

Optimization of Modular Gas Engine Configuration for Landfill Gas Energy Recovery Based on Variable Gas Production Scenarios

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Abstract—This paper presents an extension of previous research on landfill gas (LFG) generation and its utilization for electricity production by introducing an optimization approach for gas engine capacity selection. Based on previously developed mathematical models for methane generation using first-order decomposition methods, the variable nature of landfill gas production over time is considered. A case study based on the Megleni landfill scenarios is used to evaluate different configurations of internal combustion engines for electricity generation. The study compares multiple engine sizing strategies, including single large units and modular multi-engine systems, in terms of load factor, energy efficiency, and total electricity production. A methodology for dynamic operation of engines based on time-dependent gas flow is proposed, enabling improved utilization of available LFG. Results indicate that modular configurations with smaller units provide higher average load factors and increased energy output compared to single large-capacity systems. The proposed approach demonstrates that optimization of engine configuration significantly improves the efficiency and feasibility of landfill gas-to-energy systems, providing practical guidelines for the design of sustainable waste-to-energy facilities.

Keywords—landfill gas, methane, energy recovery, optimization

I. INTRODUCTION

Municipal solid waste disposal in landfills leads to the generation of landfill gas (LFG), primarily composed of methane and carbon dioxide, as a result of anaerobic decomposition processes [1]. Methane is a potent greenhouse gas with a significantly higher global warming potential than carbon dioxide, making its capture and utilization essential from both environmental and energy perspectives. At the same time, LFG represents a valuable renewable energy resource that can be used for electricity and heat generation.

The energy obtained from landfill gas will be negligible compared to the baseload coal energy or the future adaptation of natural gas in the Republic of North Macedonia [2-4]. The energy gains from landfill gas are in the range of benefits of energy efficiency of buildings [5, 6] or for some modernization and optimization of lower-level systems (boilers, turbines, engines...) [7, 8]. Also, an important

challenge is the integration of this system into the power system and its load [9, 10].

Previous studies have demonstrated that the amount of landfill gas produced can be predicted using first-order decomposition models such as LandGEM and other similar approaches [11, 12]. Based on these models, it is possible to estimate the energy potential of methane and assess the feasibility of energy recovery systems. In earlier research, mathematical modeling of landfill gas production in the Pelagonija region was performed, providing a basis for estimating long-term methane generation and its potential utilization for energy purposes [13]. Furthermore, the conversion of landfill gas into electricity using internal combustion engines was analyzed through different operational scenarios, showing that significant energy production can be achieved depending on landfill conditions and waste composition [14].

However, one of the key challenges in landfill gas-to-energy systems is the variability of gas production over time. The flow rate of LFG changes significantly during the operational and post-closure phases of a landfill, which directly affects the performance and efficiency of power generation units. Conventional approaches often rely on fixed-capacity systems, which may operate at partial load conditions, resulting in reduced efficiency and suboptimal energy utilization.

To address this issue, recent studies suggest that modular configurations and optimized engine sizing can significantly improve system performance by adapting to variable gas flow conditions [15, 16]. Proper selection of engine capacity and operational strategy can increase load factors, reduce energy losses, and enhance overall system efficiency.

In this context, the purpose of this paper is to extend previous research by introducing an optimization methodology for selecting the number and capacity of gas engines in landfill gas energy systems [17]. The proposed approach evaluates different configurations under variable gas production scenarios and determines the optimal solution based on load factor and energy output. The results provide practical recommendations for improving the design and operation of landfill gas power plants.

II. LANDFILL GAS AND ENERGY MODEL

Landfill gas generation is commonly described using first-order decomposition models, where methane production depends on waste quantity, composition and degradation rate. These models have been widely applied in practice and are recommended for preliminary assessment of landfill gas potential.

In this study, previously obtained results for landfill gas production are used as input data, where the methane flow rate varies over time according to the landfill operation and post-closure phases [13, 14]. The volumetric flow rate of landfill gas is denoted as Q_{LFG} [m^3/h].

The energy potential of landfill gas [kW] is calculated using:

$$P_{avail}(t) = \eta_{ec} \cdot AHV \cdot \eta_{gc} \cdot Q_{LFG} \quad (1)$$

where:

- η_{ec} – electrical conversion efficiency (0.25–0.35)
- AHV – average heating value ($\approx 4\text{--}6$ kWh/ m^3)
- η_{gc} – gas collection efficiency
- Q_{LFG} – landfill gas flow rate [m^3/h]

This formulation is consistent with commonly used landfill gas-to-energy models.

III. OPTIMIZATION METHODOLOGY

The main challenge in landfill gas energy systems is the mismatch between variable gas production and fixed installed engine capacity. To address this issue, an optimization approach based on load factor analysis is introduced.

A. Engine Configuration

The selection of engine configuration is a key design parameter in landfill gas energy systems. Due to the variability of landfill gas production, fixed-capacity systems may operate at partial load conditions, reducing efficiency.

According to [14], from the three scenarios made according to the capacity of the Meglenci landfill, it follows that it is necessary to install engines with a total power of 600 kW (Fig. 1, 2). Thus, three representative configurations are analyzed:

- Configuration A: Single large engine (1×600 kW)
- Configuration B: Medium modular system (3×200 kW)
- Configuration C: Highly modular system (6×100 kW).

B. Load Factor Analysis

The load factor represents the ratio between available power from landfill gas and installed engine capacity.

$$LF(t) = \frac{P_{avail}(t)}{P_{installed}} \quad (2)$$

For time-averaged analysis:

$$LF_{avg} = \frac{1}{T} \int_0^T \frac{P_{avail}(t)}{P_{installed}} dt \quad (3)$$

For the projection of the future landfill, an average value can be adopted because there is some uncertainty about the future load:

$$LF_{avg} \approx \frac{P_{avg}}{P_{installed}} \quad (4)$$

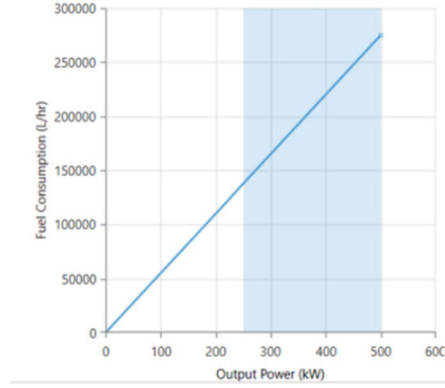


Fig. 1. Output power based on landfill gas production.

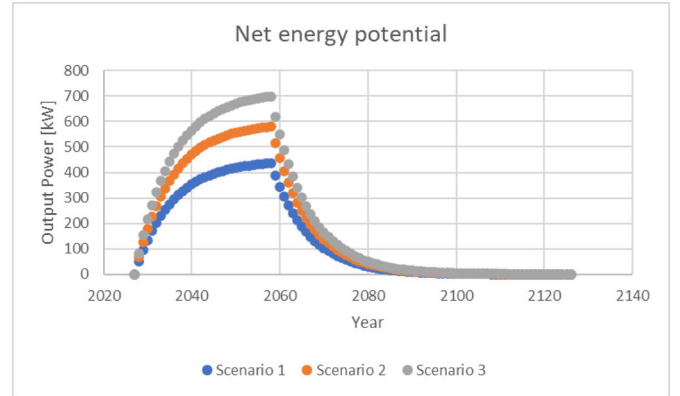


Fig. 2. Net energy potential in Meglenci landfill (Scenario 2 is used as a real waste disposal).

According to the planned capacity of the Meglenci regional landfill, 50,000 tons of waste will be deposited at the landfill annually according to Scenario 2 [14]. Accordingly, an analysis was made of the dynamics of the use of the three configurations A, B and C, obtaining results for the optimal load operating mode (Fig. 3) and annual electricity production (Fig. 4).

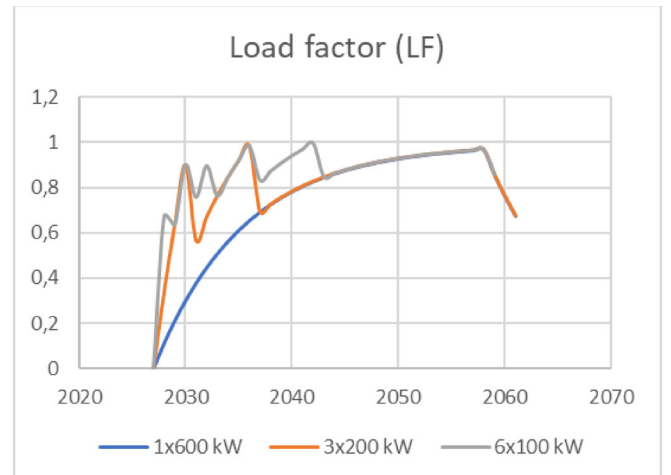


Fig. 3. Load factor for three configurations (A, B, C).

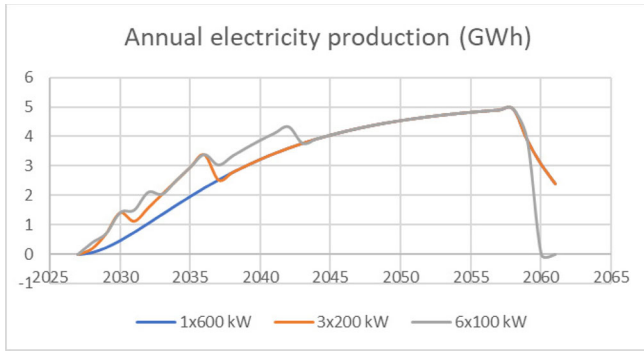


Fig. 4. Annual electricity production for three configurations (A, B, C).

Table I gives the average values for Load factor and Annual electricity production for the three configurations, noting that the configuration with six engines with a capacity of 100 kW gives optimal values.

TABLE I. RESULTS FOR THREE CONFIGURATIONS AS AVERAGE VALUES

Engine configuration	Average Load factor [-]	Average Annual electricity production [GWh]
A (1x600 kW)	0.727	3.151
B (3x200 kW)	0.813	3.335
C (6x100 kW)	0.864	3.480

IV. CONCLUSION

This study demonstrates that optimization of engine capacity plays a crucial role in improving landfill gas energy recovery systems. While conventional approaches rely on fixed-capacity systems, the proposed modular configuration enables better adaptation to time-dependent gas production.

The results indicate that smaller, multiple engine units achieve higher load factors and increased electricity production (0.864) compared to single large-capacity systems (0.727). The proposed methodology can be applied in the design of landfill gas energy plants, contributing to improved efficiency and sustainability.

This solution in such systems has the advantage of a balanced load during operation, in maintenance mode, which is justified from a techno-economic aspect.

REFERENCES

- [1] B. Dimovski, C. Dimitrieska and M. Angeleski, "The Importance of Waste Transport to a Regional Landfill," *Proceedings Ofits*, p.117, 2025.
- [2] B. Dimovski, S. Stavreva, C. Dimitrieska and I. Andreevski, "Proposed Solution for Adaptation of the Block in TPP Bitola using Gas Turbine Combined Cycle," *TEM JOURNAL-Technology, Education, Management, Informatics*, vol. 11, no.1, pp.164-168, 2022.
- [3] B. Dimovski, C. Dimitrieska, S. Stavreva, S. and V. Mijakovski, "Exergy Analysis for Thermoenergetic Blocks Adaptation with a

Combined Gas Cycle," in *20th International Conference on Thermal Science and Engineering of Serbia*, pp. 267-273, Niš, Serbia, 2022.

- [4] P. Popovski, M. Kostov, M. Atanasovski, and G. Veljanovski, "Power Load Forecast for North Macedonia using Machine Learning," *55th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, pp. 106–109, Sep. 2020.
- [5] E. Stefanoska, S. Stavreva, I. Andreevski, V. Angelevska and B. Dimovski, "Impact of Building Envelope Performance Improvements on Heat Loss Reduction: A Comparative Analysis," *60th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, June 2025.
- [6] E. Stefanoska, S. Stavreva, I. Andreevski and B. Dimovski, "Conducting an Energy Audit of a Building," "An Initial Phase in Establishing an Energy Management System," *60th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, June 2025.
- [7] P. Popovski, G. Veljanovski, B. Arapinovski and M. Atanasovski, "Electromagnetic Analysis of Synchronous Generator," *56th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, Sozopol, Bulgaria, 2021, pp. 189-192, DOI: 10.1109/ICEST52640.2021.9483490.
- [8] E. Stefanoska, S. Stavreva and I. Andreevski, "A Systematic Approach to Energy Management in an Industrial Steam Boiler Plant: Improving Energy Efficiency, Economic and Environmental Performance," *Thermal Science*, vol. 29, pp.47-47, 2025.
- [9] P. Popovski, N. Acevski, and M. Kostov, "Grounding System Analysis Using CAD Assisted Software," *59th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, Jul. 2024, DOI: 10.1109/icest62335.2024.10639632.
- [10] G. Veljanovski, P. Popovski, M. Atanasovski and M. Kostov, "Implementation of Neural Networks and Feature Selection for Short Term Load Forecast," *57th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, Ohrid, North Macedonia, 2022, DOI: 10.1109/ICEST55168.2022.9828610.
- [11] A. Alexander, C. E. Burklin, and A. Singleton, "Landfill gas Emissions Model (LandGEM) Version 3.02 user's Guide," *US Environmental Protection Agency, Office of Research and Development*, 2005.
- [12] N.J. Themelis, P.A. Ulloa, "Methane Generation in Landfills," *Renewable energy*, vol. 32, no. 7, pp. 1243-1257, 2007.
- [13] B. Dimovski, C. Dimitrieska, S. Calamani and G. Janevska, "Mathematical Model for Assessment of Production and Energy Utilization of Landfill Gas in the Pelagonija Region in Republic of N. Macedonia," *58th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, pp. 202-204, Serbia, June 2023.
- [14] B. Dimovski, C. Dimitrieska, S. Calamani and E. Stefanoska, "Utilization of Landfill Gas For Electricity Production," *60th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, June 2025.
- [15] M. Humer and P.P. Lechner, "Alternative Approach to the Elimination of Greenhouse gases from old Landfills," *Waste Management and research*, vol. 17, no. 6, pp.443-452, 1999.
- [16] Q. Xue, and L. Liu, "Study on Optimizing Evaluation and Recovery Efficiency for Landfill gas Energy Collection," *Environmental Progress & Sustainable Energy*, vol. 33, no. 3, pp.972-977, 2014.
- [17] B. Dimovski, V. Mitrevski, V. Mijakovski and C. Dimitrieska, "Optimal System for Collecting Landfill Gas: Landfill Meglenci, Republic of North Macedonia," *21st International Conference on Thermal Science and Engineering of Serbia*, 2024.