology (ACERT), which integrates air and fuel controls to comply with the Environmental Protection Agency (EPA) 2004 requirements. Instead of using the Exhaust Gas Recirculation (EGR) technology, improved air management employs a series of turbochargers to push cool, clean air into the combustion chamber. Variable valve actuation, which complements the camshaft actuation, is also used by the engine to control airflow. The emissions are further decreased using a diesel oxidation catalyst. As the electrical frequency of the network grid is 60 Hz, the engine's speed was fixed at 1800 rpm throughout all the tests.



Number	Description
1	Exhaust gas analyzer (Testo 350)
2	Stationary AC resistive load bank (ULB-R250)
3	3 phases power analyzer (Fluke MDA550)
4	Fixed speed diesel generator (300KW, 1800 rpm, 60Hz)
5	Fuel tank Storage
6	Differential flow meter (KRAL OME-13)

Figure 2. Schematic representation of the study's experimental design.



1	Load bank
2	Alternator
3	Flowmeter
4	Storage tank

Figure 3. Illustration of the test bench inside the insulated container installed in northern Quebec.

The engine specifications are presented in Table 3, while the generator specifications are in Table 4.

Table 3. Engine specifications.

Engine Type	Inline Six Cylinders, C9
Bore	112.0 mm
Stroke	149.1 mm
Displacement	8.8 L
Compression Ratio	16.1:1
Aspiration	Air to air aftercooled
Fuel system	Hydraulic electronic unit injection
Governor type	Adem A4

Table 4. Electrical generator specifications.

Standby Rating	300 ekW
Alternator design	Brushless single bearing, 4-pole
Stator	2/3 Pitch
No. of Leads	12
Voltage	208 V
Frequency	60 Hz
Voltage regulation, steady state +/−	≤0.5%

A fuel flow meter was mounted on the engine test bench to record the diesel fuel rate based on the differential measurement method. The feed line's flow rate and the consumer's return line are measured directly. The consumption formula is, therefore, the incoming minus the return flow. We used a KRAL flowmeter (OME-013 model) with a precision rate of ±0.1% of the measurement value.

A flue gas analyzer (Testo 350 model) was used to measure the temperature and the exhaust gas emissions output. This flue gas analyzer has been specifically designed for industrial emission measurements such as diesel engines, gas turbines, and thermal processes. This analyzer is equipped with an analysis box that can be operated with up to 6 gas sensors such as sulfur dioxide (SO_2), carbon dioxide (CO_2), oxides of nitrogen (NO_X), oxygen (O_2), carbon monoxide (CO), and sulfur (S). Table 5 below shows the accuracy for the different gases according to the manufacturer.

Table 5. Accuracy rates for industrial emission measurements with the Testo 350 [43].

Flue Gas	Measuring Range	Accuracy	Resolution
CO_2	0 to CO_2 max	calculated from O_2 ±0.2 Vol.%	0.01 Vol.%
O_2	0 to +25 Vol.%	±0.8% of fsv (0 to +25 Vol.%)	0.01 Vol.% (0 to +25 Vol.%)
CO	0 to +10,000 ppm	±5 % of mv (+200 to +2000 ppm) ±10 % of mv (+2001 to +10,000 ppm) ±10 ppm (0 to +199 ppm)	1 ppm (0 to +10,000 ppm)
NO	0 to +4000 ppm	±5 % of mv (+100 to +1999 ppm) ±10 % of mv (+2000 to +4000 ppm) ±5 ppm (0 to +99 ppm)	1 ppm (0 to +4000 ppm)
NOX	0 to +500 ppm	±5 % of mv (+100 to +2000 ppm) ±10 % of mv (+2001 to +5000 ppm) ±5 ppm (0 to +99 ppm)	1 ppm (0 to +5000 ppm)
SOX	0 to +5000 ppm	±5 % of mv (+100 to +2000 ppm) ±10 % of mv (+2001 to +5000 ppm) ±5 ppm (0 to +99 ppm)	1 ppm (0 to +5000 ppm)

4. Methodology

The tests were conducted at an engine speed of 1800 rev/min. The fuel used during the tests was ultra-low sulfur diesel fuel (ULSD) for off-road engines (locomotive and vessel diesel engines) containing 15 ppm sulfur, compliant with the current standard for all engine diesel fuel defined by Environment Canada [44]. The loads were varied from 0 to 156 kW, which represents 0–52% of the maximum capacity of the generator, to recreate the electrical charge profile in an isolated microgrid in northern Quebec (Figure 4). All the tests were performed under an ambient temperature of 21 °C. The readings at each load were taken after the engine reached the steady-state condition. The following experimental parameters were determined.

1. Exhaust emission characteristics include exhaust gas temperature, SO_2, CO_2, NO_x, O_2, CO, and S.
2. The effect of Brake-Specific Fuel Consumption (BSFC)

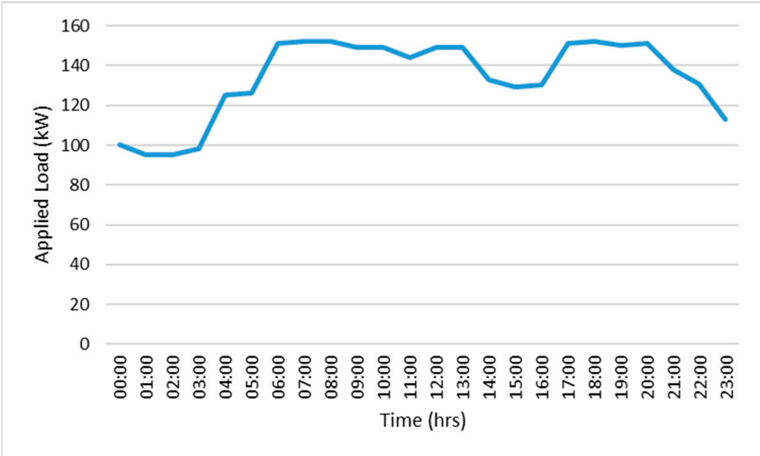


Figure 4. The remote community electrical load profile at Baie-James, Canada.

These readings were repeated three times for the very low load (0–25%), low load (26–39%), and regular load (40–52%). The tests were according to ISO 3046–1:2002 standard, including correcting the load power and fuel consumption findings to standard conditions [45].

5. Results and Discussion

5.1. Engine Performance: Brake Specific Fuel Consumption (BSFC)

Figure 5 depicts the BSFC at different loads. The analysis shows that the variation in fuel consumption as a function of the load varies instantaneously when switching from a low to a high load and vice versa, and this for both regimes: (i) normal performance regime where the engine has been subjected to a low load for a very short period (15 min), and (ii) underperformance regime where the engine has been subjected to a low load for an extended period (up to 2 h). However, an increase in fuel consumption was observed after 1.5 h of operation under loads of 4 to 35% before it was reduced and returned to normal for the last 30 min under loads ranging from 40 to 52%. For both regimes, there was no noticeable delay in the consumption curve. Moreover, regardless of the load value, the BSFC (in gallons per kWh produced) declines as the engine load increases. Higher fuel consumption is necessary to achieve the desired power output at a lower speed due to the lower pressure in the cylinders leading to lower volumetric efficiency. Therefore, BSFC decreases as engine speed increases and total energy utilization increases.

Additionally, the findings suggest that the BSFC decreases with engine load. The total energy released increases with engine load, and the proportion of output power rises because the friction loss is nearly identical [46,47]. Based on the BSFC results, fuel consumption might be viewed as a sign of low or high load operating rather than a reliable indicator of underperformance. This can be explained by the fact that the underperformance based on BSFC data is determined by the operation period (short or long time) under a low load. In this case, the operator must combine time and fuel consumption to determine if the engine performs below par. According to Caterpillar [33], the time limit for low load operation (0 to 30 percent) is fixed at 30 min.

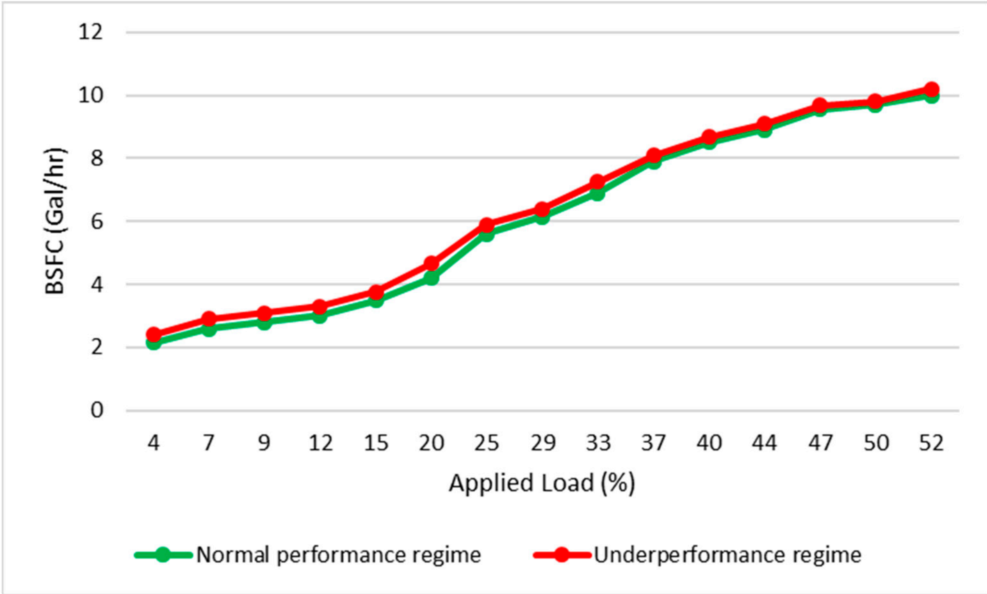


Figure 5. Break specific fuel consumption of the C9 fixed-speed diesel generator according to the applied loads under two scenarios.

5.2. Exhaust Gas Temperature

The variation of exhaust gas temperature for different load conditions is presented in Figure 6. One can see that the exhaust gas temperature increases with the load. This occurs because more fuel is burned in the cylinder when the engine load increases, raising the cylinder temperature [48]. In addition, the exhaust gas temperature is highest when the engine runs at its highest speed. However, exhaust gas temperatures were found to be slightly higher for loads between 4 and 33% for extended periods under low loads (underperformance regime). Above 35%, the temperature stayed at the same level as when the engine was run briefly at a low load (normal performance regime). This could be because the fuel/air ratio in the cylinders is no longer operating as efficiently, which leads to poor combustion and a variation in exhaust gas temperatures.

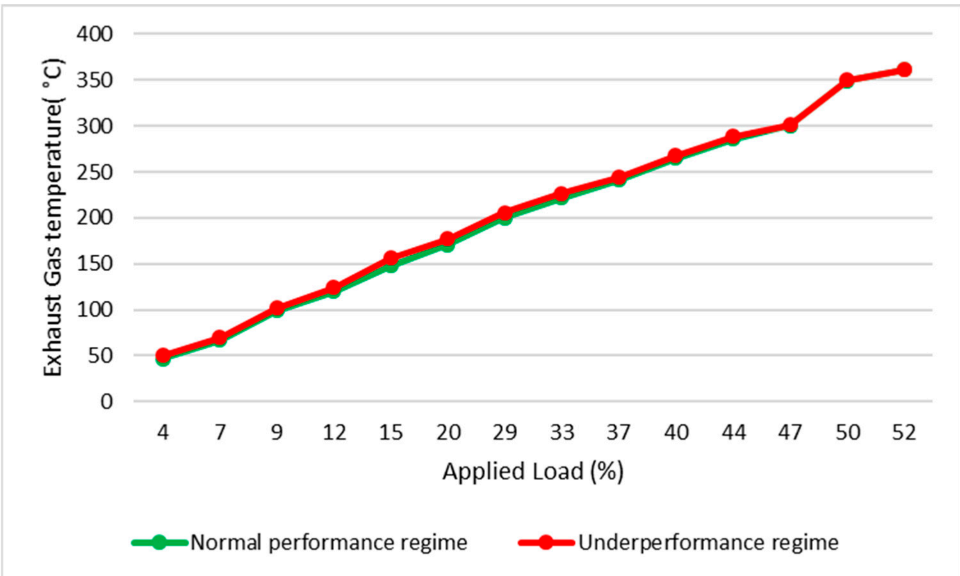


Figure 6. Exhaust gas temperature vs. load.

According to this graph, the variation of exhaust gas temperature as a function of the applied load can indicate underperformance. For example, at a very low load and low load (0–39%), the temperature does not exceed 250 °C for both regimes, while at a regular load (42–52%), the temperature reaches up to 360 °C. Furthermore, the exhaust gas temperature is linear versus the applied load. Although exhaust temperature increases with diesel engine load, we noticed during the experimental test that the temperature stabilizes in less than 12 min for both scenarios when the applied load varies, which confirms that it is possible to use this measure as an underperformance sign if operation time is taken into consideration. For example, extended time (>30 min) under low loads (≤30%) with a recorded temperature below 250 °C can be considered a sign of underperformance. In comparison, a recorded temperature of 250 °C or less for a short period (10–15 min) can be discarded.

5.3. Sulfur Emissions (S)

Burning fossil fuels that include sulfur produces the most sulfur oxide (SO_x) in the atmosphere. When sulfur combines with oxygen during combustion, sulfur dioxide is created (SO_2). Figure 7 indicates the variation of the sulfur emission for the load. The sulfur level in the exhaust gas is higher when the generator runs in the extended mode under a light load (underperformance regime) before reaching the normal value when the load increases beyond 35%. Furthermore, sulfur seems to be the best indication for underperformance detection. The sulfur level stabilizes at low load (10 ppm), while at very low load (<25%), it varies between 18 ppm to 12 ppm. This occurs because at low loads and speeds, the heat inside the combustion chamber will be inadequate for the rapid oxidation of sulfur atoms. At medium and high loads, the temperature of the combustion chamber increases, and the oxidation of all molecules is also improved [49]. Therefore, part of the sulfur content is oxidized to form SO_2, while other parts form other compounds such as aromatics and PM. Therefore, sulfur concentrations are reduced in this range.

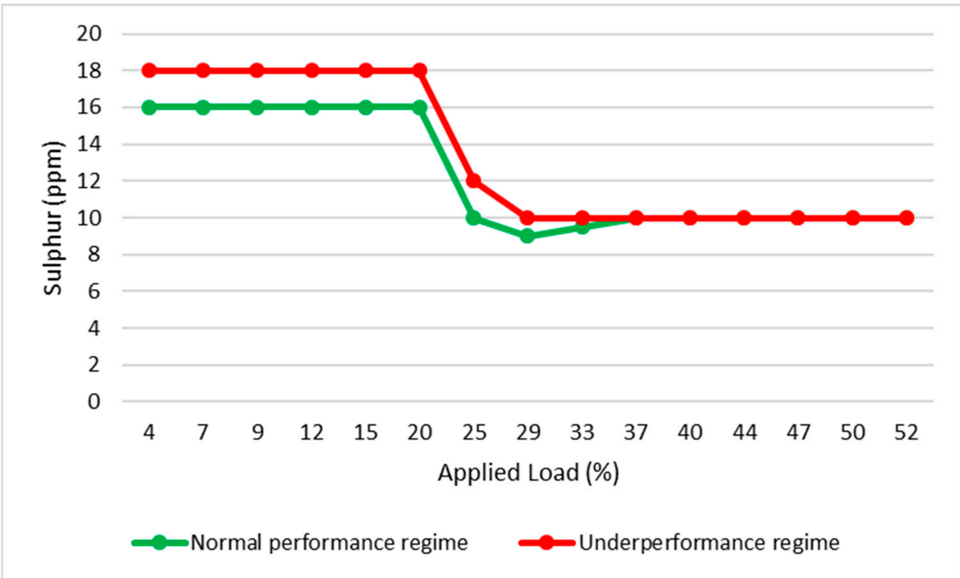


Figure 7. Variation of the S content in the exhaust gas according to the applied loads.

5.4. Sulfur Dioxide Emissions (SO_2)

Figure 8 indicates the variation of SO_2 emission with the load. It is seen that the SO_2 level stabilizes at 12–13 ppm when the load reaches 25–45% of the total available power, and the maximum percentage occurs at a very low load (12–15%) of up to 18 ppm. Based on the information presented in Figure 7, at a very low load (7–8%), the SO_2 emission rate can create confusion in diesel engine underperformance detection, as its amount is identical to that of a low load and regular load (26–40%), making it a suboptimal indicator for diesel engine underperformance. In addition, it was found at regular load (beyond 50%), the SO_2 decreases further and reaches 10 ppm. Therefore, the explanation could be insufficient heat to evaporate the fumigation fuel effectively under a very low and low load [50].

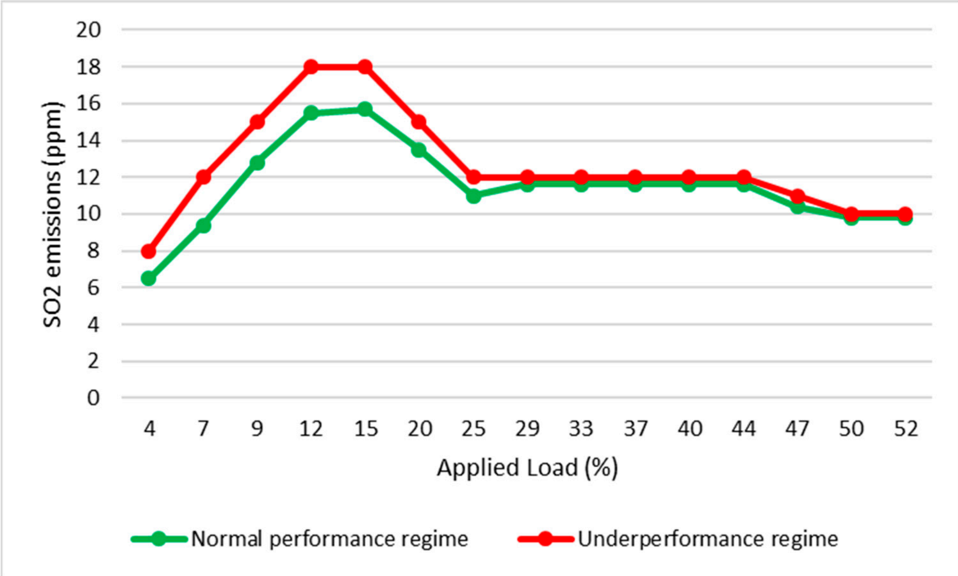


Figure 8. Variation of the SO_2 rate according to the applied loads.

5.5. Oxygen Emissions (O_2)

Figure 9 shows the variation of the oxygen rate emission with the load. In the recorded data, with an increase in load, the oxygen rate declines; for loads between 37% and 47%, the oxygen level nearly leveled out at 12 ppm, and this is for both tested regimes. In general, when the load increases, there is a greater need for fuel and oxygen in the combustion chamber, resulting in a linear decrease in oxygen emission. Therefore, oxygen rate, because of its linear behavior to the applied load, can be a good sign for the underperformance detection of a diesel engine. However, oxygen rate emission shows a decline at an underperformance regime before it returns to normal when the load reaches 40%.

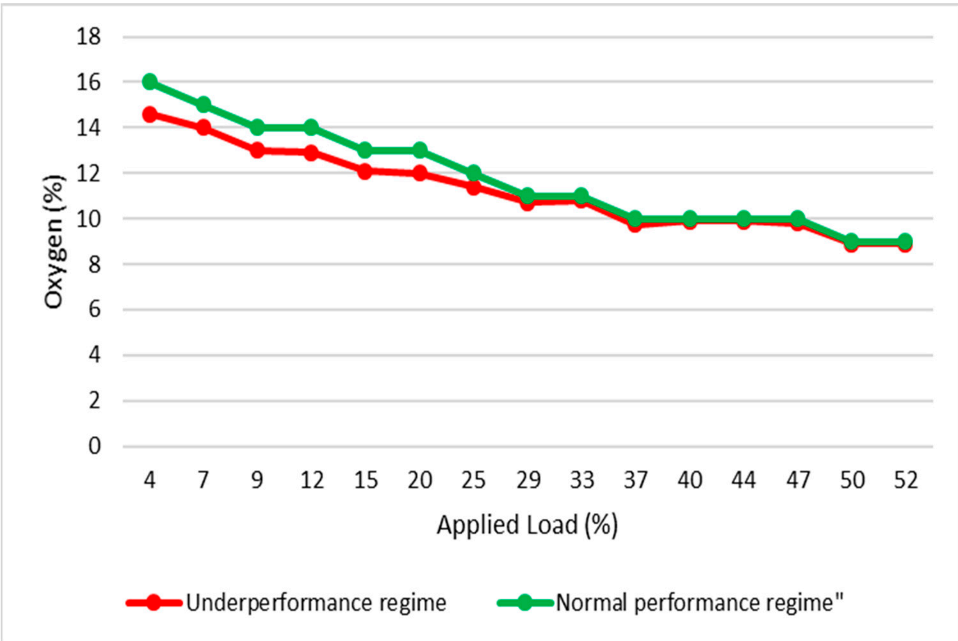


Figure 9. Variation of the O_2 rate according to the applied loads.

5.6. Carbon Monoxide Emissions (CO)

Carbon monoxide, a colorless and odorless gas, appears in exhaust gases when combustion reactions are not fully completed due to low mixing or a shortage of oxygen [51]. Figure 10 indicates the variation of the carbon monoxide at different load conditions. It is found that the CO rate, despite its fluctuation, is significantly higher under a very low load and underperformance regime, and it tends to decrease to a stable level by increasing the load. Lower CO emission results from improved mixing and higher air ratios. Therefore, according to the obtained curve, CO can play a significant role as an underperformance detection method as it tends to stabilize around regular loads (37% and up).

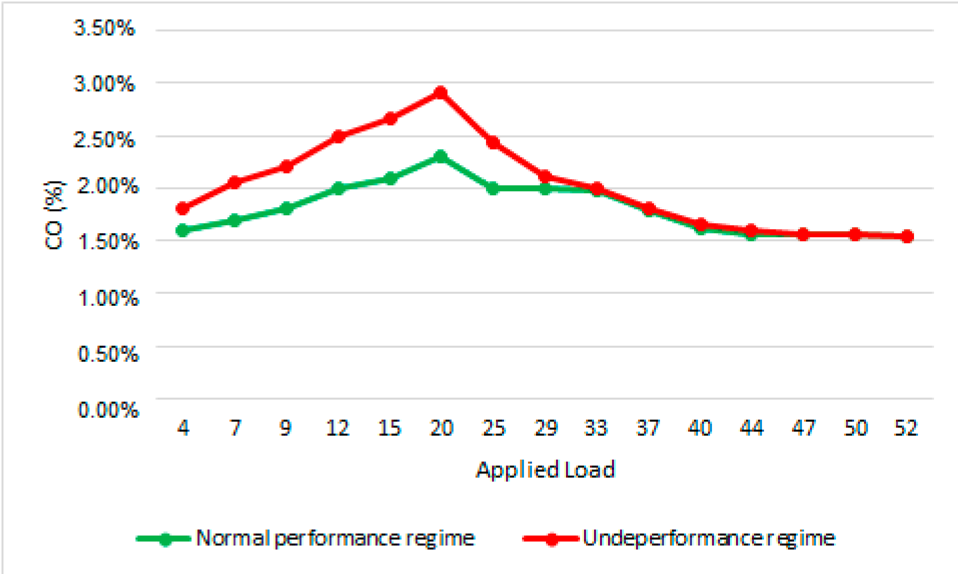


Figure 10. Variation of the CO content in the exhaust gas according to the applied loads.

5.7. Nitrogen Oxide Emissions (NO_x)

The high temperature and pressure of the combustion chamber are the leading causes of nitrogen oxide formation, which are highly harmful environmental emissions. The generation of NO_x increases as temperature and air-to-fuel ratio increase. The various NO_x concentrations in the exhaust gas emission are depicted under various loads in Figure 11. As the load level increases, the temperature in the combustion chamber rises, leading to a proportional increase in NO_x emissions, which tends to level off in regular loads. Furthermore, NO_x tends to increase under an underperformance regime. Therefore, NO_x emissions can be considered an underperformance sign for diesel engines because of stabilizing in regular loads and its higher level at operation under prolonged time low load.

5.8. Carbon Dioxide Emissions (CO_2)

Carbon dioxide is released when the carbon atoms in the fuel are wholly oxidized during combustion. Although it is typically not subject to emission regulations and is not regarded as a dangerous gas, there is a solid requirement to minimize CO_2 emissions because it is a greenhouse gas. The change in CO_2 emissions with the load is shown in Figure 12. We notice a roughly linear increase in CO_2 emissions with the load, and this is under both regimes. Additionally, CO_2 emissions increase further when the generator runs in underperformance mode. This change was observed after one hour of prolonged operation under a light load (<30%). This finding suggests that CO_2 level helps detect underperformance.

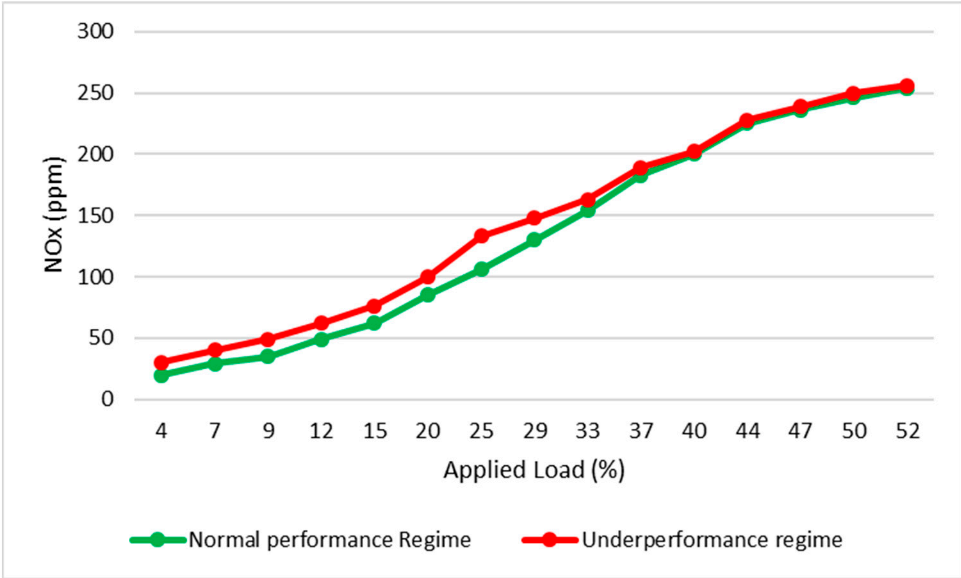


Figure 11. Variation of the NO_x content in the exhaust gas according to the applied loads.

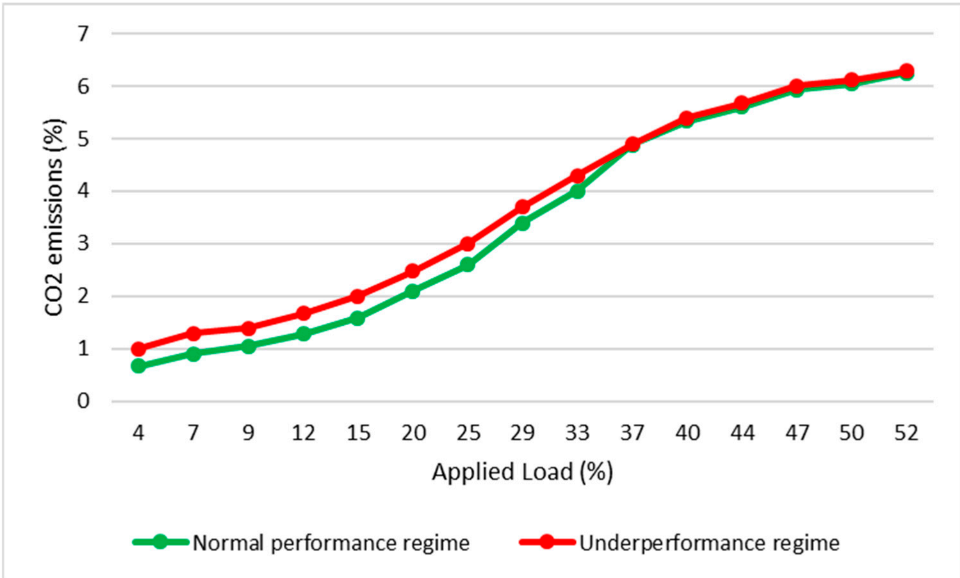


Figure 12. Variation of the CO_2 content in the exhaust gas according to the applied loads.

6. Conclusions

Remote communities are characterized by a strong dependence on imported fuels and by the high cost of energy. As a result, most of these locations supply their energy demand with diesel electrical generators either alone or in hybridization with renewable sources. However, most of these generators are oversized. In addition, because of the characteristics of their hosting power grids, they often tend to underperform for extended hours, which can have numerous negative long-term impacts on the generator.

This experimental study compares the outcomes of tests performed on a 300 kW fixed-speed diesel electric generator for the following charges during a transient regime of 15 min and another of an extended length of two hours:

1. Very low load.
2. Low load.
3. Medium load.

Analysis of the chemical composition, temperature, and fuel consumption of exhaust gases as a function of the applied load is performed to determine the transition time of emissions and identify pertinent signs when the generator is operating in underperformance mode. The test results led us to the following conclusions:

1. According to data analysis, it is found that under a very low load (0–25%), the exhaust gas temperature does not exceed 190 °C for an extended period of operation (up to 2 h), while under a 30% load, the temperature stabilizes at 220 °C; this is true for both regimes (extended period and not extended period). Therefore, it was concluded that the exhaust gas temperature could be used as an index of underperformance operation if prolonged operation time under low load is associated.
2. The BSFC showed an increase when the diesel–electric generator was subjected to a light load (≤30%) for a prolonged duration (up to 2 h) versus a short period (15 min). It recorded a 6.4 gallons/kWh consumption in underperformance operation at 30% of the applied load versus 6.14 gallons/kWh in normal operation. However, the BSFC returns to normal when the load attains 40% and registers 8.5 gallons/kWh. Based on the results obtained, the BSFC can be considered an underperformance index.
3. Analysis of gas emissions such as carbon monoxide and sulfur dioxide emissions have been discarded. This could be explained by the fact that some emission values are similar under low and normal loads.
4. Carbon dioxide emissions, nitrogen oxide emissions, and sulfur showed an increase in their levels when the generator was subjected to low load (≤30%) for a prolonged period (up to two hours) associated with underperformance operation. These gases tend to reach a normal emission level when the applied load increases to 40%. It was found that carbon dioxide emissions increase up to 0.5% under very-low and low loads (0–30%), nitrogen oxide emissions by up to 10 ppm, and sulfur by 2 ppm.
5. Finally, unlike all other gases, oxygen emissions decrease under very-low and low loads by up to 2% before reaching the normal level of emissions under a normal load (40% and above). This allows us to conclude that oxygen can be also considered an underperformance index.

Author Contributions: Conceptualization, M.G.; methodology, A.I. and M.I.; validation, M.I. and A.I.; investigation, M.G., M.I. and A.I.; resources, A.I.; writing—original draft preparation, M.G. and A.I.; writing—review and editing, M.I. and A.I.; supervision, M.I.; project administration, A.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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