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DG optimization for CO2 reduction in islolated grids with rising RES penetration: a simulation study

System Integration & Hybridization

Issam Matragi, Nantes Universite, Ecole Centrale Nantes, CNRS, LHEEA, UMR 6598, F-44000 Nantes, France

Simon Poiret, Nantes Universite, Ecole Centrale Nantes, CNRS, LHEEA, UMR 6598, F-44000 Nantes, France
Simon Le Guen, Nantes Universite, Ecole Centrale Nantes, CNRS, LHEEA, UMR 6598, F-44000 Nantes, France
Xavier Tauzia, Nantes Universite, Ecole Centrale Nantes, CNRS, LHEEA, UMR 6598, F-44000 Nantes, France
Alain Maiboom, Nantes Universite, Ecole Centrale Nantes, CNRS, LHEEA, UMR 6598, F-44000 Nantes, France
Yoann Thevenoux, MAN-ES France
Bruno Moricet, MAN-ES France

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ABSTRACT

Isolated power systems, notably those located on islands or off-grid mining sites, are experiencing an increase in the integration of renewable energy sources (RES) to mitigate CO2 emissions and reduce dependency on fossil fuels. Consequently, the role of diesel gensets (DGs) in these power systems is transitioning from primary energy producers to backup sources, particularly during instances of RES intermittency that may destabilize the system. This shift in operational dynamics highlights the potential necessity for retrofitting thermal engines to align their performance with emerging constraints.

This paper examines the benefits of optimizing the specific fuel consumption curve of a DG in an isolated power grid using a previously developed numerical model, which calculates the total fuel consumption of grid-connected DGs over a year. These optimizations align the DGs' performance with prevailing operational conditions by implementing modifications such as the inclusion of a turbocharger wastegate, adjustments to turbocharger size, and the use of either electronic or conventional fuel injection systems. Additionally, the impact of these engine modifications on turbo lag is discussed. Finally, the paper demonstrates that these specific fuel consumption optimizations positively affect the system's annual fuel consumption under increased RES penetration.

The optimal adaptation of a DG's specific fuel consumption curve depends on the predominant operation of the DG within a specific power system. This study provides a roadmap for achieving fuel reduction while considering grid stability as a constraint, applicable to various operational scenarios. Using the Tahitian power system as a case study, yearly fuel consumption is calculated using the presented numerical model and power demand data obtained from system operators. Various scenarios are compared, and the optimal DG configuration in this application is found to be the addition of a wastegate alongside a smaller turbocharger, accounting for a 3.8% decrease in yearly fuel consumption. This analysis highlights the potential benefits of DG modifications, demonstrating opportunities for improving fuel efficiency within isolated power grids.

1 INTRODUCTION

The transition towards more sustainable energy systems has accelerated the integration of renewable energy sources such as solar photovoltaic into isolated and grid-connected power systems. While renewable energy sources offer significant environmental benefits and reduce dependence on fossil fuels, their variable and intermittent nature poses challenges for maintaining power system stability and efficiency. Diesel generators remain critical in such systems, particularly in isolated grids like Tahiti, where they provide the necessary flexibility and inertia to meet demand and stabilize the grid during sudden fluctuations. However, the evolving energy mix and increasing renewable energy sources penetration necessitate a re-evaluation of diesel gensets operational strategies to improve efficiency and reduce fuel consumption.

A key challenge lies in adapting diesel gensets to the changing load profiles caused by higher renewable energy sources penetration. These profiles often push diesel gensets to operate outside their optimal efficiency range, leading to increased fuel consumption and wear. Additionally, maintaining frequency stability becomes more complex as renewable energy sources displace traditional rotating machines that provide inertia. Addressing these issues requires a combination of dispatch optimization, retrofitting of diesel gensets for better fuel efficiency, and careful consideration of frequency stability during incidents.

With over 50 years of expertise in energy solutions, MAN Energy Solutions is at the forefront of the energy transition and grid decarbonisation, particularly in isolated areas. The company has installed 12.7 GW of capacity across 96 countries, showcasing its reliability and commitment to sustainability. Focusing on innovative technologies, MAN Energy Solutions offers ultra-efficient hybrid power plants, Power-to-X solutions for converting excess electricity into synthetic fuels, and energy storage systems. These technologies ensure stability and reliability for isolated grids while reducing carbon emissions. MAN Energy Solutions collaborates with local and international partners to provide customized, impactful solutions tailored to the unique needs of isolated grids. Through this approach, the company continues to drive the transition to cleaner, more resilient energy systems globally, with this study emerging as a result of MAN Energy Solutions' research-driven partnership with Ecole Centrale de Nantes to address the challenges of evolving power systems.

Diesel engine retrofitting involves modifying existing engines to improve efficiency, reduce emissions, and extend operational life. Common retrofitting measures include dual-fuel conversion [1], installing exhaust gas aftertreatment systems [2], upgrading or tuning turbochargers [3], adding a wastegate [4], and enhancing fuel injection systems for better combustion [5]. These modifications help engines meet stricter environmental regulations, lower fuel consumption, and reduce emissions. Retrofitting is a cost-effective approach, enabling improved performance without the need for complete engine replacement. With proper tuning, diesel gensets can be better adapted to evolving load profiles.

This paper outlines a roadmap for diesel genset retrofitting in a system with increased renewable energy sources (solar photovoltaic + hydroelectricity) penetration, demonstrating its impact on efficiency and fuel consumption.

2 MATERIALS AND METHODS

This section consists of four key components:

1. Case Study: An analysis of the Tahitian electric power system, detailing the rationale behind its selection as the focus of this research.

2. Dispatch and Fuel Consumption Model: A MATLAB-based tool that manages the power dispatch of Diesel Generators (DGs) and calculates fuel consumption over a defined period, based on the selected dispatch strategy. This model operates on a larger time scale, with time-steps ranging from 30 seconds to 1 hour, allowing it to capture long-term dispatch dynamics and overall system efficiency.

3. Frequency Monitoring Model: A Simulink model that assesses the ability of the DGs to respond to sudden load variations, ensuring system stability under dynamic conditions. This model operates on a finer time scale, with time steps ranging from milliseconds to seconds, enabling it to capture transient frequency fluctuations and immediate system responses.

4. 1D Engine Simulation: A GT-Power model of the engine, used to generate updated BSFC (Brake Specific Fuel Consumption) curves, reflecting performance improvements from retrofitting. (To adjust if needed)

These components are integrated into a comprehensive methodology aimed at reducing fuel consumption and CO_2 emissions in a power system with developing Renewable Energy Sources (RES) penetration.

2.1 Case Study

Tahiti's electric grid was chosen as a case study due to its unique characteristics as an isolated power system heavily reliant on diesel generators (DGs) with an increasing share of renewable energy sources. The availability of detailed 10-minute time-step data on power generation, demand, and renewable contributions from 2015 to 2023 allowed for the creation of a realistic numerical model [6]. Collaboration with Electricité De Tahiti (EDT) through MAN ES provided critical insights into the system's hardware, operational strategies, and fuel consumption. Tahiti's grid includes eight DGs of two types, hydroelectric plants with a combined capacity of 47 MW, and 22 MW of distributed solar Photovoltaic (PV), supported by a 15 MW, 10 MWh battery energy storage system providing reserve power in case of an incident. These factors made Tahiti an ideal case to study efficiency improvements and renewable integration in isolated power systems. For the sake of this paper, a simplified version of the Tahitian power grid has been considered. In this version, only one type of DG is available, and the reserve power battery is excluded, as such systems remain uncommon. However, the demand and power distribution profiles for the studied year (2019) remain unchanged.

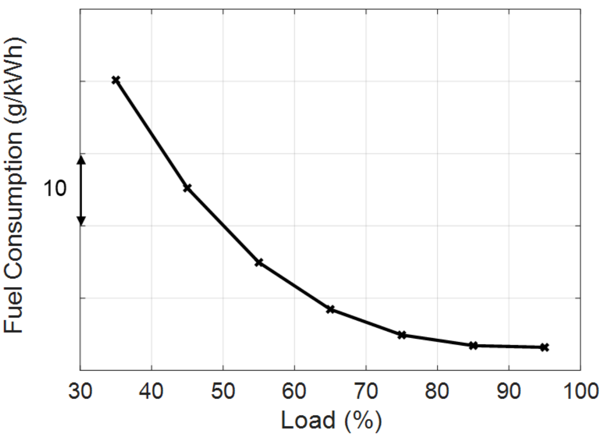

Figure 1. BSFC of used Diesel Engine

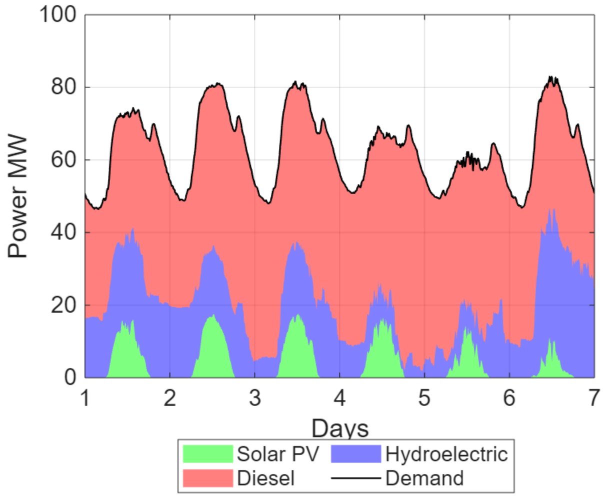

Figure 2. Power distribution between Solar PV, Hydroelectricity, and Diesel over a week with raw data [6]

The chosen diesel engine is rated at 13.7 MW and has a Brake Specific Fuel Consumption (BSFC) curve as illustrated in Figure 1. This BSFC was provided by the engine manufacturer and corresponds to an engine for which a 1D numerical model exists, as will be discussed in section 2.4.

A sample of the available data is shown in Figure 2, presenting the distribution of generated power from all available sources over a week with a 10-minute time-steps.

2.2 Dispatch and Fuel Consumption Model

The Dispatch and Fuel Consumption Model (DFC) is a MATLAB-based algorithm designed to optimize Diesel Generator (DG) dispatch and calculate their fuel consumption in isolated power systems. Operating with 30 seconds to one hour time-steps (here, 10-minute time steps are considered with the data from Tahiti), it works on a large time scale, focusing on the long-term operation and efficiency of the grid rather than short-term dynamics, which are addressed by the frequency monitoring model, presented in section 2.3. By integrating predicted demand and RES profiles, the model ensures balanced and efficient grid operation over extended periods. A quick overview of the model's functionalities is presented in this section, with a more detailed description available in [7].

2.2.1 Inputs

The model requires several inputs, including demand and RES profiles, DG specifications (capacity, BSFC, etc.), and operational strategies. In this study, only one DG type is considered, which eliminates the need for an optimizer to determine which DG to start or stop.

Predicted demand and RES power profiles are modeled using a deterministic approach that mimics real-world prediction behavior. For demand, a random factor of ±3%, adjusted every third time step, is introduced to simulate typical prediction divergences. For solar PV, a ±10% random factor is applied to account for variability caused by environmental conditions. These profiles represent typical predictive inaccuracies from demand ([8], [9]) and solar PV ([10], [11]) forecasting models.

2.2.2 Constraints:

Power Balance: The power balance ensures that electricity demand is consistently met by the combined output of renewable energy sources (RES) and diesel generators (DGs). This guarantees a reliable energy supply while integrating RES.

Spinning Reserve: To maintain grid stability, a spinning reserve equal to the largest DG output is kept available. This reserve acts as a safeguard to compensate for sudden fluctuations or losses in power generation.

Operational Envelope: The operational envelope accounts for various constraints, including minimum and maximum load limits, uptime and downtime requirements, and start-up delays for DGs. In scenarios where RES generation exceeds demand, curtailment is applied to ensure DGs can still operate above their minimum load. Finally, all connected DGs operate at the same load output.

Prediction Horizons: Prediction horizons limit foresight to better reflect real-world conditions. For instance, a 30-minute window is assumed for starting a DG, simulating the practical response times required in grid operations.

2.2.3 Model Limitations

System Stability: While spinning reserve is included, the 10-minute time-step precludes frequency stability analysis, which is handled in the Frequency Monitoring model.

Maintenance Penalty: DG maintenance costs and runtime balancing are not considered in this study but could be easily incorporated in the future with the availability of relevant data.

Warm-Up Penalty: The model excludes pre-heating and warm-up phases, though these could be incorporated with sufficient data.

RES-Only Mode: At least one DG must remain connected, as RES-only operation is beyond the study's scope.

2.2.4 Model Outputs

The model generates comprehensive results, including the total fuel consumption and associated CO_2 emissions, calculated at 3.33 tons of CO_2 per ton of fuel burned (accounting for extraction and transportation emissions). It also provides detailed metrics on diesel generator (DG) performance, such as runtime, cycling frequency, and spinning reserve usage. Additionally, the model produces graphical outputs that illustrate key operational parameters, including load distribution, contributions from RES, and the dispatch patterns of the DGs, offering a clear visualization of system behavior over the simulation period.

From these outputs, this paper focuses on the load distribution of the connected DGs over a year. This analysis helps determine whether the current DG setup and the BSFC are well-suited to the most frequently solicited load outputs.

As illustrated in Figure 3, the DGs operate for the largest share of time (44%) around 65% load output, with 75% load output accounting for 38% of the time. These operating points do not correspond to the most efficient levels based on the BSFC, as the DGs are optimized for maximum efficiency at their maximum load output.

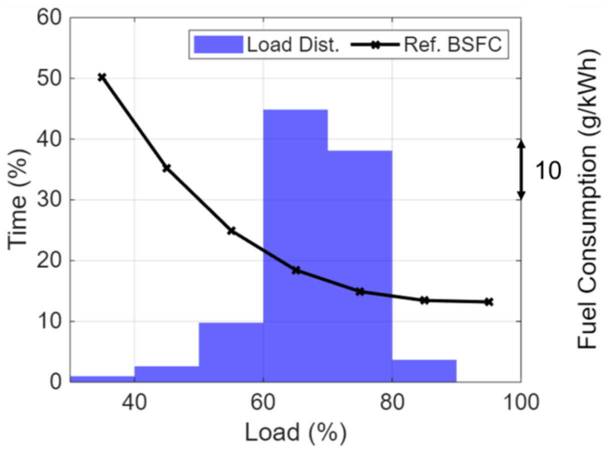

Figure 3. Histogram of the load distribution and the BSFC for the reference simulation over one year (2019)

2.3 Frequency Stability Model

The Frequency Monitoring Model is developed to evaluate the stability of power systems during sudden incidents, focusing on immediate frequency responses and stabilization. Operating on a finer time scale, it captures rapid transient dynamics that occur within milliseconds to seconds, which are critical for assessing system stability. Built in Simulink, the model represents a simplified version of the Tahitian grid, omitting components like transformers, feeders, and reactive power dynamics to prioritize active power and frequency stability. It incorporates hydroelectric plants, solar PV, batteries, and diesel gensets (DGs) with realistic parameters such as inertia constants, droop settings, and load variations. The DG block is enhanced with real-world test bench data, simulating dynamics such as turbo lag through a first-order delay system. This approach enables accurate modeling of performance trends while addressing complexities like engine speed regulation and delayed power outputs.

Despite its strengths, the model exhibits certain limitations, such as smoother responses compared to real-world oscillations, due to simplifications in turbocharger dynamics and fuel system transients.

Time constants for turbo lag, derived from empirical data, highlight significant delays for large power steps, especially from low initial loads, while smaller steps remain manageable.

The inclusion of realistic inertia constants and unique adjustments for each DG used ensures the model reflects operational behavior across various system components. While discrepancies like overshoots are not fully captured, the Frequency Stability model effectively provides a robust framework for analyzing immediate frequency stability and exploring optimization strategies for power system resilience. More detailed description of this model can be found in [12].

While the outputs of this model are not presented in this paper, it is important to highlight that frequency stability must be carefully evaluated when implementing any operational strategy changes in a power system. This consideration is crucial for achieving a more comprehensive understanding of system dynamics and ensuring reliable performance under various conditions.

2.4 1D Engine Simulation

From the forementioned results, it appears that the DG do no operate permanently at the same load but with a load distribution over a year that may change depending on the grid characteristics (such as RES penetration as will be shown later) or DG control strategy as detailed in [7].

To reduce the fuel consumption of the system, modifications could be made to the DG themselves to realign their BSFC curves with their load profile.

To investigate the potential of such modifications, an existing 1D model of the DG is used. In this model, various technical solutions can be tested, combined and refined to obtain BSFC curves more adapted to the new load profiles of the DG.

2.4.1 GT model of the Diesel Generator

The engine used for this study is a medium speed 4 stroke Diesel engine (see Table 1 for main specifications), which is used for naval propulsion and power generation. This study focuses on the power generation version sometimes used as DG in isolated power systems.

Table 1. Engine main specifications

Number of Cylinders [-]	Exists in 12 to 20
Charging System	2 TC in parallel for V versions of the engine (one per bank)
Fuel Injection System	Conventional jerk pump, with constant pump timing and multi hole injector, fed with Diesel fuel

A 1D thermodynamic model of this engine has been built using GT-Power commercial software [13]. It relies on geometrical data for intake and exhaust components and cylinder description, while valves are described with lift profiles and flow coefficients. The turbochargers are modeled using real maps supplied by the manufacturer.

The Main sub models are:

- The predictive DI-pulse for combustion
- Woschni for heat-transfer at the cylinder wall
- Extended Zeldovitch for NOx evaluation
- Linear variation with piston speed for Friction Mean Effective Pressure (FMEP)

The heat transfer model relies on cylinder wall temperatures, which were estimated from some measurements (sometimes interpolated). It was calibrated using in-cylinder pressure measurements to tune a multiplier on the Woschni model in order to minimize heat release during compression (below 2% of fuel energy) and satisfy energy balance during the closed part of the cycle (Unbalance must be less than 5% of the fuel energy).

Rate of injection profiles were provided by an independent hydraulic model of the injection system, which was fully validated against measurements. They were stored in look-up tables, for various rack positions, corresponding to various injected masses. The engine model then interpolates between these profiles.

The combustion model has four main parameters that control air entrainment, ignition delay, premixed and diffusive combustion. They were calibrated using GT's optimization tool, to minimize the Root Mean Square (RMS) error with experimental burn rate inferred from in-cylinder pressure measurements.

The NOx production calibration factor was tuned to match experimental emission at the 100% load point.

FMEP model was calibrated to maximize correlation with FMEP experimental values.

The engine model was used to simulate steady state operating points defined with engine rotation speed and power. While engine RPM was an input parameter of the simulation, a dedicated controller was used to modify the injected fuel quantity in order to achieve the required power.

After careful tuning of model calibration parameters, a comparison was made between simulation results and experimental results. The main parameters studied were pressure and temperature at the most significant locations of the air loop (compressor inlet/outlet, charge air cooler outlet, turbine inlet/outlet), TC rotation speed, engine air mass flow, BSFC and maximum in-cylinder pressure. The discrepancies on most of these parameters were below 5%, the maximum discrepancies being below 10%. This was considered as acceptable, all the more since the purpose of this study was to compare various configurations. Thus, relative evolutions were the main concern, while absolute values were not of primary importance.

Figure 4 and Figure 5 illustrate the overall good agreement between simulation and experiments, displaying the variations of boost pressure and turbine inlet pressure with engine load, as well as compressor outlet, charge air cooler outlet and turbine inlet temperatures.

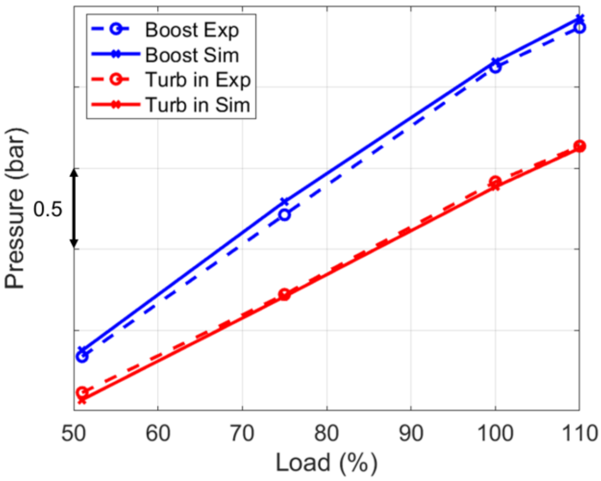

Figure 4. Comparison of experimental and simulated pressures at various engine locations vs. engine load

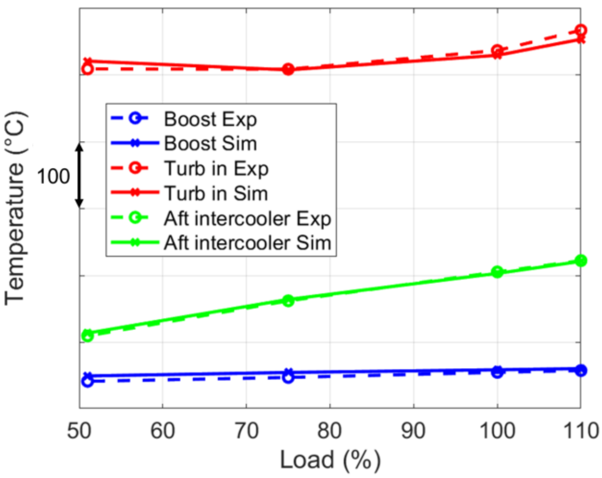

Figure 5. Comparison of experimental and simulated temperatures at various engine locations vs. engine load

2.4.2 Technical modifications

For this study, only retrofit-ready options are considered. This includes tuning parameters - such as changing the mechanical timing of the jerk pumps to modify the Start of Injection (SOI) - as well as replacing ancillaries - such as the TC or the complete injection system.

Two levels of modifications are thus considered to the injection system. The first level is a simple tuning of the engine by changing the static timing of the jerk pumps to modify the SOI over the entire operation of the engine. The base model engine has its SOI tuned to respect the mechanical constraints and pass the NOx emission levels imposed by the regulations. While the mechanical constraints remain identical with every solutions considered in this study, the implementation of a

SCR could allow higher emissions at the tailpipe and directly allow modifications to the SOI. Modifications to the TC system meanwhile could open up some margin regarding the mechanical constraints and encourage a modification of the SOI too. The second level of modifications is the more intrusive implementation of an electronic fuel injection (EFI) system allowing for variations of the SOI with the load applied on the engine. As described by Hlousek et al. [14] and [15], such systems have long been available for this type of medium speed 4-stroke engines. This allows the SOI to be tuned within the constraints for each load case.

In order to re-adjust the BSFC curve of the engine via modifications to the TC system while still being able to provide full power when required and maintaining reliability, a relief system may have to be added alongside the modified TC. In this case, a previous study [16] showed that a wastegate provides an optimal compromise between complexity and efficiency for this type of medium speed 4-stroke DG. It is thus the option selected for this study. This is modeled as a variable section orifice between the turbine inlet and the atmosphere. The TC matching is modified using multiplicative coefficients applied on compressor and turbine mass flow rates to emulate a change in TC size while maintaining similar TC technology: no big difference in TC efficiency is expected from said re-matching.

2.4.3 Optimization for the new load profile

The aforementioned technologies are tested independently or in combination to provide their best performance. Five retrofit options are studied in addition to the reference configuration (See Table 2).

Table 2. Retrofit option tested

Config. #	Turbocharger	Waste-Gate	Injection
Ref.	Ref.	No	Conv.
1	Re-matching	No	Conv.
2	Re-matching	Yes	Conv.
3	Ref.	No	EFI
4	Re-matching	No	EFI
5	Re-matching	Yes	EFI

GT's integrated optimizer is used to find the optimum set of parameters to minimize the weight averaged fuel consumption over the new load profile while respecting the mechanical constraints and the NOx constraint if the SCR is not used.

The algorithm used here is the CMA-ES (short for Covariance Matrix Adaptation Evolution Strategy). It is an evolutionary algorithm recommended for problems having many factors, with the presence of one or more constraints, and non-linear characteristics. The population size varied depending on the amount of variable parameters considered in each model – as per GT's guidelines.

The mechanical constraints considered to maintain the reliability of the engine are the maximum in cylinder pressure (Pcyl max) during the cycle and the maximum turbine inlet temperature (T4 max). The NOx constraint is evaluated as the weighted average of several operating points - as per the regulation. The values chosen for all these constraints are the ones reached by the reference engine model.

Table 3 lists the parameters adjusted to take into account each technology. Certain parameters are identical for all operating points (global parameters) and others can vary point-to-point (independent parameters).

Table 3. Variable parameters for each technology

Technology	Parameters	
TC re-matching	Mass flow multiplier on the turbine (global)	Mass flow multiplier on the compressor (global)
WG	Orifice surface (independent)	/
SOI Tuning	SOI (global)	/
EFI	SOI (independent)	/

3 RESULTS AND DISCUSSION

Figure 6 presents the BSFC curves for all five tested configurations. In all cases, the BSFC curves demonstrate improvements at low and intermediate loads, while at high loads, performance either improves or deteriorates depending on the configuration.

Configuration #2 was tested both with and without a NOx constraint, revealing minimal differences in results (less than 0.5 g/kwh for all operating points between 35 and 95%). This is likely due to the relatively permissive standard considered, which has a limited negative impact on BSFC. Consequently, NOx constraints were excluded from consideration in the other configurations.

The evolution of Peak Firing Pressure (PFP) with load for the various configurations is illustrated in Figure 7.

Turbocharger adjustments, including any re-matching, are summarized in Table 4.

Figure 8 shows the Waste Gate opening area evolution with load for retrofit configurations incorporating this device.

Figure 9 highlights the evolution of Start of Injection (SOI) in Crank Angle Degrees (CA Deg.) with engine load for the different options.

Lastly, Table 5 showcases the annual fuel consumption obtained for each tested retrofit configuration.

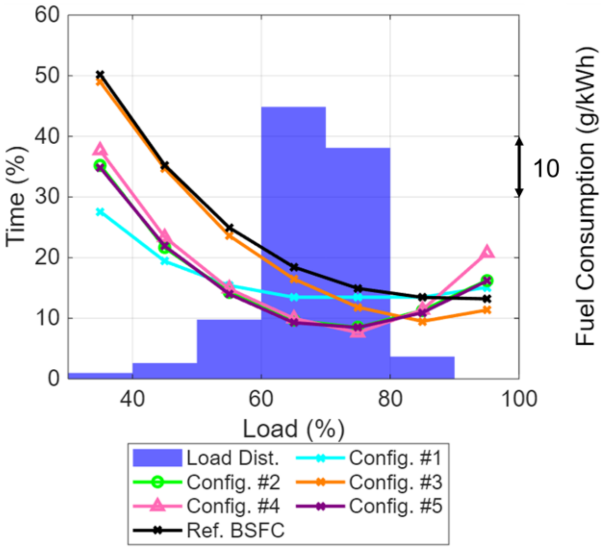

Figure 6. Histogram of the load distribution along with the reference and various retrofit BSFC

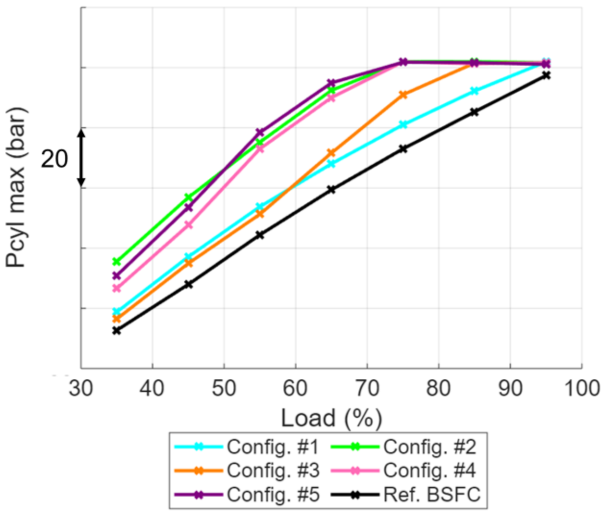

Figure 7. Peak Firing Pressure vs load for various retrofit configurations

Table 4. Turbocharger matching for various retrofit configurations

Config. #	Compressor multiplier	Turbine multiplier
Ref	100	100
1	94	89
2	104	80
3	100	100
4	101	84
5	104	80

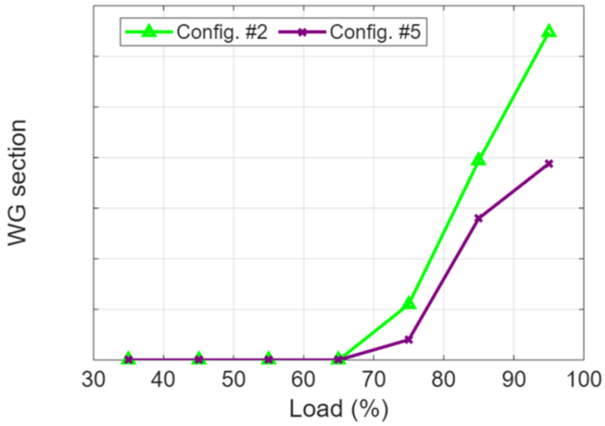

Figure 8. Waste Gate opening vs load for corresponding retrofit configurations

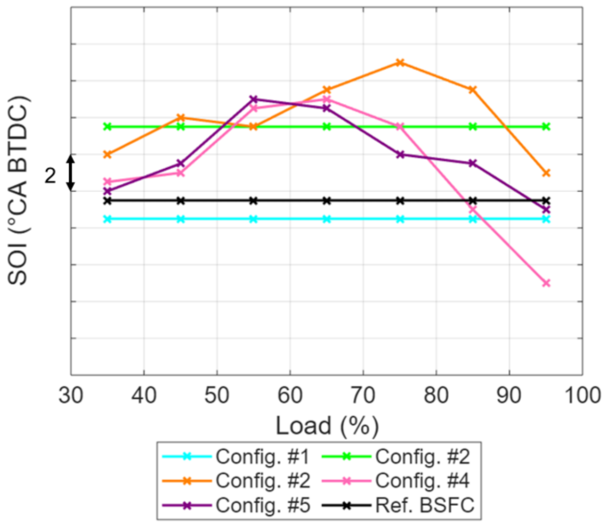

Figure 9. Start of Injection vs load for various retrofit configurations

Table 5. Annual fuel consumption and CO_2 emissions for various retrofit configurations

Config. #	Annual fuel consumption (kt)	Rel. ∆	Annual CO2 emission (kt)
Ref	76.5	0.0%	254.7
1	75.3	-1.6%	250.6
2	73.7	-3.6%	245.4
3	74.8	-2.2%	249.1
4	73.6	-3.8%	245.1
5	73.6	-3.8%	245.1

3.1 Charging system retrofit

The simplest retrofit for the charging system involves turbocharger re-matching (Config #1). In this case, it entails slightly reducing the sizes of the compressor and turbine, with respective flow multipliers of 0.94 and 0.89 (see Table 4). This new turbocharger setup improves BSFC for loads below 85%, which are more frequently encountered according to the load profile, while it results in a slight deterioration at higher loads.

Additionally, the maximum peak firing pressure is reached at 95% load (see Figure 7), indicating that at 100% load—excluded from the load profile used for optimization—the PFP would slightly exceed the limit. However, this could be acceptable if the engine operates at 100% load only on rare occasions. Thus, this retrofit could be interpreted as a slight engine de-rating.

The injection timing of the conventional injection system is slightly delayed by 1 crank angle degree to accommodate the higher boost pressure achieved with the new turbocharger matching (see Figure 9). Compared with the reference engine, Config #1 enables an annual fuel consumption reduction of 1.2 kt (1.6%), while the CO_2 emitted amounts to 250.6 kt, as shown in Table 5.

A more advanced option involves re-matching the turbocharger while implementing a waste gate (Config #2). In this configuration, the turbocharger matching differs from Config #1, featuring a smaller turbine (0.80 multiplier vs. 0.89, as shown in Table 4) and a slightly larger compressor compared to the reference configuration (1.04 multiplier vs. 0.94 without the waste gate). The waste gate (WG) opening is illustrated in Figure 8, showing a progressive opening at high loads to mitigate over-boost and prevent turbocharger over-speeding, which could damage the engine.

Compared to both the reference engine and Config #1, Config #2 demonstrates significantly improved BSFC at low and intermediate loads. However, at loads above 90%, the WG opening leads to efficiency losses as excess exhaust gases bypass the turbocharger. This configuration, however, allows the engine to operate at 100% load without exceeding the PFP limit, provided the WG opens sufficiently.

The injection timing of the conventional injection system is advanced by 4 crank angle degrees (CAdeg) in this setup. This advancement enhances engine efficiency at part loads while managing PFP at high loads with the WG's assistance—an improvement over the reference engine and Config #1. Notably, maximum PFP is reached between 75% and 100% load, with a 25-bar increase at 75% load compared to the reference engine.

Config #2 achieved an annual fuel consumption of 73.7 kt, representing a 3.6% reduction compared to the reference value of 76.5 kt (see Table 5), and more than twice the gain provided by Config #1. 245.4 kt of CO_2 are emitted with this configuration.

At very low loads (not visible in this study), the advantage of a re-matched, smaller turbocharger is minimal because the turbocharger operates less actively and generates limited boost pressure. In this range, the engine relies more on naturally aspirated performance, reducing the impact of turbocharger tuning.

3.2 EFI

Config #3 involves replacing the conventional injection system with Electronic Fuel Injection (EFI), which enables variable injection timing based on load (and speed, though speed variation is not relevant for DG operation). The charging system remains unchanged compared to the reference engine.

This configuration achieves only a slight reduction in BSFC within the 65%-90% load range, with minimal differences observed at lower and higher loads. The limited improvement can be attributed to the already well-optimized injection timing of the conventional system. As illustrated in Figure 9, the maximum timing shift is a 7.5 CA degree advance at 75% load, which corresponds to the maximum BSFC gain. At low loads (below 50%), the EFI system advances injection timing by 2.5-4 CA degrees, but the resulting BSFC gain is minimal, at around 1 g/kWh. At high loads, injection timing is constrained by the PFP limit, further limiting BSFC improvement.

Over the course of a year, Config #3 achieves a fuel consumption reduction of 2.2%, lowering total usage to 74.8 kt compared to the reference system's 76.5 kt, while the CO2 emitted amounts to 249.1 kt.

3.3 Combined

Configurations #4 and #5 combine EFI with charging system retrofits, specifically turbocharger re-matching, with and without a wastegate (WG), respectively. The ability of EFI to optimize injection timing at varying engine loads has a significant impact on the turbocharger matching process.

For Config #4 (EFI + TC re-matching without WG), the use of EFI allows for a smaller turbine (0.84 multiplier vs. 0.89 in Config #1) and a larger compressor (1.01 multiplier vs. 0.94). This configuration suggests a higher boost pressure at high loads, made feasible by the delayed injection timing of 3.5 CA degrees at 95% load compared to Config #1, and 4 degrees compared to the reference engine. Conversely, injection timing is advanced at intermediate loads (55-75%), where EFI enhances efficiency.

This setup achieves the lowest BSFC at 75% load, with a reduction of 7.5 g/kWh compared to the reference engine. However, at lower loads, the BSFC is slightly higher (+1 to 3 g/kWh) than the best WG-equipped solution. At high loads (95%), Config #4 performs the worst due to the significant injection timing retardation required to stay within PFP constraints.

Overall, Config #4 demonstrates notable improvements at intermediate loads but is less effective at extreme load points. It results in a fuel consumption reduction of 73.6 kt/year, representing a 3.8 % improvement compared to the reference engine. CO2 emissions for this configuration is 245.1 kt/year.

When a WG is integrated with EFI in Config #5, the TC matching closely resembles the setup used with conventional injection in Config #2. The BSFC evolution across the load range is nearly identical to Config #2, with discrepancies of less than 1 g/kWh.

The injection timing in Config #5 also aligns closely with that of Config #2, differing by less than 2 CA degrees under most operating conditions. However, at high loads (95%), the PFP constraint is managed differently. In Config #5, the WG opening is slightly reduced, and the injection timing is slightly more retarded compared to Config #2, balancing efficiency and PFP constraints.

As a result, the annual fuel consumption and CO2 emissions for Config #5 is very close to Config #2 and Config #4, demonstrating minimal additional benefits from combining EFI with a WG in this configuration. Detailed yearly fuel consumption values can be found in Table 5.

Finally, the comparison between the various retrofit configurations reveals that:

- Re-matching the turbocharger to align with the load profile can result in a significant reduction in yearly fuel consumption.
- Additional gains are achieved by introducing flexibility with respect to load, either through the variable opening of a WG or the variable injection timing provided by EFI. However, combining the two systems does not yield substantial additional improvements.

It is important to note that these systems may offer other advantages not covered in this study, such as reducing smoke emissions with EFI. A complete evaluation should also account for aspects such as cost and reliability, which are critical for selecting the most suitable configuration.

3.4 Diesel engine retrofitting impact on grid stability

It can be confidently suggested that the modifications will not negatively impact the response time of the DGs and may even result in potential improvements. Figure 10 and Figure 11 illustrate the turbocharger speed and boost pressure, respectively, as functions of the load for both the reference system and Config #5.

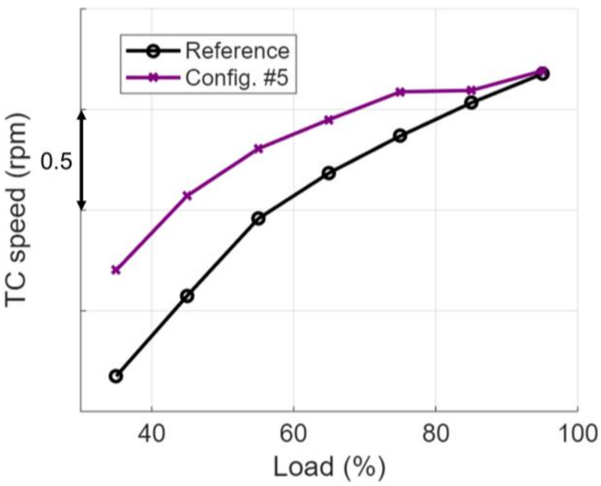

Figure 10. Turbocharger speed in function of the load for the reference and Config. #5

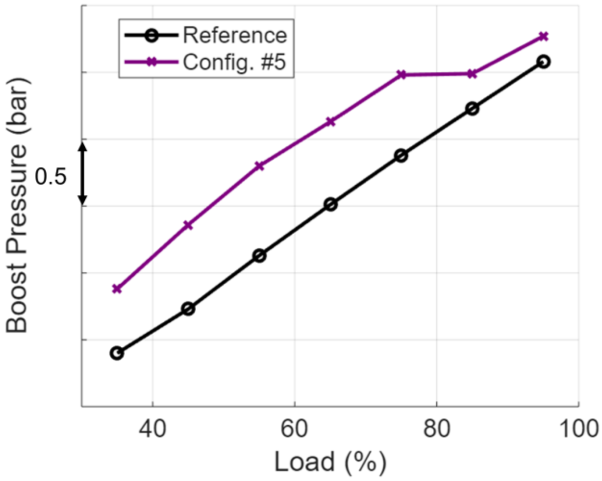

Figure 11. Boost Pressure in function of the load for the reference and Config. #5

At lower to mid-load ranges, the modified system's significant advantage in turbocharger speed and boost pressure highlights improved performance under partial load conditions. This enhancement likely reduces turbo lag and increases engine responsiveness by delivering a higher volume of compressed air to the engine. However, as engine load rises, the turbocharger speeds of both systems converge, and the difference in boost pressure decreases (as the wastegate opening increases). This suggests a diminishing performance gap and reduced responsiveness improvements at higher loads, where both systems approach their operational limits.

3.5 Solar PV Penetration Impact on DG Load Distribution

The optimized BSFC achieved with the combined retrofit discussed in the previous section remains valid for the studied DG load distribution over the selected year. With the rapid evolution of power systems, particularly due to increasing RES penetration, this section aims to quantify the benefits of the combined retrofit in two scenarios: a system without solar PV and a system with three times the current solar PV capacity.

3.5.1 No Solar PV

Using the 2019 data from Tahiti, the solar PV contribution was set to zero. To compensate, the unit commitment algorithm increased the DG power share to maintain power equilibrium. This adjustment caused the load distribution of the DGs to shift to higher values compared to the reference load distribution, as illustrated in Figure 12. It is important to note that both the reference BSFC and Config #5 BSFC remain as previously presented, as the optimization was not re-run to account for the new load distribution.

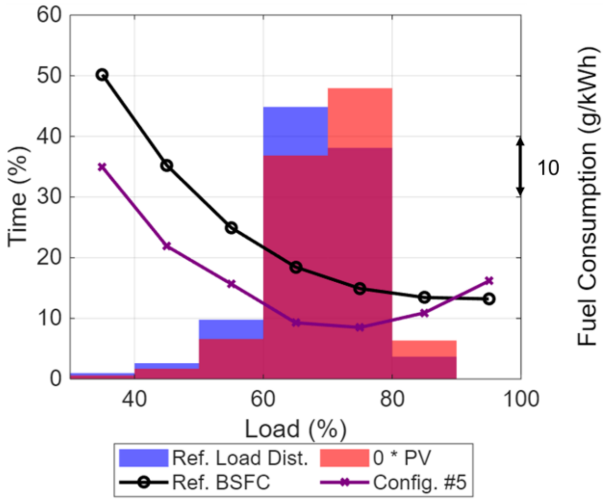

Figure 12 Load distribution comparison between the reference scenario, and one with no solar PV.

3.5.2 Increased solar PV Penetration by a factor of three

To simulate an increase in solar PV penetration, the reference PV power output profile for a year was scaled up by a factor of three. This approach preserves the daily patterns of PV output while increasing their amplitude. With a greater portion of the demand met by solar PV, the DG load distribution over the year shifts toward lower values compared to the reference distribution, as shown in Figure 13. Once again, the BSFC curves for both the reference scenario and the retrofitted DG scenario remain identical to those used in the reference solar PV simulation.

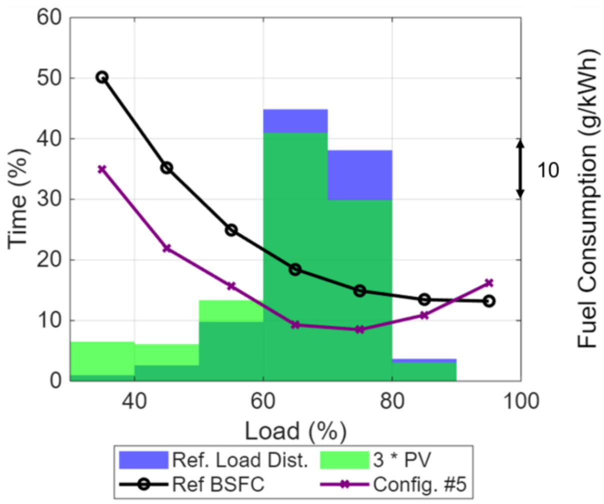

Figure 13 Load distribution comparison between the reference scenario, and one with 3 * PV.

3.5.3 Results

The results from these scenarios are represented in Table 6.

Table 6 Solar PV penetration impact on yearly fuel consumption with optimized and reference BSFC

\	No PV	Ref. PV	3 * PV
Ref. BSFC	84.3 kt	76.5 kt	62.1 kt
Opt. BSFC	81.4 kt	73.6 kt	59.5 kt
Rel. ∆	-3.5 %	-3.9 %	-4.3 %

In the absence of solar PV, fuel consumption is at its highest, with the reference DG consuming 84.3 kt, while the retrofitted DG reduces this to 81.4 kt, achieving a 3.5% relative improvement. With the reference level of solar PV, fuel consumption decreases to 76.5 kt for the reference DG and 73.6 kt for the retrofitted DG, reflecting a 3.9% improvement. At three times the PV penetration, fuel consumption drops significantly to 62.1 kt for the reference DG and 59.5 kt for the retrofitted DG, achieving a 4.3% improvement. These results highlight that increasing solar PV penetration substantially reduces fuel consumption, with the retrofitted DG consistently delivering additional savings. Notably, the benefits of optimization become more pronounced at higher PV penetration levels, as lower DG loads align with the BSFC curve's improved efficiency at reduced loads. This demonstrates the compounding advantage of combining increased PV penetration with DG retrofitting, even though the optimization was based on the reference PV output.

4 CONCLUSION AND FUTURE WORK

This study demonstrates the effectiveness of diesel generator retrofitting as a means to improve operational efficiency and reduce fuel consumption in isolated power systems, particularly in the context of increasing renewable energy source penetration. By combining dispatch optimization with technical retrofitting measures, such as wastegate implementation, turbocharger tuning, and electronic fuel injection, it is possible to realign diesel gensets' performance with the evolving load profiles associated with higher solar photovoltaic integration. These retrofitting strategies reduce specific fuel consumption across critical load ranges and deliver measurable annual fuel savings, with improvements becoming more pronounced as solar photovoltaic penetration increases.

The findings underscore the importance of adapting diesel gensets' operations to future energy landscapes. As renewable energy sources penetration grows, the ability to reduce fuel consumption while maintaining system stability and responsiveness becomes paramount. While this paper focuses on the technical and operational aspects of diesel gensets' retrofitting, future studies should explore the long-term economic and environmental impacts of these upgrades. The results presented herein provide a foundation for further research and practical implementation of retrofitting strategies in similar isolated power systems worldwide.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BSFC: Brake Specific Fuel consumption

DG: Diesel Genset

EDT: Electricité de Tahiti

EFI: Electronic Fuel Injection

FMEP: Friction Mean Effective Pressure

PFP: Peak Firing Pressure

PV: Photovoltaic

RES: Renewable Energy Sources

RMS: Root Mean Square

RPM: Revolution per minute

SCR: Selective Catalytic Reduction

SOI: Start Of Injection

TC: Turbocharger

WG: Wastegate

$P_{cyl}max$: Maximum in-cylinder pressure

T_4max: Turbine inlet temperature

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8 CONTACT

Xavier TAUZIA, Centrale Nantes, xavier.tauzia@€c-nantes.fr

Yoann THEVENOUX, MAN-ES, yoann.thevenoux@man-es.com