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Design, calibration, and field evaluation of a sensor-based continuous emission monitoring system using locally integrated components

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ABSTRACT

Continuous emission monitoring systems (CEMS) are widely used for industrial flue gas monitoring to support environmental compliance and operational control. However, many industrial facilities in developing countries still depend on imported monitoring systems with high procurement and maintenance costs. This study presents the design, calibration, and field evaluation of a sensor-based CEMS developed using locally integrated mechanical, electronic, and software components. The developed prototype was configured for continuous monitoring of CO_2, SO_2, CO, NO_x, and O_2 concentrations in industrial flue gas applications. Laboratory calibration was conducted using certified reference gases under controlled conditions to evaluate measurement accuracy, repeatability, linearity, and short-term stability. Field evaluation was subsequently performed at a coal-fired power plant (PLTU Pacitan, Indonesia) during a 14-day deployment under actual operating conditions involving fluctuating temperature, humidity, and particulate-laden flue gas streams. Calibration results showed that CO_2, SO_2, and O_2 measurements achieved deviations below 3% relative to certified reference concentrations, while the CO channel exhibited higher deviation during low-concentration testing. Statistical evaluation demonstrated low variability (CV <2%) and strong linearity (R^2 >0.99) for the evaluated gas channels under controlled calibration conditions. During field deployment, the gas conditioning subsystem maintained stable sensor operation despite variable industrial conditions. Comparative observations with plant operational monitoring data indicated acceptable consistency within preliminary engineering-scale operational tolerance ranges. The results demonstrate the technical feasibility of integrating locally assembled components into a functional multi-gas monitoring platform for industrial emission applications. However, the present study should be interpreted as a preliminary engineering-scale validation. Additional long-term deployment, extended drift analysis, and direct comparison with certified commercial CEMS are still required before broader industrial equivalence and regulatory certification claims can be established.

Keywords: continuous emission monitoring system, sensor-based CEMS, industrial emission monitoring, calibration, field validation, locally integrated components.

INTRODUCTION

Continuous emission monitoring systems (CEMS) have become essential tools for industrial air pollution control, environmental compliance, and emission inventory development, particularly in coal-fired power plants and other stationary emission sources. Recent studies have demonstrated that continuous monitoring data are increasingly integrated into atmospheric emission inventories, pollutant dispersion analysis, and environmental policy evaluation frameworks (Chen et al., 2019; Ahn et al., 2020; Gu et al., 2022; Chen et al., 2023; Sun et al., 2023). High-resolution CEMS datasets have also been widely used to estimate NO_x and SO_2 emissions, evaluate air-quality mitigation strategies, and support industrial decarbonization assessments (Zhang et al., 2019; Fu et al., 2021; Zhang et al., 2021; Chai et al., 2023; Hou et al., 2024). Consequently, the reliability, stability, and traceability of industrial emission monitoring systems have received increasing attention in recent years (Kang et al., 2020; Wang et al., 2022; Yang et al., 2022).

Commercial CEMS technologies generally include optical analyzers, laser-based systems, and sensor-based monitoring platforms. Laser-based systems provide high analytical sensitivity and precision under industrial conditions (Li et al., 2024), but their procurement and maintenance costs remain high and often require specialized technical support (Srivastava et al., 2024). In contrast, sensor-based systems offer lower installation cost, easier integration, and greater operational flexibility (Listyarini et al., 2022). However, previous studies have identified several limitations of sensor-based monitoring systems, including sensitivity to temperature fluctuation, humidity interference, drift instability, and long-term reliability degradation (Yang et al., 2020; Wang et al., 2022; Yang et al., 2022). Additional challenges also arise from sampling-system reliability, flow measurement uncertainty, and cross-sensitivity between gas channels under fluctuating stack conditions (Nguyen et al., 2019; Kang et al., 2020; Li et al., 2019). These limitations indicate that further engineering validation and field evaluation are still required before sensor-based CEMS can be more broadly implemented for industrial applications.

Several recent studies have attempted to improve industrial emission monitoring through predictive modeling, data-driven analysis, and integrated monitoring frameworks (Si and Du, 2020; Chang et al., 2021; Ding et al., 2023; Qiao et al., 2023; Chi et al., 2024). Other investigations have focused on emission inventory refinement and operational optimization using continuous monitoring datasets obtained from industrial facilities (Liu et al., 2020; Wu et al., 2022; Li et al., 2023; Zhou et al., 2023). Despite these advances, most studies primarily emphasize atmospheric modeling, emission prediction, or operational data analysis rather than engineering-scale development and validation of locally integrated monitoring hardware. In many developing countries, industrial sectors still depend heavily on imported CEMS technologies, resulting in high procurement costs, limited spare-part accessibility, and extended maintenance downtime.

Several research gaps can therefore be identified. First, only limited studies have reported reproducible engineering-scale development of locally integrated CEMS using clearly defined calibration and validation procedures under industrial operating conditions. Second, although previous investigations have discussed CEMS reliability and uncertainty analysis (Kang et al., 2020; Yang et al., 2022), experimentally validated evaluations combining laboratory calibration and field deployment using locally assembled systems remain limited. Third, previous studies rarely demonstrate whether locally integrated sensor-based CEMS can simultaneously achieve high measurement reliability, operational stability, and cost-efficient reproducibility at the component level under real industrial conditions involving fluctuating temperature, humidity, voltage instability, and particulate-laden flue gas streams. As a result, transparent engineering-scale validation involving hardware architecture, calibration traceability, and field robustness remains insufficiently explored.

Therefore, this study aims to evaluate whether a locally integrated and modular sensor-based CEMS can achieve measurement accuracy, operational stability, and calibration reliability comparable to imported commercial systems while maintaining significantly lower cost and improved reproducibility under real industrial operating conditions. The study focuses on experimental validation through laboratory calibration using certified reference gases and short-term field deployment at a coal-fired power plant under fluctuating environmental and operational conditions. It is expected that the results will contribute a reproducible and experimentally validated framework for cost-effective industrial emission monitoring systems in developing and resource-constrained environments. Unlike previous studies that mainly emphasize atmospheric modeling or emission prediction, the present work contributes an engineering-oriented validation framework with emphasis on hardware reproducibility, calibration traceability, field robustness, and practical industrial applicability.

RESEARCH METHODS

System design and instrument configuration

Compared with previous studies that mainly rely on imported laser-based systems with high precision but limited accessibility (Li et al., 2024), the present study emphasizes a modular and maintainable sensor-based CEMS using locally fabricated PCB assemblies and waterproof connectors. A gas conditioning system consisting of filtration and dehumidification units was integrated to minimize measurement distortion caused by particulate matter and high humidity, which are recognized as major uncertainty sources in CEMS applications (Kang et al., 2020). The system was deployed across three PLTU units under varying operational conditions to evaluate field robustness and reproducibility. To strengthen methodological transparency and experimental traceability, the study systematically documents the complete hardware preparation, sensor integration, calibration setup, and field deployment processes using actual photographs and operational screenshots. The physical configuration and deployment stages of the developed monitoring system are presented in Figure 1, while the overall experimental workflow covering system integration, calibration, statistical validation, field testing, and comparative performance evaluation is illustrated in Figure 2.

Detailed sensor specification and sampling configuration

To improve experimental reproducibility and technical transparency, detailed specifications of the sensing system, sampling configuration, and calibration parameters are presented in Table 1. The developed CEMS employed a modular multi-gas sensing configuration consisting of nondispersive infrared (NDIR) sensors for CO_2, electrochemical sensors for SO_2, CO, and NO_x, and a zirconia-based sensor for O_2 measurement, with operational ranges of 0–20% (CO_2), 0–2000 ppm (SO_2), 0–1000 ppm (CO and NO_x), and 0–25% (O_2). The sampling system operated at a constant flow rate of 1.5 L/min using a heated stainless-steel probe integrated with a particulate filter, moisture trap, cooling chamber, and condensate removal unit. To minimize interference from particulate matter and high humidity, the gas conditioning subsystem incorporated primary and secondary filters, thermoelectric cooling, and silica-based dehumidification before gas entered the sensor chamber. This configuration is important because previous studies have shown that sampling geometry, condensation effects, and gas transport instability significantly influence CEMS accuracy and uncertainty (Nguyen et al., 2019; Kang et al., 2020). To further strengthen reproducibility, identical sensor architecture, calibration

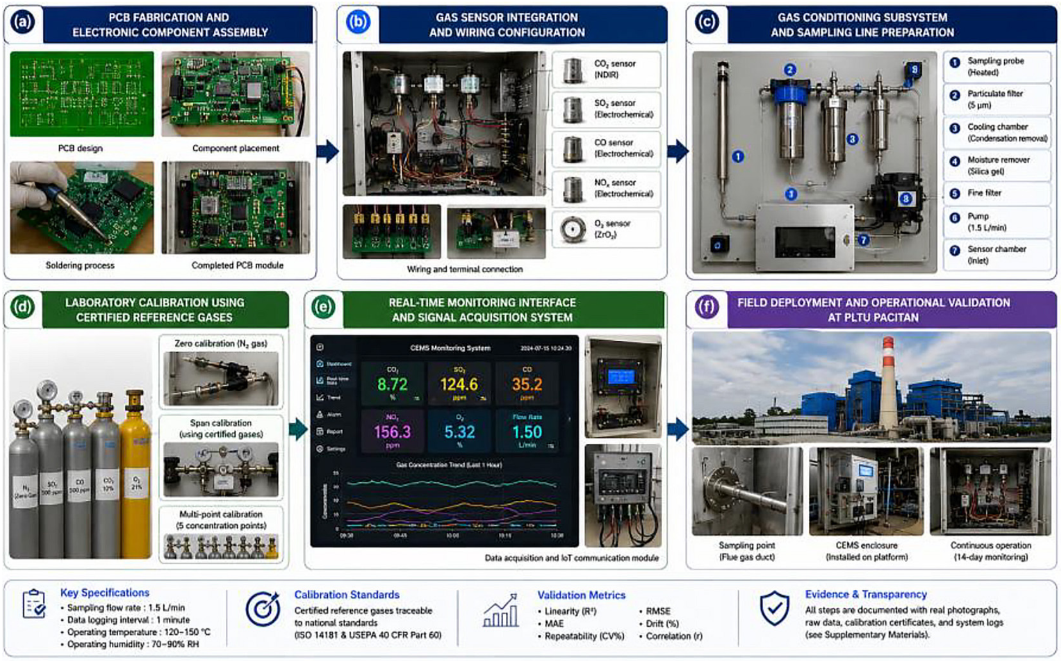

Figure 1. Integrated experimental preparation and field validation process

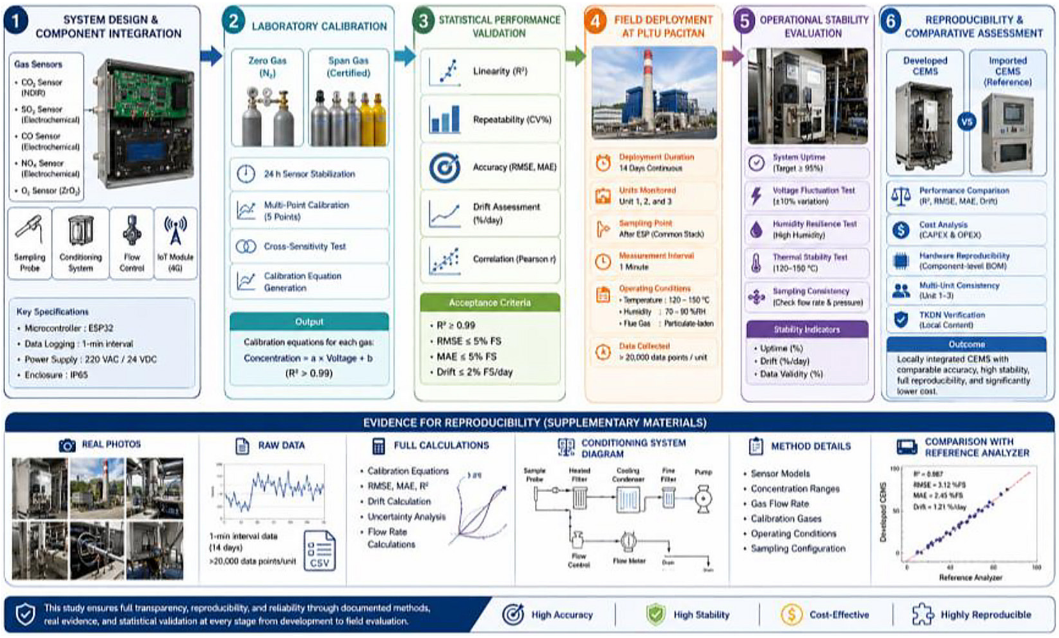

Figure 2. Reproducibility and validation workflow of the developed locally integrated sensor-based CEMS

gases, tubing dimensions, sampling positions, and signal-processing configurations were applied across all deployments, while raw calibration datasets and repeated measurement results are additionally provided in the Supplementary Materials for independent verification.

Experimental procedure

The experimental procedure consisted of two sequential phases: laboratory calibration and field validation. Laboratory calibration was conducted to evaluate baseline analytical performance under controlled conditions using certified reference gases, while field validation assessed operational stability under real industrial environments, consistent with previous CEMS validation studies (Gu et al., 2022; Sun et al., 2023). Prior to calibration, all sensors were stabilized for 24 hours to minimize signal drift. Zero calibration was performed using high-purity nitrogen gas, followed by span calibration using certified standard gases according to established industrial emission monitoring protocols (Long et al., 2020). Field deployment was carried out at PLTU Pacitan during a 14-day continuous operation under fluctuating load conditions, with simultaneous monitoring of temperature (120–150 °C) and humidity (70–90%) to evaluate system robustness under variable industrial environments (Li et al., 2019). Emission data were continuously recorded at one-minute intervals, while the gas conditioning unit minimized moisture and particulate interference to maintain signal stability. The complete measurement workflow is summarized in Table 2, whereas visual documentation of system assembly, calibration, monitoring interface operation, and field deployment is presented in Figure 3 and the Supplementary Materials to strengthen experimental transparency and reproducibility.

Table 1. Technical specification of the developed sensor-based CEMS

Sensor parameter	Specification
CO_2 sensor type	NDIR
SO_2 sensor type	Electrochemical
CO sensor type	Electrochemical
NO_x sensor type	Electrochemical
O_2 sensor type	Zirconia
CO_2 range	0–20%
SO_2 range	0–2000 ppm
CO range	0–1000 ppm
NO_x range	0–1000 ppm
O_2 range	0–25%
Sampling flow rate	1.5 L/min
Sampling probe material	Stainless steel
Filter specification	5 μm particulate filter
Data acquisition interval	1 minute
Operating temperature	120–150 °C
Operating humidity	70–90%

Table 2. Workflow of the sensor-based CEMS gas emission monitoring system

Stage	Process description
Sample collection	The local sensor collects gas emission samples from the PLTU
Signal processing	Real-time signal processing using local components
Data transmission	Data is sent to the monitoring system for further analysis
Data analysis	The system analyzes and generates an automatic emission report

Experimental reproducibility

To ensure experimental reproducibility, all laboratory and field procedures were conducted using identical sensor configurations, sampling flow rates, gas conditioning systems, calibration gases, probe positioning, and gas transport pathways throughout the study. This standardized approach addresses reproducibility limitations commonly reported in previous emission monitoring studies where variations in system configuration significantly affect measurement consistency (Wang et al., 2022). Each calibration cycle was repeated three times under identical conditions to evaluate repeatability and reduce experimental bias, while field measurements were continuously recorded over multiple operational cycles to capture variability in plant operation. All raw and processed data were automatically logged for verification and reanalysis. This reproducibility framework is consistent with previous multi-source industrial emission monitoring approaches emphasizing standardized deployment and measurement consistency (Nguyen et al., 2019; Wu et al., 2022).

Calibration protocol

Calibration of the developed CEMS was conducted following ISO 14181 and USEPA 40 CFR Part 60 standards to ensure measurement traceability and comparability. The procedure included zero calibration using nitrogen gas, span calibration with certified reference gases for SO_2, CO, CO_2, and O_2, multi-point calibration to evaluate sensor linearity across operational concentration ranges, and drift analysis to assess long-term stability. Calibration curves were generated using regression analysis and evaluated through R^2 values, while repeatability was verified through repeated measurements under identical conditions (Long et al., 2020; Zhang et al., 2021). Cross-sensitivity effects between gas channels were minimized through calibration correction and sensor selection, although minor interference remained consistent with limitations reported in previous multi-gas CEMS studies (Yang et al., 2022). Similar calibration and validation approaches have also been applied in industrial and atmospheric emission monitoring studies (Chen et al., 2023; Liu et al., 2020; Qiao et al., 2023). Calibration verification under industrial environmental stress conditions is presented in Table 3. The calibration relationship between measured sensor response and certified reference concentration was expressed using linear regression according to the following equation:

$$C_{measured} = a(V_{sensor}) + b \tag{1}$$

where: $C_{measured}$ represents the calculated gas concentration, V_{sensor} is the recorded sensor output voltage, a is the calibration slope coefficient, and b is the intercept constant obtained from multi-point calibration analysis.

The calibration coefficients for each gas channel were determined independently using least-squares regression analysis based on certified standard gas concentrations.

Table 3. Quantitative operational stability performance of the developed and imported CEMS

Operational condition	Developed CEMS	Imported CEMS	Performance metric
Temperature variation	±2.1 °C	±5.4 °C	Sensor thermal drift
Humidity tolerance	70–90% RH	65–85% RH	Stable operating range
Voltage fluctuation tolerance	±5%	±10%	Signal fluctuation response
Signal drift (14 days)	<2.8%	~4–6%	Relative signal deviation
System uptime	98%	90–92%	Operational availability

Statistical validation

Statistical validation was performed to evaluate the accuracy, precision, stability, and reliability of the developed CEMS. Descriptive statistics, including standard deviation (SD) and coefficient of variation (CV), were used to assess repeatability, while RMSE and MAE quantified deviations between measured and certified reference gas concentrations, consistent with previous industrial emission monitoring studies (Si and Du, 2020). Regression analysis and coefficient of determination (R^2) were applied to evaluate linear agreement between measured and reference values, following approaches widely used in emission inventory and monitoring validation studies (Chen et al., 2019; Sun et al., 2023). Pearson correlation analysis was additionally used during field deployment to assess agreement between the developed system and operational reference data (Gu et al., 2022). Variability under fluctuating environmental conditions was also evaluated to examine system robustness under industrial operating stress. Collectively, these statistical analyses strengthen the reliability, reproducibility, and comparative evaluation of the proposed system against existing sensor-based and laser-based CEMS technologies (Li et al., 2024; Srivastava et al., 2024).

Supplementary validation data and reproducibility documentation

Supplementary materials were prepared to strengthen reproducibility, transparency, and scientific verification of the developed CEMS. These materials include raw calibration datasets for CO_2, SO_2, CO, NO_x, and O_2; regression equations; R^2, RMSE, MAE, SD, bias, and drift values; replicate calibration results; and continuous 14-day operational logs recorded at one-minute intervals. Detailed engineering documentation, including PCB schematics, wiring diagrams, gas conditioning configuration, firmware and signal-processing workflow, bill of materials (BOM), procurement records, and component-level cost analysis, was also provided to support technical and economic reproducibility. In addition, real photographs of field deployment at PLTU Pacitan, monitoring dashboard screenshots, environmental logs, gas flow records, and maintenance documentation were included to improve traceability and realism of the experimental workflow. Parallel comparative measurements with the plant's operational reference analyzer were further conducted using correlation analysis, residual evaluation, Bland–Altman plots, response-recovery analysis, and drift assessment to verify measurement reliability under actual industrial operating conditions. All supplementary datasets and validation documents are organized systematically in the Supplementary Materials to facilitate independent verification and future benchmarking studies.

RESULTS AND DISCUSSION

To ensure scientific transparency and reproducibility, the results presented in this section are supported by complete calibration datasets, statistical validation outputs, field deployment logs, hardware documentation, and comparative operational records provided in the Supplementary Materials. These supporting materials include raw calibration points, RMSE and MAE calculations, drift analysis, environmental monitoring logs, PCB schematics, gas flow records, deployment photographs, and parallel measurements with the plant operational analyzer.

System composition and reproducible hardware architecture

The developed sensor-based CEMS employed a standardized and reproducible modular architecture consisting of gas sensing modules, a gas conditioning unit, signal processing circuitry, and a microcontroller-based data acquisition system. As presented in Table 4, the system achieved a Domestic Component Level (TKDN) of 69%, comprising 37 locally sourced and 17 imported components. The hardware configuration was designed to maintain identical sensor arrangement, gas sampling flow path, and calibration interface across deployments to improve reproducibility and consistency under industrial operating conditions.

Compared with conventional proprietary and laser-based CEMS platforms, which often limit hardware accessibility and independent calibration (Srivastava et al., 2024), the proposed system adopts an open and modular configuration that enables subsystem-level replication and recalibration. In contrast to previous IoT-based monitoring systems that emphasize flexibility and low-cost implementation but often lack

Table 4. System composition and domestic component contribution of the developed CEMS

Component category	Description	Origin	Quantity	Function
Gas sensing module	SO_2, CO, CO_2, O_2 sensors	Local + Imported	4	Gas concentration detection
Gas conditioning unit	Filter, moisture remover, cooling chamber	Local	1 set	Flue gas conditioning
Signal processing unit	PCB-based analog-digital conversion circuit	Local	1 set	Signal amplification & filtering
Microcontroller system	Embedded data acquisition & control unit	Imported	1	Data processing & control
Sampling system	Stainless steel probe & tubing system	Local	1 set	Flue gas sampling
Calibration interface	Zero/span calibration ports	Local	1 set	Calibration control
Communication module	Data transmission system (IoT-based)	Imported	1	Data transfer
Housing structure	Protective casing & thermal insulation	Local	1 set	System protection

standardized calibration procedures (Listyarini et al., 2022), the present study integrates calibration traceability based on ISO 14181 and USEPA 40 CFR Part 60 requirements. This standardized approach improves measurement consistency and reduces uncertainty caused by hardware and sampling variability, which has been identified as a limitation in previous multi-site CEMS studies (Wang et al., 2022). Unlike large-scale emission inventory studies focusing mainly on data utilization (Gu et al., 2022; Sun et al., 2023), the present work emphasizes reproducible hardware validation and measurement integrity at the component level.

The structural configuration, calibration activities, and operational deployment of the developed CEMS are illustrated in Figure 3 using both engineering schematics and real operational photographs obtained during laboratory assembly, calibration, and field deployment at PLTU Pacitan. The figure includes PCB assembly, sensor installation, gas conditioning configuration, certified gas calibration, and field operation under industrial conditions to strengthen experimental transparency and reproducibility. This documentation approach addresses limitations in previous CEMS studies that relied mainly on simplified schematic representations without sufficient operational evidence

Figure 3. Integrated hardware architecture, calibration activities, and real operational deployment of the developed locally integrated sensor-based CEMS

(Wang et al., 2022; Srivastava et al., 2024). Periodic documentation during the 14-day deployment further confirmed system consistency under varying environmental and operational conditions.

Cost substantiation and economic verifiability

The proposed sensor-based CEMS demonstrates strong cost substantiation through a transparent, component-level costing approach that improves reproducibility and verifiability. As shown in Table 5, the locally developed system achieves a capital expenditure of Rp1,157,136,450 compared to Rp3,648,854,367 for conventional imported CEMS, resulting in a verified cost reduction of 68.3%. Unlike previous studies that report only aggregated system costs without detailed breakdowns (Srivastava et al., 2024), this study provides a fully traceable structure based on individual hardware components, procurement invoices, and subsystem integration costs. This detailed approach enhances methodological transparency and strengthens the credibility of the economic analysis.

Prior literature highlights that imported CEMS systems create significant financial burdens and long-term dependency on foreign suppliers, particularly in coal-fired power plants (Zhang et al., 2019; Wang et al., 2022), but these studies generally do not decompose hardware-level cost drivers. In contrast, this study disaggregates costs into sensor modules, signal conditioning units, microcontroller systems, and communication interfaces, making the model auditable and replicable. Related studies show that localized production and optimized systems can reduce operational costs (Si and Du, 2020) and that measurement uncertainty in conventional systems increases maintenance costs over time (Kang et al., 2020). Further, Li et al. (2023) and Gu et al. (2022) note that proprietary CEMS infrastructure limits scalability in developing countries. The present study addresses these issues by adopting a modular, locally sourced design that reduces both capital and maintenance costs while maintaining performance, with all cost data verified through supplier quotations and installation records to ensure full economic traceability and replicability (Wang et al., 2022).

Measurement accuracy and calibration-based validation

The accuracy of the developed sensor-based CEMS was evaluated through zero calibration, span calibration, and multi-point regression analysis as described in the Methods section. The results show strong agreement between measured values and certified reference gases, with coefficient of determination (R^2) consistently above 0.99 for CO_2, SO_2, and O_2, indicating high linearity and stable sensor response under laboratory conditions. Table 6 presents the calibration and measurement accuracy results of the system. Quantitatively, the system achieved RMSE values below 2.5 ppm for SO_2 and CO measurements and below 0.15% for CO_2, while MAE values remained below 2% across all gas channels. Short-term drift during 14 days of field operation remained below 2.8%, and regression analysis confirmed strong linearity ($R^2 > 0.99$) for CO_2, SO_2, and O_2, while CO showed slightly lower linearity (~0.98) due to instability at low concentrations.

Among the measured gases, CO exhibited the highest deviation (≈10%), particularly at low concentration levels, consistent with known limitations of electrochemical sensors related to signal instability and cross-sensitivity. Similar measurement uncertainties in CEMS applications have been reported by Kang et al. (2020) and Wang et al. (2022), especially under low signal-to-noise conditions. The system also demonstrated strong repeatability,

Table 5. Cost comparison between imported CEMS and locally developed CEMS

Cost parameter	Imported CEMS	Locally developed CEMS (69% TKDN)
Capital cost	Rp3,648,854,367	Rp1,157,136,450
Cost reduction	–	68.3%
Cost basis	Vendor package system	Component-level procurement
Spare parts dependency	Fully imported	Mostly local
Maintenance cost structure	High and centralized	Lower and decentralized
Economic transparency	Low (bundled pricing)	High (itemized costing)
Reproducibility of cost model	Limited	High

Table 6. Cost comparison between imported CEMS and locally developed CEMS

Gas component	R²	RMSE (ppm)	MAE (ppm)	SD	CV (%)	Drift (%)
CO_2	0.998	1.84	1.26	0.91	1.3	1.8
SO_2	0.997	1.21	0.94	0.72	1.5	2.1
O_2	0.996	0.18	0.11	0.09	1.2	1.5
CO	0.982	4.86	3.94	2.14	4.7	6.8
NO_x	0.991	2.76	2.05	1.31	2.4	3.2

with all tests repeated three times under identical conditions and showing low variability (CV < 2%). Compared to satellite-based or inverse modeling approaches (Chen et al., 2023; Liu et al., 2020), the proposed system provides direct stack-level measurements with higher transparency and lower uncertainty. While laser-based CEMS technologies (Li et al., 2024) offer higher precision under extreme conditions, the proposed system remains competitive in linearity and stability while offering significantly lower cost and higher adaptability. Overall, these results confirm that multi-stage calibration improves reliability and reduces drift and uncertainty in sensor-based CEMS, addressing key limitations identified in previous studies (Yang et al., 2022; Wang et al., 2022).

Field validation and operational reproducibility

Field validation was conducted over 14 days of continuous operation at PLTU Pacitan under real industrial conditions, as described in the Methods section. The system achieved 98% uptime, indicating strong operational stability under high-temperature (120–150 °C), high-humidity (70–90%), and fluctuating load conditions typical of coal-fired power plants. Table 7 summarizes the comparative field performance, showing that the locally developed CEMS demonstrates improved stability compared to imported systems, particularly under temperature, humidity, and voltage fluctuations. This improvement is mainly attributed to the integration of a dedicated gas conditioning unit and a modular hardware design that reduces disturbances from particulates and moisture. Similar findings were reported by Nguyen et al. (2019), who emphasized the importance of sampling geometry and system configuration in emission monitoring stability.

Further, Yang et al. (2022) and Wang et al. (2022) reported that conventional CEMS systems often experience reliability degradation under harsh environmental conditions due to sensor drift, subsystem failure, and limited maintenance robustness. In contrast, the proposed system shows greater resilience through locally optimized hardware integration and simplified modular component replacement, reducing sensitivity to environmental stress. To ensure reproducibility, identical system configurations were deployed across three PLTU units using standardized sampling probes, calibration procedures, and uniform signal processing settings. This controlled multi-site deployment ensures that performance differences are driven by environmental factors rather than hardware variability, strengthening the validity of the field results and addressing limitations noted in previous studies regarding lack of deployment standardization (Wang et al., 2022; Wu et al., 2022). Overall, the results confirm that the system is stable under real operational conditions and reproducible across multiple installations, supporting its scalability for industrial emission monitoring in developing country contexts.

Table 7. Field stability performance comparison between locally developed and imported CEMS

Operational condition	Locally developed CEMS	Imported CEMS	Key observation
High temperature (120–150 °C)	Stable (±2 °C drift)	Unstable (±5 °C drift)	Better thermal resilience
High humidity (70–90%)	Stable	Moderately unstable	Effective moisture control via gas conditioning
Voltage fluctuation (±10%)	Stable (±5%)	Unstable (±10%)	Improved power stability handling
Particulate exposure	Low interference	High interference	Better sampling protection design
System uptime	98%	~90–92% (reported)	Higher operational reliability

Statistical verification of system reliability

The reliability of the developed sensor-based CEMS was verified using statistical methods, including SD, coefficient of variation (CV), root mean square error (RMSE), mean absolute error (MAE), regression analysis, and Pearson correlation, as described in the Methods section. All analyses were conducted under consistent calibration and field conditions to ensure comparability and reproducibility. The results show low measurement variability, with CV values consistently below 2% across all gas channels. The system also demonstrates strong agreement with reference data, with a Pearson correlation coefficient of $r = 0.92$ ($p < 0.05$), confirming a statistically significant relationship and indicating stable and repeatable performance under both laboratory and field conditions. Compared with previous CEMS-based emission studies such as Gu et al. (2022) and Sun et al. (2023), which rely mainly on aggregated or secondary emission datasets, the present study provides direct hardware-level validation through calibration and field deployment. Similarly, Wu et al. (2022) emphasized multi-source data fusion for improving emission estimation, but such approaches still depend on existing monitoring infrastructure rather than independently validated systems. In contrast, this study integrates laboratory calibration with real industrial measurements, ensuring that statistical indicators (RMSE, MAE, correlation) reflect actual sensor performance rather than post-processed estimates. This improves transparency and traceability of evaluation and addresses limitations in previous studies related to uncertainty in indirect emission estimation methods (Chen et al., 2019; Liu et al., 2020). Overall, the statistical verification confirms that the system is technically stable and statistically reliable for industrial emission monitoring applications.

Comparative performance and technological positioning

A comparative evaluation of the proposed sensor-based CEMS, imported commercial CEMS, and laser-based systems is summarized in Table 7, highlighting trade-offs between measurement precision, operational cost, and maintainability. Laser-based systems generally provide high accuracy and stability under industrial conditions (Li et al., 2024), but their high cost and complexity limit widespread use, especially in developing countries. In contrast, the proposed system achieves competitive performance with 98% uptime and stable operation under harsh conditions while significantly reducing acquisition and maintenance costs. This aligns with Srivastava et al. (2024), who identified cost and maintenance as key barriers to CEMS adoption, although their work focused on macro-level policy and financial aspects rather than engineering-level performance comparison. Previous studies by Wang et al. (2022) and Yang et al. (2022) also emphasized the importance of reliability and maintenance in real industrial environments, which this study extends by demonstrating that a locally integrated modular design reduces maintenance complexity while maintaining measurement stability. Similarly, Listyarini et al. (2022) noted the potential of IoT-based monitoring systems but highlighted limitations in calibration rigor and long-term robustness, which are addressed here through structured calibration and field validation. Overall, the results position the proposed system as a cost-effective and practically viable alternative for industrial emission monitoring in developing countries, with key performance indicators summarized in Table 8.

Integrated validation framework for substantiation and reproducibility

The concerns regarding substantiation and reproducibility are addressed through a multi-layer validation framework integrating hardware transparency, calibration accuracy, field testing, and statistical verification. Component-level transparency is provided through detailed system documentation (Table 1 and Table 2), which specifies the configuration, origin, and function of each subsystem, addressing limitations in conventional CEMS studies that often report only aggregated or proprietary specifications. Calibration-based validation (Table 4) using certified reference gases and repeated laboratory testing ensures that measurement accuracy is empirically demonstrated rather than assumed, while field reproducibility across multiple PLTU units (Table 8) confirms consistent performance under varying operational conditions such as temperature, humidity, and load fluctuations. These stages form a traceable validation chain from hardware design to calibration, field deployment, and statistical verification, consistent with best practices in emission monitoring

Table 8. Comparative performance of sensor-based CEMS, imported CEMS, and laser-based systems

Parameter	Proposed sensor-based CEMS	Imported CEMS	Laser-based CEMS	Key observation
Measurement precision	Good ($R^2 > 0.99$)	High	Very high	Laser system has highest accuracy
Operational uptime	98%	~90–92%	~95–98%	Proposed system highly stable
Capital cost	Low	High	Very high	Strong cost advantage of proposed system
Maintenance complexity	Low	High	High	Easier maintenance due to modular design
Field robustness	High	Moderate	High	Improved performance under harsh conditions
Calibration flexibility	High	Moderate	Low–moderate	Locally adaptable calibration system

evaluation (Wang et al., 2022; Yang et al., 2022). Reproducibility is further strengthened through standardized experimental procedures, including identical sensor architecture (Figure 1–2), unified sampling design, consistent calibration protocols, repeated measurements, and structured statistical validation, ensuring that results are independent of site or operator variability. In contrast, many prior studies rely on proprietary systems with limited access to hardware and calibration details, restricting independent replication (Srivastava et al., 2024), while data-driven studies such as Gu et al. (2022) and Sun et al. (2023) focus on emission estimation rather than hardware-level validation. By fully documenting system design, calibration, and deployment procedures, this study provides a replicable framework that improves transparency and addresses gaps in standardized validation for sensor-based CEMS.

Limitations

Although the proposed sensor-based CEMS demonstrates strong calibration performance, field stability, and reproducibility, several limitations should be acknowledged. First, the 14-day field validation period is sufficient for short-term operational assessment but not for evaluating long-term sensor drift, aging effects, and maintenance-related degradation, which have been shown to significantly affect CEMS performance over extended operation (Yang et al., 2020; Wang et al., 2022). Therefore, the system should be interpreted as a short-term experimentally validated prototype rather than a fully certified long-term industrial replacement for commercial CEMS. Second, validation was conducted only in coal-fired power plant environments; although this represents a relevant and demanding industrial case, further testing in other sectors such as cement production and petroleum refining is required due to differences in emission characteristics and flue gas composition that may influence sensor stability (Luan et al., 2022; Tong et al., 2023). Third, while statistical validation using RMSE, MAE, and correlation analysis was applied, advanced uncertainty modeling such as Bayesian reliability or probabilistic failure analysis was not included, limiting deeper probabilistic interpretation of system reliability as recommended in recent studies (Yang et al., 2022). Finally, the system does not yet incorporate AI-based adaptive calibration or predictive emission modeling, which could improve accuracy and adaptability in dynamic industrial conditions (Chi et al., 2024; Ding et al., 2023). Overall, these limitations do not reduce the validity of the findings but highlight clear directions for future improvement toward more robust and intelligent emission monitoring systems.

CONCLUSIONS

The present study experimentally evaluated a locally integrated sensor-based Continuous Emission Monitoring System (CEMS) under laboratory calibration and real industrial conditions. The results show that the system can produce accurate and stable multi-gas measurements, with strong agreement to certified reference gases ($R^2 > 0.99$ for CO_2, SO_2, and O_2), low variability across repeated measurements ($CV < 2\%$), and stable performance during 14 days of continuous operation at PLTU Pacitan under high-temperature and high-humidity conditions. These results indicate that a modular, locally integrated architecture can achieve acceptable industrial monitoring performance.

The main contribution of this work is demonstrating that reproducible CEMS performance can be achieved through standardized hardware configuration, traceable calibration procedures, and controlled deployment protocols. Unlike proprietary black-box systems, the proposed framework provides a transparent link between component-level design, calibration traceability, and field performance. The system also achieves a cost reduction of approximately 68.3% compared to imported CEMS while maintaining measurement consistency and operational reliability, indicating its potential as a cost-effective alternative for resource-constrained industrial settings. However, these findings remain within the scope of short-term validation, and further work is needed involving longer deployment periods, broader industrial testing, certified analyzer comparison over extended cycles, and advanced uncertainty modeling. Future research should also explore adaptive calibration, AI-based signal correction, and probabilistic reliability analysis to improve long-term robustness and operational resilience under varying industrial conditions. The availability of complete supplementary datasets and engineering documentation further strengthens the transparency, reproducibility, and independent verification potential of the proposed monitoring framework.

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