LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2025, N 6

DOI: 10.2478/lpts-2025-0045

INNOVATIVE LANDFILL GAS TREATMENT SYSTEM IN LATVIA: EVALUATION OF A FULL-SCALE PURIFICATION PROTOTYPE

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Landfill gas (LFG), a by-product of anaerobic waste decomposition, represents both an environmental liability and a renewable energy resource. This study presents the development and performance evaluation of a prototype LFG purification system installed at a major landfill in the Baltic region – Landfill A. The system integrates desulphurisation, cooling and drying, siloxane separation, and activated carbon filtration to ensure high-quality fuel gas for energy recovery. Gas quality was monitored at five treatment points to determine purification efficiency. The results demonstrated stable methane concentrations (55.8–56.6 %) throughout all stages, confirming minimal energy loss. Hydrogen sulfide levels decreased by more than 97 %, from 1930 mg/m³ to below 40 mg/m³, while ammonia was reduced by >99 %. Siloxane compounds, a major cause of engine damage, were almost completely removed (>99.8 % reduction). Volatile organic compounds decreased by ~89 % overall, with final concentrations of ~65 mg/m³. The prototype achieved its design flow of 1500 m³/h, supplying three CHP units with 2.8 MW of instantaneous electrical output. These findings confirm the system's effectiveness, modularity, and applicability for broader deployment in EU waste-to-energy facilities. The technology enables cost-efficient energy recovery, compliance with EU environmental standards, and the potential future upgrading of LFG to biomethane for injection into natural gas grids or use as transport fuel.

Keywords: *Biogas, desulphurisation, gas purification, landfill gas, siloxane removal, waste recycling.*

1. INTRODUCTION

Landfill gas (LFG) is generated through the anaerobic degradation of municipal solid waste and is primarily composed of methane (CH_4), carbon dioxide (CO_2), and trace amounts of volatile organic compounds (VOCs), hydrogen sulfide (H_2S), siloxanes, and other contaminants [1]–[3].

In the European Union (EU), the management and utilisation of LFG have received increasing attention due to climate change mitigation targets, renewable energy policies, and environmental protection frameworks [4]. The composition of untreated LFG typically consists of 45–55 % CH_4, 35–45 % CO_2, and minor fractions of nitrogen, oxygen, and contaminants. Direct flaring of untreated LFG has historically been applied to minimise greenhouse gas (GHG) emissions, but this practice is considered inefficient compared to energy recovery strategies. Consequently, purification and upgrading of LFG into usable forms of energy have become key technological pathways [5], [6].

The purification of LFG usually involves several stages [7]. Desulphurisation techniques, such as activated carbon adsorption or biological scrubbers, are employed to eliminate H_2S, which is corrosive and toxic. Siloxanes, originating from disposed cosmetics and personal care products, are removed through adsorption processes to prevent turbine and engine damage [8]. Moisture removal is commonly performed using condensation and drying units, as water vapour interferes with combustion efficiency and pipeline transport. CO_2 separation is the critical step in LFG upgrading, allowing for the concentration of CH_4 to levels above 95 % for biomethane production. Methods employed include pressure swing adsorption, membrane separation, water scrubbing, and chemical absorption using amines [9].

Once purified, LFG can be utilised in several forms. Electricity and heat generation through combined heat and power units (CHPs) remain the most widespread option across the EU member states [10]. In parallel, the upgrading of LFG to biomethane suitable for injection into the natural gas grid has gained traction, particularly in countries such as Germany, Sweden, and the Netherlands [11]. Biomethane can also be compressed or liquefied for use as a renewable transport fuel, contributing to the EU decarbonisation strategies in the mobility sector [12], [13].

The regulatory framework in the EU provides strong incentives for LFG recovery and utilisation [14]. The Renewable Energy Directive recognises biomethane as a renewable energy carrier eligible for support schemes [15]. The Landfill Directive 1999/31/EC obliges the member states to minimise biodegradable waste disposal, indirectly reducing future gas generation but also emphasising efficient utilisation of existing emissions [16].

As mentioned above, LFG, which is produced in municipal and industrial wastewater treatment plants, as well as in landfills, contains H_2S, which must be removed to prevent corrosion of equipment such as gas engines, boilers, and pipelines. Sulphur removal is a mandatory requirement when LFG is to be upgraded to natural gas quality and fed into the grid [17]. The principle of operation of a desulphurisation system consists of several purification stages that allow for the separation of sulphur from H_2S. The complete system consists of the main units and auxiliary devices, each of which performs a specific task.

Innovative prototype of LFG purification system with purification capacity of 1500 m^3/h has been developed for needs of Landfill A – the biggest and the most versatile in the Baltic States [18], which handles 22 % of all waste generated in Latvia and processes more than 50 % of unsorted municipal waste and over 70 % of biodegradable waste. Its infrastructure includes reclaimed landfill zones, operational waste disposal cells, a bioreactor, and waste processing and administrative facilities, all situated on nearly 90 hectares. Established in the 1970s, it has undergone extensive modernisation since the 1990s to comply with EU environmental standards, particularly following Latvia's accession to the EU. Today, Landfill A is often highlighted as a best-practice model for sustainable landfill management in Eastern Europe.

The complex manages municipal solid waste generated in Riga and surrounding municipalities. A significant share of its operations is devoted to LFG capture and utilisation, leachate treatment, and the gradual transition toward a circular economy-based waste treatment system.

LFG management at Landfill A is particularly noteworthy. As organic waste undergoes anaerobic decomposition, methane-rich gas is captured through an engineered system of wells and pipes. The gas is purified to remove contaminants such as H_2S, water vapour, and siloxanes. Subsequently, it is used in CHP units to generate electricity and thermal energy. The electricity is supplied to the grid, while the heat is used both on-site and in innovative applications such as greenhouse horticulture. From environmental perspective, the Landfill A complex demonstrates the viability of transforming a landfill into a resource recovery hub [19].

The primary goal of this study is to design, implement, and evaluate a prototype LFG purification system capable of delivering high-quality fuel gas suitable for energy recovery in CHP units and future biomethane upgrading. By focusing on H_2S, ammonia, siloxanes, and VOCs, the system aims to address the most critical contaminants that compromise equipment performance, efficiency, and environmental compliance.

The hypothesis of the study is that a modular, multi-stage LFG purification system integrating desulphurisation, cooling and drying, siloxane separation, and activated carbon filtration can achieve more than 95 % removal efficiency for targeted contaminants without significant CH_4 loss, thus ensuring both energy yield and compliance with the EU renewable energy ambitions.

Research questions guiding the study include:

- How does each stage of the prototype contribute to the removal of specific contaminants?
- What is the overall purification efficiency across the chain for hydrogen sulfide, siloxanes, and VOCs?
- Does purified gas meet the quality requirements for continuous CHP operation and potential biomethane production?
- What are the operational constraints and integration challenges when deploying the system in a large-scale landfill setting?

Limitations of the study arise from the site-specific conditions of the selected landfill, including waste composition, seasonal variations in gas yield, and infrastructure constraints. The prototype has been tested under defined operating conditions (nominal flow 1500 m^3/h), and while the results provide strong evidence of scalability, further long-term monitoring is required to assess durability, cost-effectiveness, and performance under fluctuating gas quality. Laboratory analysis has been conducted on representative samples; however, real-time monitoring data may exhibit variability not captured in this study.

The methodological background integrates established gas purification technologies into a single modular system [20]. Desulphurisation has been carried out using scrubbing towers with chemical oxidation, moisture reduction has been achieved through a cooling and drying unit, siloxane removal is based on adsorption media with regeneration capability, and final polishing is ensured by activated carbon filtration. Gas composition has been analysed at five points in the chain, with parameters such as CH_4, CO_2, O_2, N_2, H_2S, NH_3, VOCs, and total silicon compounds measured to evaluate stage-by-stage performance.

The novelty of the research lies in the integration of multiple purification steps into a compact, high-capacity prototype specifically tailored to LFG characteristics in the Baltic region. Unlike stand-alone purification systems, the proposed chain demonstrates synergistic removal efficiency, ensuring CH_4 stability while reducing all major contaminants to near-zero levels. The modularity of the system allows for flexible deployment, adaptation to diverse landfill conditions, and potential extension to other biogas sources. This study contributes to the advancement of waste-to-energy technologies by demonstrating a practical, scalable, and EU-compliant solution that not only mitigates GHG emissions but also valorises LFG as a renewable energy carrier for electricity, heat, and future biomethane applications.

2. MATERIALS AND METHODS

The prototype of LFG purification system at Landfill A combines desulphurisation, siloxane separation, and activated carbon filter technology. Desulphurisation technology performs the separation of H_2S from LFG, siloxane separation technology performs the adsorption of siloxanes and volatile organic compounds, while the activated carbon filter provides final purification (polishing).

The block diagram (Fig. 1) of a prototype LFG purification plant illustrates the sequential technological processes designed to purify LFG from pollutants and prepare it for further use in energy production or other useful purposes. Figure 2 shows the principle technological scheme of a prototype LFG purification system.

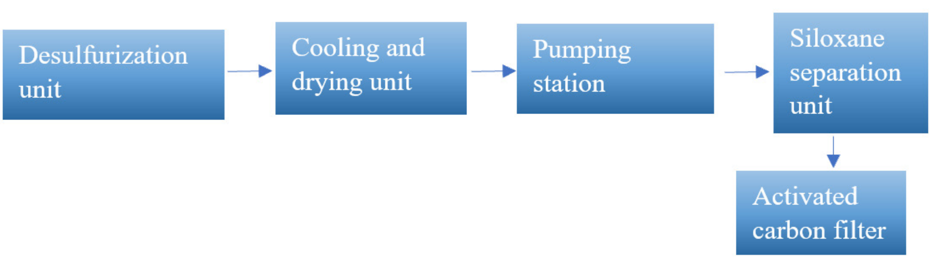


Fig. 1. Visualisation of sequential technological processes designed for LFG purification.

Figure 2 also illustrates the sequential technological processes designed to purify LFG from pollutants and prepare it for further use in energy production or other useful purposes.

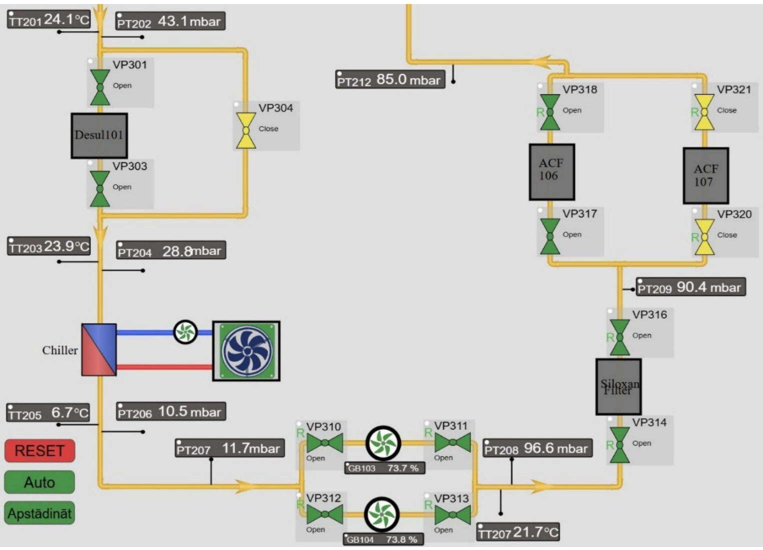


Fig. 2. The principle technological scheme of a prototype LFG purification system.

As shown in Fig. 1, the system consists of five principal technological elements arranged in sequential stages. The first element is the desulphurisation stage, consisting of polypropylene scrubbing towers and oxidation tanks. This unit employs chemical scrubbing with controlled reagent dosing to oxidize and remove H_2S from the raw gas stream. Removal efficiency exceeds 95 %, reducing H_2S from thousands of ppm to levels below 40 mg/m³, thus preventing corrosion and catalyst poisoning in engines.

Desulphurisation unit (see Fig. 3) with a working parameter summarised in Table 1 has been chosen for the project. This unit removes sulphur compounds, such as H_2S from the gas, which is an essential step to prevent equipment corrosion and improve LFG quality.

Fig. 3. Desulphurisation unit.

Table 1. Desulphurisation Unit Parameters

Parameter	Value
Nominal gas flow	1500 Nm^3/h
H_2S removal efficiency	95 %
Maximal gas temperature	60 °C
Maximal gas pressure	50 mbar
Scrubbing towers, 2 items	
Material	Polypropylene
Dimensions	d-2.4m x h-7.4m each
Anti-sweat device	Cell type, Polypropylene
Recirculation pump	3 P=7.00 kW, each
Equipment	- Multi-level, anti-clogging, removable spray nozzles - Cleaning solution distribution pipes - Inspection hatches - Level sensor - Bottom drain system - Gas sampling point - Connecting pipes
Oxidation tank, 2 items	
Material	Polypropylene
Dimensions, for 2 items	1.90m(p) x 2.20m(a) x 8.00m(g)
Air blowers	1 P=3.00 kW
Air diffuser	bubble disc type, polypropylene
Equipment	- Level sensor - pH/Redox sensor - Dosing pumps - Automatic water preparation and replenishment system - Bottom drain system - Reagent dosing pump - Connecting pipes
Sedimentation tank, 1 item	
Material	Fiberglass
Dimensions	d-2.5m x h-5.0m
Filling pump	1 gab, P=0.3 kW
Equipment	- Automatically controlled sediment release valve - Overflow control device

The second element lowers gas temperature to approximately +5 °C and condenses water vapour. Moisture removal prevents condensation in pipelines, enhances downstream purification efficiency, and stabilises gas properties. The cooling system is chiller-based, with 102 kW cooling capacity, supported by circulation pumps and condensate separation mechanisms. During the prototype development, a cooling and drying unit (see Fig. 4) with the parameters shown in Table 2 has been selected.

Fig. 4. Cooling and drying unit.

Table 2. Cooling and Drying Unit Parameters

Parameter	**Value**
Type	Pipe
Nominal gas flow	1500 Nm^3/h
Gas inflow temperature	5 °C
Relative moisture (inflow)	100 %
Relative moisture (outflow)	100 %
Minimal gas pressure	-500 mbar
Maximal gas pressure	500 mbar
Gas pipe connection	DN250 PN10
Cooling power, with outdoor air temperature +35 °C	102 kW
Electric power	40 kW
Dimensions	7700x2300x3000 mm
Location	Mounted on the frame

The third element is a multistage pumping system that ensures steady gas flow and compensates for pressure losses caused by purification. Equipped with sensors, compensators, and control systems, it maintains a stable flow of 1500 m^3/h at pressures suitable for further treatment. Redundancy is ensured through two parallel pumps. Gas is directed through a pumping station (see Fig. 5), which ensures a steady gas flow and pressure maintenance throughout the purification process.

Fig. 5. Pumping station.

The pumping station is a critical stage in maintaining optimal conditions for gas transfer and purification. During the prototype development, a pumping station with the parameters specified in Table 3 has been selected.

Table 3. Pumping Station Parameters

Parameter	**Value**
Type	Multistage
Location	Outdoors
Number of pumps	2
Nominal gas flow	1500 Nm^3/h, each pump
Gas inflow temperature	70 °C
Gas outflow temperature	120 °C
Gas outflow pressure	175 mbar
Minimal working pressure	-30 mbar
Maximal working pressure	1000 mbar
Gas pipeline connection	DN150 PN6
Electric power	18.5 kW
Dimensions	1370x420x160mm, each pump
Equipment	- compensators - pressure sensors - temperature sensors - pressure gauges - thermometers

The fourth element consists of adsorption tanks filled with specialised media designed to capture siloxanes and volatile organic compounds. Operating with >95 % efficiency, this stage eliminates compounds that would otherwise form abrasive silica deposits during combustion. Regeneration fan and heater allow for a cyclic operation of parallel tanks, ensuring continuity. Siloxane removal unit (see Fig. 6). Siloxanes are VOCs that can cause deposits and damage to equipment components such as engines and catalytic converters. Their removal is important to ensure efficient gas utilisation. During prototype development, a siloxane separation device with the parameters shown in Table 4 has been selected.

Fig. 6. Siloxane removal unit.

Table 4. Siloxane Removal Unit Parameters

Parameters	**Value**
Siloxane removal unit	
Nominal gas flow	1500 Nm^3/h
Siloxane removal efficiency	95 %
Type	On the frame
Location	Outdoors
Pressure losses	20 mbar
Maximal temperature	60 °C
Maximal gas pressure	500 mbar
Equipment	- Regeneration fan - Regeneration heater - Gas flow switch - Pressure sensors - Temperature sensors - CH_4 sensors - Pressure gauges

Prefilter	
Constructive requirements	Stainless steel AISI 304
Degree of filtration	5 microns
Filter efficiency	90 %
Filter pressure losses	5 mbar
Equipment	- easy-to-open filter cover - inlet/outlet flanges PN10 - differential pressure gauge for determining the level of contamination
Postfilter	
Constructive requirements	Stainless steel AISI 304
Degree of filtration	5 microns
Filter efficiency	90 %
Filter pressure losses	5 mbar
Equipment	- easy-to-open filter cover - inlet/outlet flanges PN10 - differential pressure gauge for determining the level of contamination

The final purification stage employs stainless steel tanks filled with activated carbon to remove residual contaminants, including VOCs and trace H_2S. This polishing stage reduces pollutants to near-zero concentrations, providing high-quality gas for CHP units or biomethane upgrading. Together, these five elements form a modular, compact system installed within 200 m², capable of delivering clean, stable, and EU-compliant LFG for energy generation. Activated carbon filter is illustrated in Fig. 7. This filter effectively removes residual pollutants such as VOCs to ensure the highest quality biogas. Activated carbon filters with the parameters specified in Table 5 have been selected during prototype development.

Fig. 7. Activated carbon filter.

Table 5. Activated Carbon Filters with the Parameters

Parameter	Value
Type	Tank
Number of filters	2
Tank material	AISI304
Maximum working pressure	500 mbar
Pipe connection	DN200 PN10
Nominal gas flow	1500 Nm^3/h
Tank volume	$5m^3$, each
Equipment	Loading through the top Emptying through the side

There are also several auxiliary equipment items used in the system: a gas analyzer, pipeline installations, valve kit, as well as biofilter.

Fig. 8. Auxiliary equipment items: A gas analyzer (see Fig. 8A), pipeline installations (see Fig. 8B), valve kit (see Fig. 8C), as well as biofilter (see Fig. 8D).

LFG purification prototype is compact and is installed in an area of 200 m^2, which ensures the possibility of installing it in almost any potential facility.

3. RESULTS

To determine the efficiency of the prototype LFG purification system, LFG analyses have been performed at the certified laboratory "SGS INSTITUT FRESENIUS" GmbH, Germany. The quality of the LFG gas has been measured at 5 points:

- PT-202 – untreated LFG;
- PT-204 – after the desulphurisation unit;
- PT-206 – after the cooling and drying unit;
- PT-209 – after the siloxane separation unit;
- PT-212 – after the activated carbon filter.

A summary of the analysis results is shown in Table 6.

Table 6. Results of the LFG Quality Monitoring in Points PT-202, PT-204, PT-206, PT-209, and PT-212

	CH_4, %	CO_2, %	O_2, %	N_2, %	Ammonia, mg/m^3	H_2S, mg/m^3	H_2S, ppm	Sum silicon compounds, mg/m^3	Sum silicon, mg/m^3	VOC, mg/m^3
PT-202 – raw (untreated) gas	55.8	41.9	0.5	1.8	23.2	1930	1287	122	44.3	582
PT-204 – after desulphurisation	56.5	41.1	0.5	1.9		31	21	120	44	648
PT-206 – after cooling and drying						31	21	116	42.5	449
PT-209 – after siloxane separation	56.6	41.2	0.4	1.7		31	21	0.2	0.1	72
PT-212 – after activated carbon filtration	56.6	41.2	0.4	1.7	0.2	39	26	0	0	65

The analysis reveals clear trends in contaminant removal efficiency, stability of the main combustible fraction (CH_4), and the overall suitability of the gas for energy recovery.

As shown in Table 6 and Fig. 9, CH_4 concentration remains stable throughout purification, ranging from 55.8 % in raw gas to 56.6 % after final treatment. This indicates that the purification chain effectively removes impurities without methane loss, thus maintaining calorific value. Similarly, CO_2 concentration is relatively constant (41.1–41.9 %), showing that CO_2 is not targeted by the current treatment steps, as the focus is on harmful trace components rather than full biomethane upgrading.

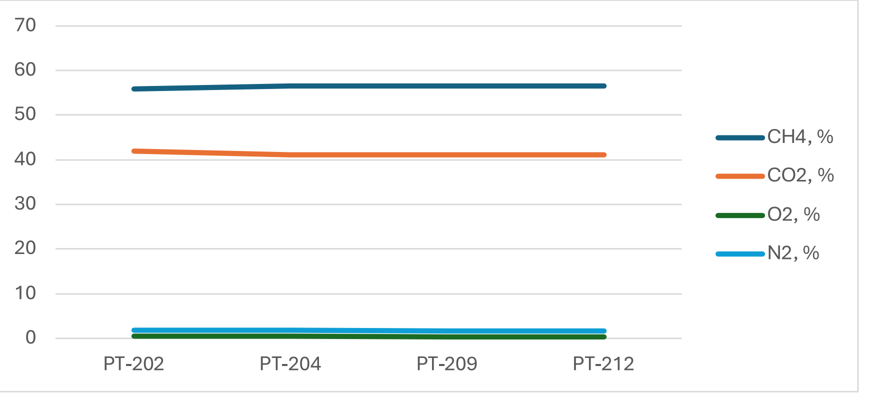


Fig. 9. Stability of the main combustible fractions.

O_2 and N_2 contents remain low and stable (O_2: 0.4–0.5 %; N_2: 1.7–1.9 %), confirming the anaerobic integrity of the landfill system and minimal dilution with atmospheric air. These values are acceptable for combustion applications and indicate that leaks or intrusion of air into the gas collection system are limited.

H_2S shows a dramatic reduction. From an initial concentration of 1930 mg/m³ (1287 ppm), it drops to 31 mg/m³ (21 ppm) immediately after desulphurisation and remains at similar levels through subsequent stages. A slight increase to 39 mg/m³ (26 ppm) after activated carbon is likely due to analytical variability or partial desorption phenomena, but overall removal efficiency exceeds 97 %. This is critical, as H_2S is corrosive and toxic, and its removal is essential for engine protection and emission compliance.

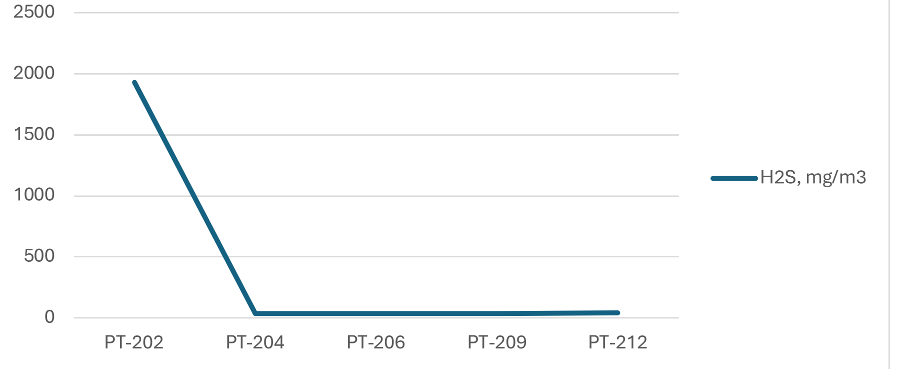


Fig. 10. H_2S reduction curve.

NH_3 decreases from 23.2 mg/m³ in raw gas to 0.2 mg/m³ in the final stage, representing >99 % removal efficiency. This is important since NH_3 can contribute to catalyst poisoning and formation of secondary pollutants during combustion.

Siloxanes are effectively eliminated. The total silicon compound concentration decreases from 122 mg/m³ (44.3 mg/m³ as elemental silicon) in raw gas to 0.2 mg/m³ (0.1 mg/m³ as Si) after siloxane separation, and finally to non-detectable levels at the activated carbon stage.

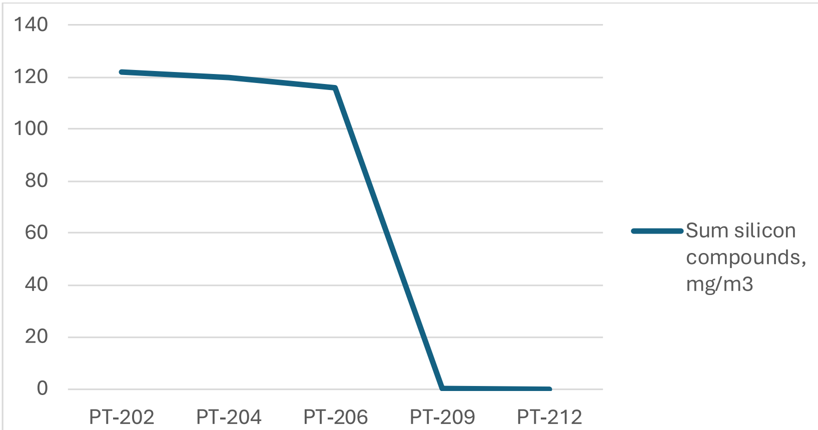
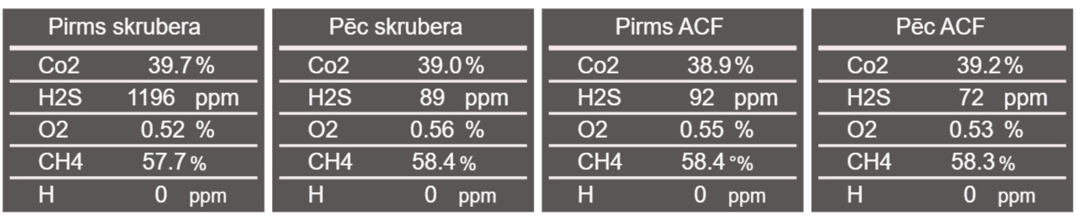


Fig. 11. The total silicon compound concentration decreases curve.

Given that siloxanes form abrasive silica deposits upon combustion, their near-total removal demonstrates the robustness of the purification system.

VOCs also decrease significantly. From 582 mg/m³ in raw gas, levels rise to 648 mg/m³ after desulphurisation (a slight anomaly likely due to adsorption–desorption dynamics) but then decline steadily to 72 mg/m³ after siloxane separation and 65 mg/m³ after activated carbon. This represents an overall >88 % reduction. The removal of VOCs is critical for improving combustion quality and minimising toxic emissions.

Figure 12 shows information on the quality of the LFG being treated and the overall performance of the system, which is continuously monitored.



	Pirms skrubera	Pēc skrubera	Pirms ACF	Pēc ACF
Co2	39.7 %	39.0 %	38.9 %	39.2 %
H2S	1196 ppm	89 ppm	92 ppm	72 ppm
O2	0.52 %	0.56 %	0.55 %	0.53 %
CH4	57.7 %	58.4 %	58.4 %	58.3 %
H	0 ppm	0 ppm	0 ppm	0 ppm

Fig. 12. Quality of LFG and the overall performance of the system.

Figure 13 again depicts a screenshot from the SCADA system indicating an instantaneous gas flow of 1492 m³/h, which corresponds to the planned capacity of the gas purification prototype of 1500 m³/h.

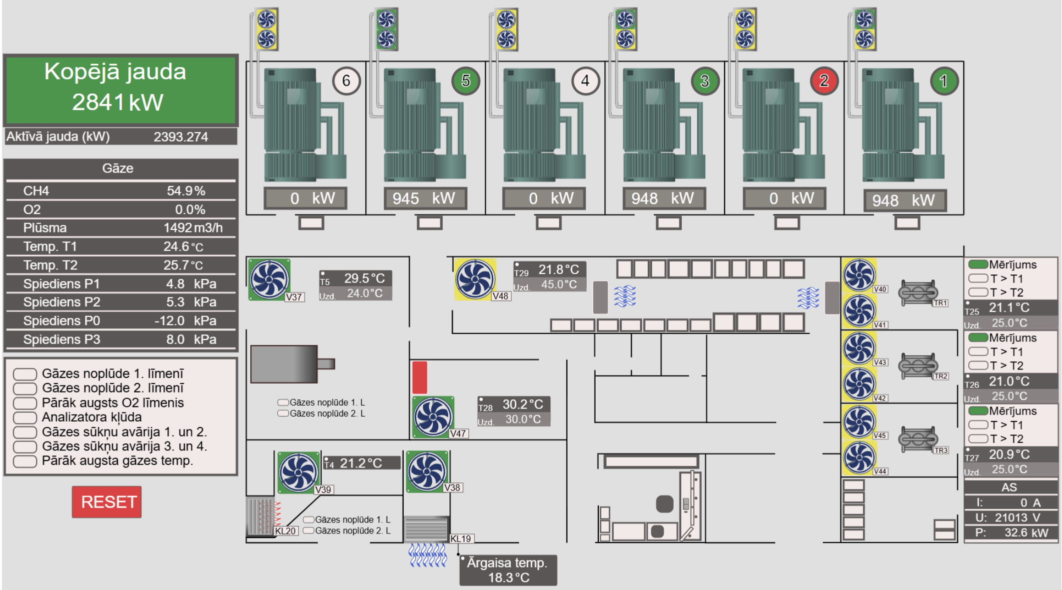


Fig. 13. SCADA system screenshot indicating the gas flow of 1492 m³/h.

At the time of taking the screenshot, the purified gas flow has been provided for the operation of three CHP units of Landfill A with a total instantaneous electrical capacity of 2841 kW.

4. CONCLUSIONS

- LFG purification prototype is easy to integrate into an operating facility. It can be adapted to the infrastructure of the facility where it is installed with minimal downtime, since most of the work can be done without stopping the operating technological processes.
- The integration of the LFG purification prototype into an operating facility creates a negligible gas pressure drop, which is successfully compensated by the installation of a gas pumping station.
- The desulphurisation unit operates with >95 % efficiency, thus successfully ensuring the purification of LFG from H_2S. It has a modular operating mode that ensures automatic change of operating modes depending on the volume and quality of the gas being introduced.
- The gas cooling and drying unit ensures gas cooling to +5 °C, thus ensuring the removal of condensate separated from the gas flow during cooling, which, in turn, ensures the improvement of the physical parameters of the gas for its further purification.
- The pumping station ensures the compensation of gas pressure losses caused by the components of the gas purification prototype, thus ensuring the reduction of the impact of the overall gas purification prototype on the gas infrastructure of the facility. The pumping station is equipped with two parallel gas pumps, which prevents the possibility of system failure.

- The siloxane separation unit operates with >95 % efficiency, thus successfully ensuring the purification of LFG from siloxanes and volatile organic compounds contained in it. The siloxane separation unit is based on two parallel-mounted tanks filled with adsorption material. The operation of the tanks is cyclically changed, thus ensuring the continuity of the gas purification process.
- The activated carbon filter ensures complete purification of the gas from impurities contained in it, as well as provides a basic gas purification function during the rejection or maintenance of other prototype components.
- LFG purification prototypes can be used for the purification of gases of various origins, quality and volume; thus, it can be used by a wide range of potential consumers.
- The components of the LFG purification prototype are manufactured in the European Union, which ensures their high constructive quality, as well as allows for their installation in facilities owned by the state and municipalities.
- The purified gas of LFG purification prototype can be used in CHPs, and, by installing additional technological equipment, it can be used to produce biomethane, which can subsequently be widely utilised for transport, injection into the common natural gas network, etc.

ACKNOWLEDGEMENT

The research is being conducted based on agreement with Ltd. ETKC (Centre of Competence for Energy and Transportation) within the framework of the project "Development of an Innovative Landfill Gas Purification System" No. 5.1.1.2.i.0/2/24/A/CFLA/002 co-funded by the Recovery and Resilience Facility.

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