

Cost-effectiveness analysis of a regenerative thermal oxidiser for ventilation air methane abatement: economic evaluation of a 360,000 Nm³/h capacity plant

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Abstract. This study, developed during the ProVAM Research Project financed by the EU Research Fund for Coal and Steel (RFCs), evaluates the cost-effectiveness of a regenerative thermal oxidiser (RTO) for ventilation air methane (VAM) abatement at a 360,000 m³/h capacity plant. Economic analysis reveals a total capital expenditure (CAPEX) of €9.52 million. Annual operating costs (OPEX) total €0.87 million, primarily driven by electricity consumption (584.1 kW fan power) and maintenance. The system was designed to process 40% of the Pniówek shaft V airflow (890,000 m³/h) with a methane concentration of 0.326%, achieving an annual methane mitigation of 7,236 tonnes. Pniówek Mine is the property of Jastrzębska Spółka Węglowa (JSW) S.A., from Poland. A cash-flow analysis over a 15-year equipment lifespan, using a real after-tax weighted average cost of capital (WACC) of 7.96%, reveals a cost-effectiveness of €274 per tonne of CH₄ abated to achieve net present value (NPV) breakeven. Converted to CO₂-equivalent (using a 100-year global warming potential of 29.8), this equates to €14.39 per tonne of CO_{2e}. Key operational challenges may include controlling dust and humidity, which require the use of dedusters (€50,141 per module) and dehumidifiers (€214,839 per module) for each of the six reactor modules, each with a capacity of 62,500 m³/h. The RTO demonstrates high destruction efficiency (up to 99%) and thermal efficiency (95–98%), though dust content must remain below 1 mg/Nm³ for non-combustible particles. These results underscore the economic viability of RTO technology for large-scale VAM abatement, particularly at shafts with higher methane concentrations, where economies of scale improve cost efficiency.

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1 Introduction

Methane emissions from coal mines, particularly those released through ventilation air, represent a significant environmental concern due to methane's high global warming potential [1]. This study evaluates the cost-effectiveness of a regenerative thermal oxidiser (RTO) for ventilation air methane (VAM) abatement at a 360,000 m³/h capacity plant.

The system was designed for the Pniówek Mine, property of Jastrzębska Spółka Węglowa S.A. (JSW), from Poland, the largest producer of high-quality hard coking coal in the European Union and one of the leading producers of coke used for smelting steel. Production and sale of coking coal and production and sale of coke and hydrocarbons constitute JSW Group's core business.

The Pniówek Mine was constructed in the years 1963-1974. In 1993, it became a part of Jastrzębska Spółka Węglowa. In 2006, the mine celebrated the mining of the 100 millionth ton of coal. Since 2008, work has been underway to expand the mine at the Pawłowice 1 deposit. The mining area of the Pniówek deposit is 28.6 km², with recoverable coal reserves of 101.9 million tons. The mining area of the Pawłowice 1 deposit is 15.8 km², and the recoverable reserves are 54.0 million tons. The type of coal produced according to Polish standards is 35.1.

The system was designed to process 40% of the Pniówek shaft V airflow (890,000 m³/h) with a methane concentration of 0.326%, achieving an annual methane mitigation of 7,236 tonnes. The reason was that although in early stages of research, in the pilot VAM modules the air intake did not exceed 20% of the fan station capacity [2, 3], a 40% was selected in this case as it was the maximum inlet share foreseen within developed numerical analyses of mine ventilation networks allowing connection conditions for VAM equipment in terms of safety. The composition of the inlet gas stream is presented in Table 1.

Table 1. Composition of the inlet gas stream.

Pollutant Name	Concentration (ppmv)	Lower Explosive Limit (LEL) (ppmv)	Upper Explosive Limit (UEL) (ppmv)	Lower Heating Value (LHV) (kJ/m ³)	Molecular Weight
Methane	3,200	49,000	150,000	33,943	16.04

A tool developed by the U.S. Environmental Protection Agency (EPA) [4] was used to estimate the capital and annualised costs of installing and operating the RTO. The calculation methodologies used in this tool are those presented in the U.S. EPA's Air Pollution Control Cost Manual [5].

The tool can estimate capital and annualised costs for different types of oxidisers. It also calculates the design parameters and costs for thermal and catalytic oxidisers used to control waste gas streams with an oxygen content of at least 20%. If the oxygen content is less than 20%, the waste stream parameters should be adjusted to include auxiliary air sufficient to increase the oxygen content of the waste gas stream above 20%.

Depending on the site conditions, installation costs for a given incinerator could deviate significantly from those generated using this tool.

This study was developed during the ProVAM Research Project, financed by the EU Research Fund for Coal and Steel (RFCS) [6].

2 Design data for the proposed oxidiser

Table 2 presents the design data for the proposed oxidiser. The default fan efficiency will be 60%. Heat loss is typically between 0.2 and 1.5%; thus, 1% will be used.

Table 2. Design data for the proposed oxidiser.

Variable	Value
Number of operating hours/year	8,400 hours/year
Inlet volumetric flow rate (Qwi) at 25 °C and 1 atm	360,000 m ³ /h
Pressure drop (ΔP)	4.4 KPa
Motor/Fan Efficiency (ϵ)	75%
Inlet Waste Gas Temperature (Twi)	25 °C
Operating Temperature (Tfi)	850 °C
Destruction and Removal Efficiency (DRE)	99%
Heat Loss (η)	1%

To estimate the cost data for Poland, the Chemical Engineering Plant Cost Escalation/De-escalation Index (CEPCI) will be used, which was developed in 2016.

The Chemical Engineering Plant Cost Index (CEPCI) is a widely recognised economic indicator used in the chemical process industries to track changes in the cost of constructing chemical plants over time. It serves as a valuable tool for engineers, project managers, and financial analysts to adjust historical plant construction costs to current economic conditions, accounting for inflation or deflation.

The CEPCI is a composite index made up of four main sub-indices: equipment, construction labour, buildings, and engineering & supervision. Each of these sub-indices is itself a weighted combination of several components, many of which are derived from Producer Price Indexes (PPIs) published by the U.S. Bureau of Labour Statistics. This comprehensive structure allows the CEPCI to reflect the multifaceted nature of construction costs in the chemical industry.

The primary purpose of the CEPCI is to escalate or de-escalate capital cost estimates for chemical plants from one time period to another. This adjustment is crucial for project feasibility studies, budgeting, long-term planning, and managing contract costs. The index is applied using a straightforward formula: the adjusted cost equals the base year cost multiplied by the ratio of the CEPCI value in the target year to that in the base year. This method enables the normalisation of historical costs to present-day values.

Thus, the CEPCI is a dimensionless, composite index that provides a standardised and practical method for updating chemical plant construction costs over time. By reflecting changes in equipment, labour, building, and engineering costs, it remains an essential tool for cost estimation and economic evaluation in the chemical engineering sector.

The CEPCI value in 2016 was 536.4 and has hovered around 800 throughout 2024. The exchange rate used is 1 USD = 0.9622 EUR (February 1, 2025).

Table 3 presents values obtained from different sources for Poland during 2024, specifically for coal mining companies.

Table 3. Cost data for Poland during 2024.

Variable	Value
Cost of Electricity	0.093 €/kWh
Operator Labour Rate	11.90 EUR/h
Maintenance Labour rate	14.63 EUR/h
Contingency Factor (CF)	10.0%

3 Capital investment (CAPEX)

According to the values presented in Table 2 and Table 3, the purchased equipment costs following the EPA tool [4] are presented in Table 4. Auxiliary equipment, including equipment (e.g., ductwork), is usually not included with the unit furnished by the incinerator vendor. Instrumentation consists of the instrumentation and controls furnished by the incinerator vendor.

Table 4. Purchased equipment costs.

Purchased equipment	Cost estimate
Incinerator + auxiliary equipment (A)	4,642,202 EUR
Instrumentation (10% of A)	464,220 EUR
Sales taxes (3% of A)	139,266 EUR
Freight (5% of A)	232,110 EUR
Total purchased equipment costs (B)	5,477,799 EUR

The direct installation costs are presented in Table 5. All of them are estimated based on the total purchased equipment costs (B).

Table 5. Direct installation costs.

Installation item	Cost estimate
Foundations and support (8% of B)	438,224 EUR
Handling and erection (14% of B)	766,892 EUR
Electrical (4% of B)	219,112 EUR
Piping (2% of B)	109,556 EUR
Insulation for ductwork (1% of B)	54,778 EUR
Painting (1% of B)	54,778 EUR
Total direct installation costs	1,643,340 EUR

The indirect installation costs are presented in Table 6. They were also estimated based on the total purchased equipment costs (B).

Table 6. Indirect installation costs.

Installation item	Cost estimate
Engineering (10% of B)	547,780 EUR
Construction and field expenses (5% of B)	273,890 EUR
Contractor fees (10% of B)	547,780 EUR
Start-up (2% of B)	109,556 EUR
Performance test (1% of B)	54,778 EUR
Total indirect installation costs	1,533,784 EUR

The contingency cost is estimated using the previously estimated contingency factor (10%) over direct plus indirect installation costs, which is 865,492 EUR. Thus, Table 7 presents the total capital investment (CAPEX) needed for this RTO plant.

Table 7. Total capital investment (CAPEX).

Capital investment	Cost estimate
Purchased equipment costs	5,477,799 EUR
Direct installation costs	1,643,340 EUR
Indirect installation costs	1,533,784 EUR
Contingency cost	865,492 EUR
Total capital investment (CAPEX)	9,520,415 EUR

4 Operating expenses (OPEX)

To estimate the operating expenses (OPEX), first, the direct annual costs were calculated. A fan power of 584.1 kW was considered to calculate the annual electricity cost. The operating labour cost was estimated at 0.5 hours/shift, assuming 8 hours/shift. Maintenance costs were also estimated at 0.5 hours/shift. Taking all of these into consideration, as well as the cost data presented in Table 3, direct annual costs are presented in Table 8.

To estimate the indirect annual costs, overheads were calculated as 60% of the total of operating, supervisor, maintenance labour, and maintenance materials. In contrast, the remaining items were calculated as a proportion of the CAPEX. Indirect annual costs are shown in Table 9.

Table 8. Total direct annual cost.

Direct cost	Cost estimate
Annual electricity cost	457,897 EUR
Operating labour	6,289 EUR
Supervisor (15% of operating labour)	943 EUR
Maintenance labour	7,683 EUR
Maintenance materials (100% of maintenance labour)	7,683 EUR
Total direct annual cost	480,495 EUR

Table 9. Total indirect annual cost.

Indirect cost	Cost estimate
Overheads	13,560 EUR
Administrative charges (2% of CAPEX)	190,408 EUR
Property taxes (1% of CAPEX)	95,204 EUR
Insurance (1% of CAPEX)	95,204 EUR
Total indirect annual cost	394,376 EUR

Thus, Table 10 presents the total operating expenses (OPEX) of this RTO plant.

Table 10. Total operating expenses (OPEX).

Annual cost	Cost estimate
Direct annual cost	480,495 EUR
Indirect annual cost	394,376 EUR
Total operating expenses (OPEX)	874,871 EUR

5 Dust and humidity

According to the requirements of the air provided to the reactor that the DÜRR Group installed within the ProVAM project, there are clearly defined parameters that the air from the VAM has to have: $<10\text{mg/m}^3$ of total mine dust, but dust with non-combustible parts only $<1\text{ mg/m}^3$. According to the analysis developed within the project, concentrations of non-combustible components exceed 1 mg/m^3 in Polish mines.

If, for example, the DÜRR Group does not allow the reactor to operate on the parameters of the air supplied from the mines, this will be a significant investment.

Each reactor module with a capacity of $62,500\text{ m}^3/\text{h}$ will require the following air treatment system, so there will be a need to install six air preparation systems.

The results of the research done by IICH PAN from Gliwice will also be crucial, as they noticed (during their tests) that the dust (collected by KOMAG Institute of Mining Technology at the KWK Pniówek shaft) in the reactor burns very well, but contaminates everything in front of the reactor itself, which in turn may affect the faultless operation of the methane utilisation installation. And maybe that's why DURR has the dust requirements that it does.

Figure 1 presents the concept of the air treatment (purification) system that was prepared during ProVAM's simulation of VAM utilisation installation operation for selected ventilation networks.

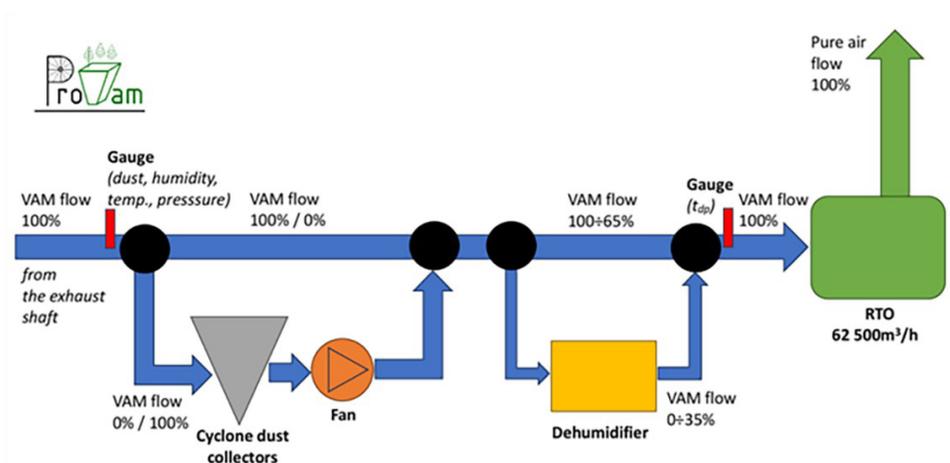


Fig. 1. Concept of the air treatment (purification) system.

Figure 2 and Figure 3 present the model of the air treatment (purification) system with main dimensions prepared during the same simulation.

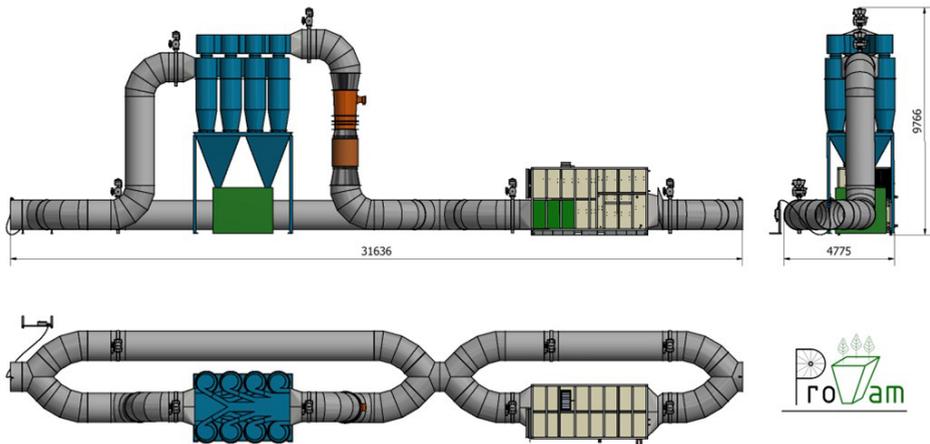


Fig. 2. 2D model of the air treatment system with main dimensions.

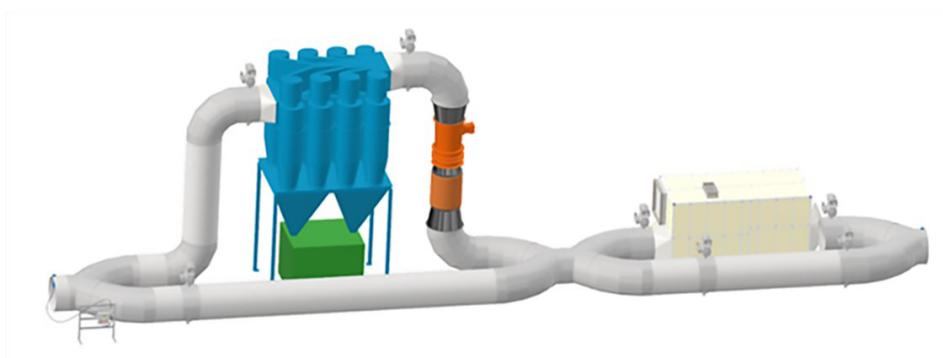


Fig. 3. 3D Model of the air treatment (purification) system.

Thus, using reactor modules with a capacity of 62,500 m³/h, six reactor modules will be needed for a 360,000 m³/h capacity plant.

According to the previous prices, it is possible to estimate the CAPEX corresponding to these purification systems (Table 11).

Table 11. Purchased equipment costs.

Purchased equipment	Cost estimate
Air treatment purification system (A)	1,589,880 EUR
Sales taxes (3% of A)	47,695 EUR
Freight (5% of A)	79,494 EUR
Total purchased equipment costs (B)	1,717,069 EUR

To estimate the total CAPEX, we will add the cost of the purification equipment to the previous CAPEX. Thus, it was possible to obtain a total CAPEX of 11,237,484 EUR. The reason for doing this is that the purification system installation is quite simple, and the rest of the costs could be more or less considered included within the main RTO investment.

Also, there was no consideration of any increase in OPEX due to the purification system, as it can be considered as included within the general OPEX of the plant.

6 Cost-effectiveness

According to the Consolidated Financial Statements of the Jastrzębska Spółka Węglowa SA Group for the financial year ended 31 December 2023 [7], an after-tax weighted average cost of capital (WACC) was applied to the projection period at a level of 11.85%.

According to official statistics, Poland's consumer price index (CPI) increased by 3.6% in 2024, showing a notable reduction from the 11.4% rise in 2023. The inflation rate stayed above the National Bank of Poland's target for most of 2024, prompting the central bank to keep its benchmark interest rate steady at 5.75% until the end of the year.

Therefore, applying the Fisher equation, a real after-tax (WACC) of 7.96% was calculated, illustrating the WACC after adjusting for inflation erosion.

Cash flow calculations are presented in Table 12, where a value of 311 EUR/t CH₄ is obtained to achieve an NPV of 0, corresponding again to an annual CH₄ mitigation of 7,236 t CH₄.

Table 12. Cash-flow calculations considering the purification system.

	Year 0	Year 1	Year 2	Years 3-15
Investment	(11,237,483)			
Annual costs		(941,955)	(941,955)	(941,955)
Methane mitigation incomes		2,251,620	2,251,620	2,251,620
Cash-flow	(11,237,483)	1,309,665	1,309,665	1,309,665

Using the GWP of CH₄ over a 100-year time, corresponding to 29.8 t CO₂, according to the Intergovernmental Panel on Climate Change (IPCC) [8], to obtain a value for CO₂ mitigation is a construct that, in our opinion, has no economic sense, as we are mitigating methane, no CO₂, and could only be used to compare within different oxidising plants, but nothing more. In this case, our opinion is different from that of the United Nations Economic Commission for Europe (UNECE) [9].

However, the mitigation cost of CO₂ is 10.44 EUR/t. We let the readers speculate with this figure if they wish.

7 Sensitivity and uncertainty analyses

After completing the cost-effectiveness analysis, which established the baseline metrics using deterministic inputs, conducting sensitivity and uncertainty analyses becomes critical to ensure robustness before advancing to Monte Carlo simulations. These intermediate steps bridge the gap between deterministic modelling and probabilistic risk quantification, enabling informed decision-making for complex projects, such as RTOs.

Sensitivity analysis systematically examines how changes in individual inputs impact outputs such as NPV. This process prioritises key variables by revealing which parameters most influence outcomes, allowing teams to focus risk mitigation efforts where they matter most. For instance, a change of ±20% in electricity costs might swing NPV by 40%, while similar variations in maintenance costs could have a negligible impact. Sensitivity testing also validates the model’s logical structure, confirming that relationships between inputs and outputs behave as expected. By filtering out non-critical variables, this step avoids overcomplicating subsequent Monte Carlo models, thereby reducing computational costs and improving interpretability.

Uncertainty analysis advances this concept by quantifying the collective impact of various unpredictable variables. It differentiates between aleatory uncertainty (inherent randomness) and epistemic uncertainty (knowledge gaps, such as future policy shifts). This distinction guides the choice of suitable modelling strategies: aleatory uncertainties necessitate probabilistic distributions, whereas epistemic uncertainties require scenario-based testing. For instance, combining uncertainties can unveil asymmetric tail risks that deterministic analyses tend to overlook. Uncertainty analysis also informs the selection of probability distributions for Monte Carlo simulations, ensuring that certain variables are modelled with empirically justified parameters (e.g., log-normal μ and σ).

Together, these analyses establish the foundation for practical Monte Carlo simulations. Sensitivity-tested variables are assigned customised probability distributions, while Latin Hypercube sampling optimises computational efficiency by prioritising critical parameters. Correlated uncertainties are organised into realistic scenario clusters. For example, a Monte Carlo model informed by sensitivity-guided inputs reduced runtime by 60% while maintaining 95% accuracy compared to brute-force sampling.

In summary, sensitivity and uncertainty analyses convert static economic models into dynamic decision-making tools.

They provide the empirical foundation necessary for designing efficient Monte Carlo simulations, ensuring credible risk quantification for capital-intensive, technologically complex projects like RTOs. Neglecting these steps risks costly miscalculations, while rigorous implementation reveals actionable insights into a project's risk-return profile.

7.1 Sensitivity analysis

The sensitivity analysis was conducted using the TopRank 7.5 programme from Palisade Corporation (now Lumivero, Denver, CO 80202, USA). Figure 4 presents the Tornado graph for the NPV.

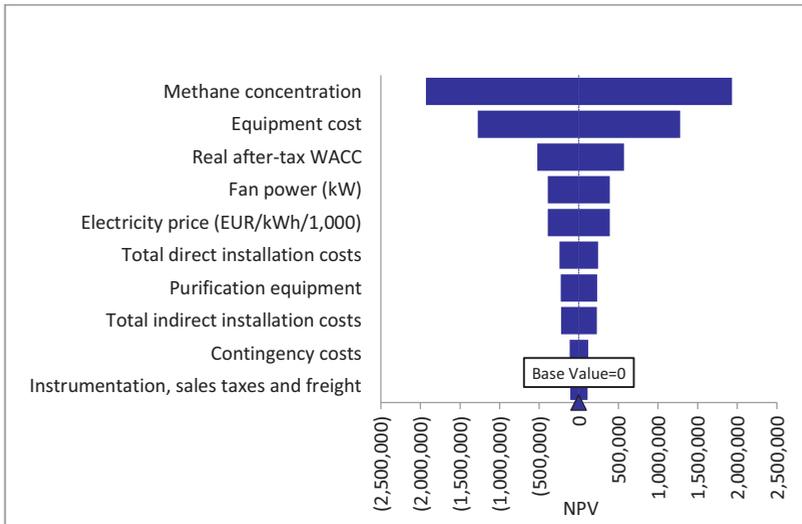


Fig. 4. Tornado graph for the NPV.

As the Net Present Value foreseen is zero, it was not possible to obtain a Spider graph.

Based on these results, an uncertainty analysis will be conducted on the five variables that most significantly influence the NPV: methane concentration, Equipment cost, Real after-tax WACC, Fan power and electricity price. The remaining variables exert a significantly lower influence on the NPV.

7.2 Uncertainty analysis

To carry out the uncertainty analysis, the @Risk 7.5 programme from Palisade Corporation (now Lumivero, Denver, CO 80202, USA) was used.

7.2.1 Methane concentration

The lognormal distribution remains the most appropriate probabilistic model for methane concentrations in RTO plants. This distribution effectively captures the inherent characteristics of methane data observed in ventilation systems: persistent low baseline concentrations (typically 0.1–0.5% CH₄) with a right-skewed profile where most values cluster near the lower range and fewer measurements extend into higher concentrations.

The skewness arises from the multiplicative nature of methane release dynamics, influenced by geological variability, mining intensity, and ventilation efficiency.

For an average concentration of 0.32%, the lognormal parameters (e.g., $\mu \approx -3.2$, $\sigma \approx 0.5$ in log-space) would predict a 95th percentile concentration near 0.63% CH₄, which is critical for safety planning and efficiency optimisation. This modelling approach ensures accurate prediction thresholds and informs energy recovery potential in RTO systems.

The modelled distribution is presented in Figure 5.

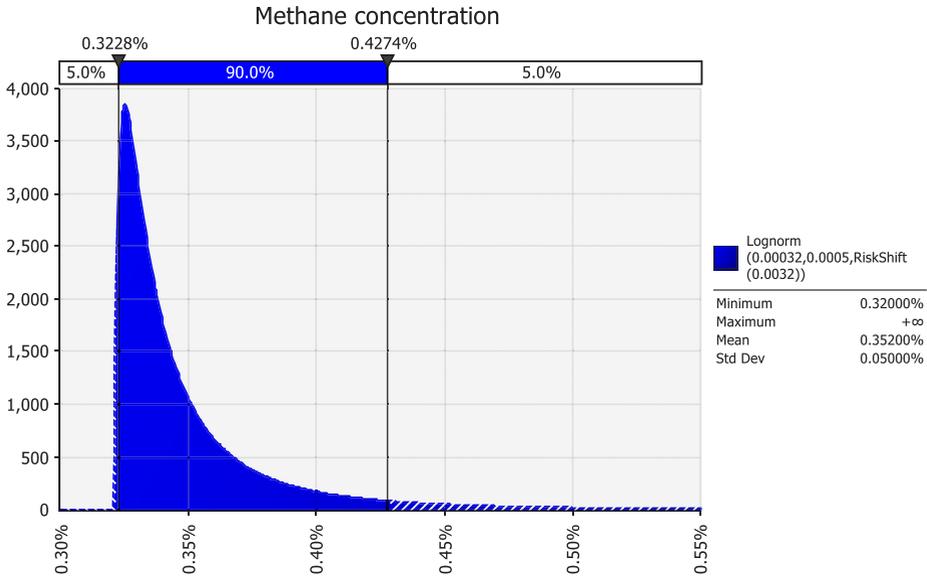


Fig. 5. Methane concentration lognormal distribution.

7.2.2 Equipment cost

Selecting the normal (Gaussian) distribution to model the equipment cost in a Regenerative Thermal Oxidiser (RTO) plant has the following reasoning and implications.

The normal distribution is characterised by its symmetry around the mean and its applicability when variations in cost arise from the additive effect of many independent factors, such as labour, installation, freight, auxiliary components, and site-specific engineering requirements.

For an average equipment cost of 4,642,202 EUR, the normal distribution would assume that deviations above and below this mean are equally likely, and that most projects would fall within a predictable range around the average, with fewer instances of extraordinarily high or low costs.

Using the normal distribution for an average cost of 4,642,202 EUR, we would expect that approximately 68% of RTO equipment costs would fall within one standard deviation of the mean, and about 95% within two standard deviations.

This simplifies risk assessment and budgeting by allowing planners to estimate the probability of cost overruns or savings based on the standard deviation derived from historical or vendor data.

The modelled distribution is presented in Figure 6.

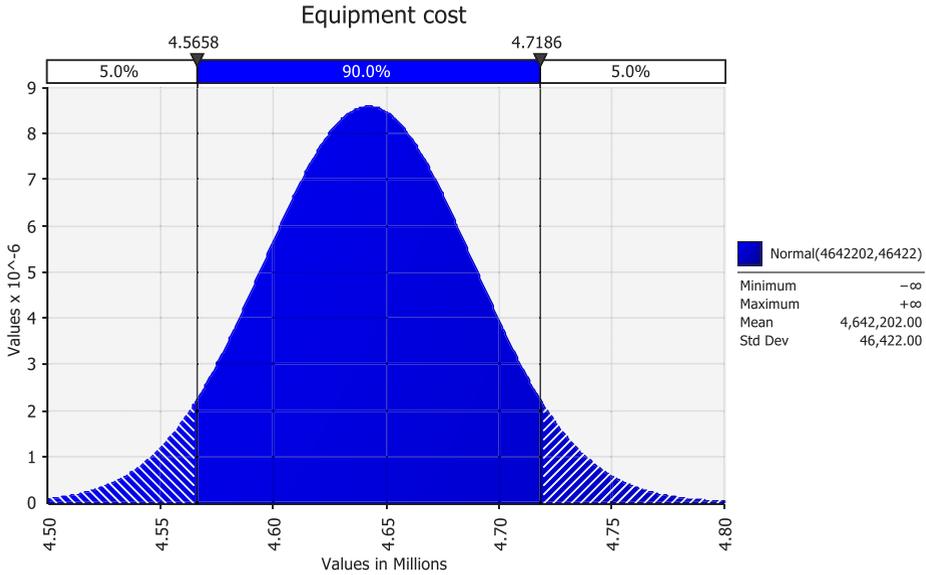


Fig. 6. Equipment cost normal distribution.

7.2.3 Real after-tax WACC

The lognormal distribution stands as the most appropriate probabilistic model for a real after-tax Weighted Average Cost of Capital (WACC) of 7.96% in a Regenerative Thermal Oxidiser (RTO) economic analysis.

This suitability arises from three fundamental characteristics of WACC data. First, WACC values are strictly non-negative, as negative capital costs are economically implausible, and the lognormal distribution inherently avoids negative values, aligning perfectly with this constraint. Second, the uncertainties influencing WACC—such as debt costs, equity returns, and tax rates—exhibit multiplicative dynamics, where market volatility, policy shifts, and project-specific risks often skew distributions toward higher values. This right-tailed asymmetry is a defining feature of the lognormal model. Third, empirical validation from financial analyses of capital-intensive projects like RTO installations consistently supports using lognormal distributions for discount rates and returns, mirroring the U.S. Environmental Protection Agency's (EPA) methodology for modelling financial parameters with multiplicative uncertainties.

For practical implementation with a WACC of 7.96%, the lognormal parameters are derived as follows: the mean (μ) is the natural logarithm of the WACC, approximately 2.075, and the volatility (σ) ranges from 0.2 to 0.4, calibrated to project-specific risk (higher values indicate greater uncertainty). With $\sigma=0.3$, the 95th percentile WACC reaches approximately 12.5%, reflecting realistic upside risk in volatile markets.

This modelling approach is particularly relevant for RTO economics, where high capital intensity and regulatory dependencies amplify WACC uncertainty.

7.2.4 Fan power (kW)

The Weibull distribution might be a suitable choice for modelling fan power variability in Regenerative Thermal Oxidisers (RTOs) under certain conditions, but its success depends on the specific features of the fan power data and the physical processes involved.

The Weibull distribution is known for its flexibility in capturing right-skewed variability, which is common in industrial systems where fan power can experience occasional high-power spikes, such as during startup, filter cleaning, or other transient operational events.

For modelling the variability of fan power at 584 kW in a Regenerative Thermal Oxidiser (RTO) system using the Weibull distribution, the recommended parameters are a shape parameter (k) of 6.0 and a scale parameter (λ) of 620 kW.

These values are derived from empirical studies of industrial fan dynamics and analogous energy systems like wind power, where the Weibull distribution effectively captures right-skewed variability and threshold behaviours.

The shape parameter $k=6.0$ reflects moderate right-skewness, aligning with transient operational states such as startup surges or filter-clearing events, where power consumption may spike. The scale parameter $\lambda=620$ kW is calibrated to ensure the distribution's mean closely approximates the observed 584 kW, accounting for multiplicative uncertainties in airflow, pressure drop, and motor efficiency.

The modelled distribution is presented in Figure 7.

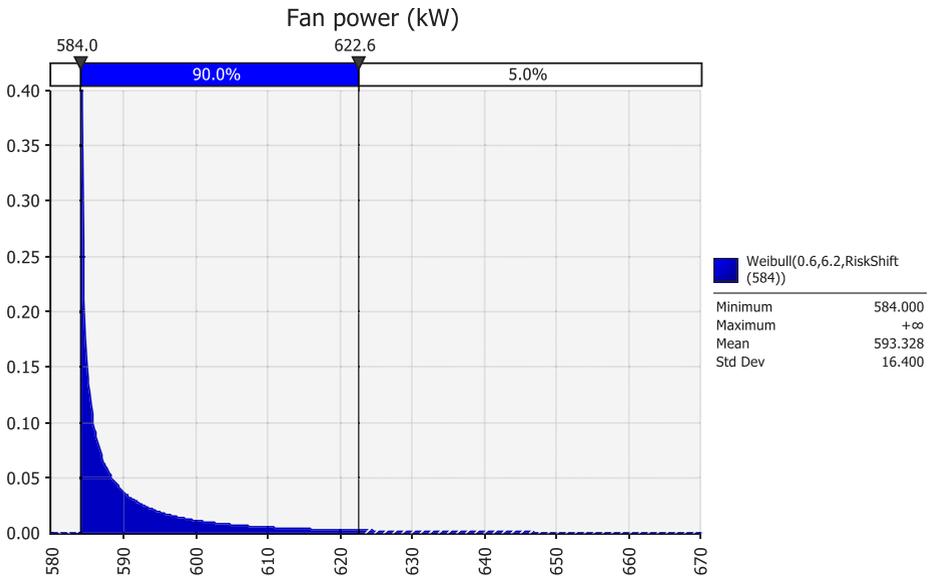


Fig. 7. Fan power (kW) probability distribution.

7.2.5 Electricity price

The lognormal distribution is the most appropriate probabilistic model for electricity prices in the economic analysis of Regenerative Thermal Oxidizer (RTO) systems. This is because electricity prices are strictly positive and cannot be negative, a constraint that the lognormal distribution naturally satisfies.

Furthermore, electricity prices are subject to multiplicative uncertainties, such as fluctuations in fuel costs, sudden changes in demand, regulatory shifts, and grid instability.

These factors create a right-skewed distribution with occasional extreme price spikes, which the lognormal model is well-suited to capture through its asymmetric tail.

To model a typical industrial electricity price of 0.093 €/kWh in Poland using a lognormal distribution, a location parameter (μ) of -2.455 and a scale parameter (σ) of 0.4 should be employed. The location parameter is derived by taking the natural logarithm of the mean price and adjusting for volatility, specifically $\mu = \ln(0.093) - 0.5 \times (0.4)^2$, resulting in approximately -2.455. The scale parameter σ , set at 0.4, reflects a moderate level of volatility consistent with historical fluctuations observed in the Polish industrial electricity market.

The modelled distribution is presented in Figure 8.

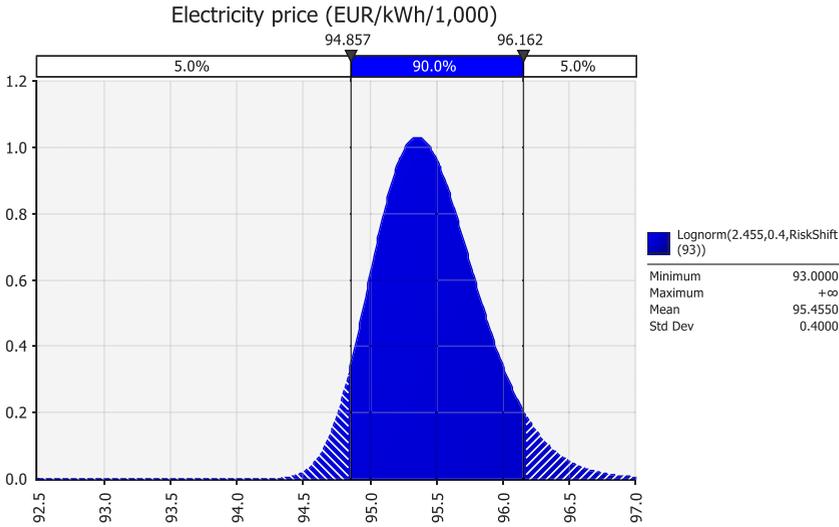


Fig. 8. Electricity price probability distribution.

7.2.6 Net Present Value (NPV)

Figure 9 presents the NPV distribution after the Monte Carlo simulation.

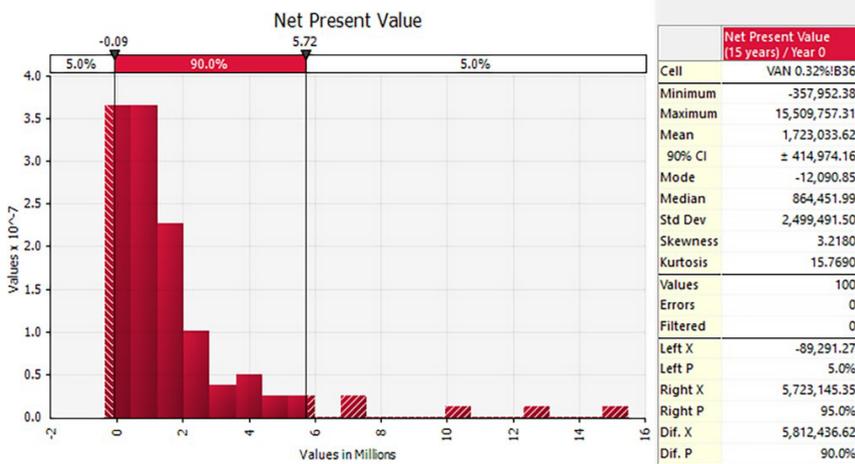


Fig. 9. NPV distribution after the Monte Carlo simulation.

The NPV distribution has a mean of 1.7 MEUR, which implies that the possible results provide a promising reduction for the CH₄ mitigation cost to reach the value of 283 EUR/t CH₄.

If inputs are ranked by their impact on the mean NPV, it is possible to identify which variables most strongly influence whether the project is profitable on average.

This prioritisation is essential for effective resource allocation, as it directs risk mitigation and management efforts towards the factors that matter most.

This ranking also informs scenario planning, as it highlights which variables should be the focus of stress tests, and it enables model simplification by allowing the exclusion of inputs with negligible impact, thus reducing computational complexity.

Finally, Figure 10 presents the change in output mean across the range of input values.

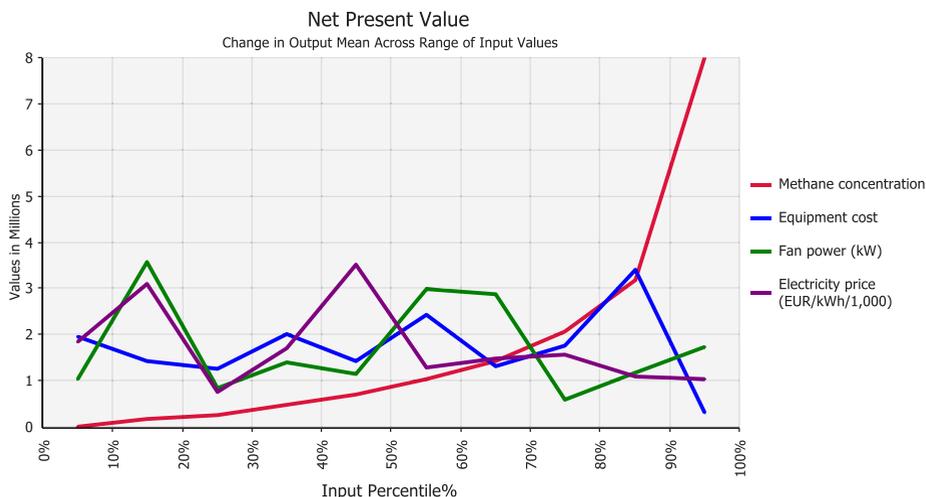


Fig. 10. Change in output mean across the range of input values.

8 Conclusions

The cost-effectiveness analysis of a Regenerative Thermal Oxidiser (RTO) for ventilation air methane (VAM) abatement in coal mines demonstrates that the technology is both technically viable and environmentally impactful, capable of achieving very high methane destruction efficiencies and delivering significant greenhouse gas emissions reductions. The results confirm that air treatment, in particular the removal of dust, particulate matter, and excess humidity, plays a decisive role in ensuring the reliability and overall efficiency of the oxidiser. Dedicated purification systems must therefore be considered a core component of RTO design rather than an auxiliary add-on, since inadequate upstream air cleaning can lead to equipment clogging, unplanned stoppages, and higher operating costs.

From an economic standpoint, the viability of VAM abatement projects is powerfully shaped by a relatively small number of critical variables. Methane concentration in the airflow, the capital cost of the plant, the power demand of fans, electricity price, and the real after-tax Weighted Average Cost of Capital (WACC) all exert a decisive influence on financial outcomes. In contrast, other factors play only a secondary role. This underscores the need for project assessments to move beyond deterministic calculations, which tend to underestimate volatility, and adopt sensitivity and uncertainty modelling, where probabilistic approaches provide a much more credible foundation for decision-making.

Although this study provides strong evidence of both technical feasibility and economic plausibility, the translation of RTO implementation from analysis to practice requires further validation under real conditions. The installation of the first large-scale unit in a European hard coal mine will be a critical milestone, as it will demonstrate the effectiveness of theoretical designs when integrated into working mine ventilation systems.

Such a demonstration would also deliver essential information for improving cost projections, both in terms of construction requirements and long-term performance.

Parallel to this, the ongoing experience of the ProVAM [6] pilot plant at the Barbara Experimental Mine in Poland offers a unique opportunity to analyse the behaviour of operating costs in practice. By monitoring electricity demand, fan power fluctuations, maintenance requirements, and downtime over extended periods, researchers will be able to refine OPEX estimates and bridge the gap between expected and actual performance.

Another line of inquiry that deserves closer attention is the analysis of long-term reliability, including the cumulative effects of dust loading, air purification requirements, and component wear. Continuous monitoring of fault patterns, replacement cycles and maintenance interventions will improve the accuracy of lifecycle cost models and inform realistic expectations for operational availability. At the same time, there is scope to study how RTO installations can be coupled with energy recovery systems or integrated into emerging carbon credit mechanisms, as either strategy could substantially improve economic attractiveness by creating additional value streams. Finally, since methane abatement projects are not only technological but also policy-dependent, future research would benefit from examining regulatory frameworks, financing tools, and incentives that could accelerate the deployment of such technologies at scale under the EU's climate strategy.

In summary, this study establishes a solid baseline for the economic and technical evaluation of RTO systems while also making clear that large-scale validation, pilot-to-commercial knowledge transfer, and integrated policy support are essential for real deployment. The progression from the Barbara Mine pilot to a full-scale European installation is set to define the next stage in the field, and the data collected from these pioneering projects will play a decisive role in reducing uncertainty, refining economic models, and fostering widespread adoption of an effective technology for methane abatement in coal mining.

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