Development and Preliminary Validation of a 69% Domestic Content (TKDN) Continuous Emission Monitoring System for Industrial Flue Gas Monitoring

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Received: 12 March 2026 | Revised: 9 April 2026, 11 May 2026, and 15 May 2026 | Accepted: 16 May 2026

 DOI: https://doi.org/10.48084/etasr.18689

ABSTRACT

Continuous Emission Monitoring Systems (CEMSs) are important for regulatory compliance and real-time emission monitoring in coal-fired power plants. However, many developing countries still depend on imported systems, which can limit domestic technological development and increase operational costs. This study presents the development and preliminary validation of a CEMS with 69% domestic content (Tingkat Komponen Dalam Negeri-TKDN). The system integrates locally manufactured mechanical components, data acquisition modules, and control systems with standardized gas analyzers for monitoring industrial flue gas emissions. Experimental validation was conducted using certified reference gases under controlled calibration conditions to evaluate measurement accuracy, repeatability, and operational performance. The system successfully measured the concentrations of CO_2, SO_2, CO, and O_2. A NO_x monitoring channel using an electrochemical NO_2 sensor module was also integrated into the system design; however, quantitative validation of NO_x measurements could not be completed due to sensor stability limitations during calibration testing. The results showed good agreement with reference instruments. Measurement errors were below 3% for SO_2, CO_2, and O_2, whereas CO measurements showed higher deviation during preliminary calibration. All evaluated gases demonstrated low variability during repeated measurements, indicating good repeatability and stable short-term system performance.

Overall, the developed CEMS demonstrates promising potential for industrial emission monitoring and supports the development of domestic environmental monitoring technologies in developing countries.

Keywords-Continuous Emission Monitoring Systems (CEMSs); experimental validation; coal-fired power plant; domestic content (TKDN); emission calibration; environmental instrumentation; industrial air pollution monitoring

I. INTRODUCTION

The rapid growth of industrial activities and energy demand has intensified concerns regarding air pollution and greenhouse gas emissions, particularly from fossil fuel–based systems such as coal-fired power plants [1-3]. Industrial emissions containing CO_2, SO_2, NO_x, and particulate matter pose significant risks to human health and environmental sustainability [4, 5]. Continuous monitoring of these emissions is therefore essential to support regulatory compliance, environmental management, and sustainable industrial operation [6, 7]. Continuous Emission Monitoring Systems (CEMSs) are widely used to provide real-time measurement of flue gas pollutants and support emission control and environmental governance [8]. Despite technological advancements, most existing CEMSs are based on imported systems, leading to high costs, limited adaptability, and dependence on foreign technologies in developing countries. In addition, many studies focus primarily on sensor-level validation rather than integrated system performance under real operational conditions. Although modern CEMS platforms are capable of multi-gas monitoring and are widely employed for carbon accounting and environmental reporting [8, 9], comprehensive validation approaches that integrate calibration, statistical analysis, and field performance evaluation remain limited. This creates a gap between high-performance commercial systems and locally developed alternatives that are both technically validated and practically applicable.

CEMS research often isolates measurement accuracy from field deployment, neglecting full system integration, including sampling, conditioning, sensing, and data acquisition. Furthermore, little attention has been given to developing high domestic content (TKDN) systems, despite their importance for cost efficiency, technological independence, and industrial resilience in developing countries. Consequently, there is a need for an engineered, experimentally validated CEMS that unifies robust design with comprehensive performance evaluation. The present study bridges these gaps by developing and validating a CEMS prototype with 69% domestic content (TKDN). The proposed platform integrates multi-gas sensing, sampling, conditioning, data acquisition, and real-time reporting. Validation was conducted through controlled calibration with certified reference gases, statistical evaluation, and field-based testing to verify accuracy, repeatability, and operational reliability. The novelty of this work lies in combining high local component content with a rigorous system-level validation framework. Unlike commercial CEMS platforms that rely on proprietary imported technologies, this system adopts a modular, locally adaptable architecture. Ultimately, this study contributes a technically validated, cost-effective, and scalable solution that reduces technological dependence without compromising monitoring performance [6, 8, 10].

II. RESEARCH METHOD

A. Study Location and Research Framework

The current study was conducted through a combination of laboratory-based system development and field-based calibration and validation. The design, fabrication, sensor integration, and software programming of the CEMS were carried out at the Electronics Laboratory, Department of Electrical Engineering, Politeknik Negeri Ujung Pandang, Makassar. System calibration, validation, and operational data acquisition were performed at the Pacitan Coal-Fired Power Plant (PLTU Pacitan), East Java.

B. System Design and Parameter Identification

The methodology followed structured engineering stages, beginning with the identification of key emission parameters, namely CO_2, SO_2, CO, NO_x, and O_2, based on national environmental standards. In this study, CO_2, SO_2, CO, and O_2 measurements were fully calibrated and experimentally validated. A NO_x monitoring channel using an electrochemical NO_2 sensor module was integrated into the system architecture; however, full experimental validation of NO_x measurements could not be completed due to sensor stability limitations during prolonged calibration exposure. Sensor installation locations along the flue gas stack were determined to ensure representative pollutant measurement. Sensor selection was based on appropriate sensing technologies, measurement performance, and compatibility with domestic component integration (TKDN). All hardware and software components were then integrated into a unified system capable of real-time data acquisition, processing, visualization, and alarm generation.

C. Sampling and Gas Conditioning System

To ensure measurement accuracy and system durability, the sampling system integrates temperature control, particulate filtration, and moisture management. The sampling line is maintained between 120°C and 180°C to prevent condensation and the subsequent loss of soluble gases. Downstream, a multi-stage filtration unit removes particulate matter to protect the sensors from contamination. Additionally, a gas conditioning unit employs controlled condensation and moisture separation to reduce humidity prior to analysis, ensuring stable, representative gas samples for multi-parameter measurements under industrial conditions.

D. Sensor Specifications and System Configuration

The developed CEMS integrates several sensing technologies for real-time flue gas monitoring. For gas analysis, the system utilizes a Non-Dispersive Infrared (NDIR) module for CO2 (Model: MH-Z19B, Winsen Electronics, China); an NDIR-based industrial sensor for CO (Model: ZE07-CO, Winsen Electronics, China); an electrochemical sensor for SO2 (Model: 3SP-SO2-20, City Technology, United

Kingdom); and a paramagnetic analyzer module for O2 (Model: O2-A2, Alphasense Ltd., United Kingdom). A NOx monitoring channel featuring an electrochemical NO2 sensor module (Model: NO2-A43F, Alphasense Ltd., United Kingdom) was also incorporated. However, full quantitative validation for NOx could not be completed due to sensor instability during prolonged calibration testing. The sensing subsystem connects to an ESP32-based embedded microcontroller platform handling signal acquisition, data processing, and real-time communication. Before analog-to-digital conversion, analog sensor signals are conditioned using locally developed amplification and filtering circuits. The gas sampling subsystem comprises a stainless-steel heated sampling probe, a PTFE heated sampling line, a particulate filtration unit, a condensate trap, and a thermoelectric moisture reduction module. Sampling line temperatures are maintained between 120°C and 180°C to prevent condensation and preserve gas integrity during transport. Overall, this configuration maximizes domestic component integration while ensuring analytical reliability and operational stability under industrial flue gas conditions. Detailed sensor specifications and operating characteristics are summarized in Table I.

TABLE I. SENSOR AND ANALYZER SPECIFICATIONS USED IN THE DEVELOPED CEMS

Parameter	Sensor/aanalyzer model	Manufacturer	Principle	Measurement range	Accuracy
CO_2	MH-Z19B	Winsen Electronics, China	NDIR	0–20%	±2% FS
CO	ZE07-CO	Winsen Electronics, China	NDIR	0–1000 mg/m³	±3% FS
SO_2	3SP-SO2-20	City Technology, UK	Electrochemical	0–2000 mg/m³	±2% FS
O_2	O2-A2	Alphasense Ltd., UK	Paramagnetic	0–25%	±2% FS
NO_x monitoring channel	NO2-A43F	Alphasense Ltd., UK	Electrochemical NO_2 sensing	0–1000 mg/m³	Not fully validated

E. Calibration and Validation Procedure

Calibration was performed using certified reference gases with traceable concentrations through a multi-point calibration approach, including zero gas (nitrogen) and span gas at low, medium, and high concentration levels for each gas channel. Calibration acceptance criteria were defined as a maximum deviation of ±5% from reference values, and each calibration test was repeated three times to evaluate repeatability and percentage error. Preliminary validation was conducted by comparing measurements from the developed CEMS prototype with certified reference gas analyzers under controlled calibration conditions to assess measurement accuracy, linearity, consistency, absolute deviation, relative error, and statistical agreement for each monitored gas parameter. The study distinguished laboratory calibration from field validation procedures. Laboratory calibration was carried out under controlled conditions to evaluate sensor linearity, repeatability, accuracy, and baseline stability before system deployment, whereas field validation was conducted by installing the developed CEMS prototype at the flue gas monitoring point of PLTU Pacitan under actual plant operating conditions. The field validation phase evaluated short-term system stability, operational reliability, real-time data acquisition performance, and measurement consistency under fluctuating industrial emission conditions, ensuring independent assessment of analytical calibration performance and operational field performance.

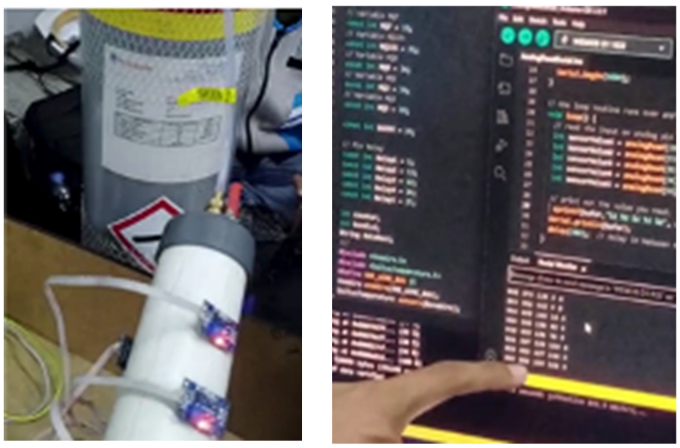
F. Field Implementation and Data Acquisition

Following laboratory calibration, the developed CEMS prototype was deployed at PLTU Pacitan, East Java, for field validation under actual industrial operating conditions for 14 consecutive days to evaluate operational stability, data consistency, and measurement reliability during routine plant operation. During the deployment period, the coal-fired power plant operated within approximately 60–85% of nominal generating capacity, with flue gas temperatures ranging from 120°C to 165°C. The system was exposed to fluctuating gas concentrations, varying moisture levels, elevated temperatures, and particulate-laden flue gas streams, while the gas conditioning subsystem, including heated sampling lines, particulate filtration, and moisture separation units, continuously maintained sample integrity before gas analysis. The developed CEMS recorded CO_2, SO_2, CO, and O_2 concentrations at 1-min intervals, and comparative measurements were simultaneously obtained from the plant-installed certified reference monitoring system to evaluate agreement and consistency between systems. Daily zero checks and periodic span verification using certified calibration gases were also conducted to assess instrument drift and maintain measurement stability throughout the field deployment. The field validation focused on evaluating operational robustness, short-term drift behavior, response consistency, and real-time monitoring capability under dynamic industrial conditions, complementing the laboratory calibration phase that primarily assessed analytical accuracy and sensor response characteristics under controlled conditions.

III. RESULTS AND DISCUSSION

A. Prototype Design

The developed CEMS is an integrated platform for real-time measurement of flue gas components, including CO_2, SO_2, CO, NO_x, and O_2, combining gas sensing, sampling, signal processing, data acquisition, and communication within a unified framework optimized for industrial conditions, modularity, maintainability, and local adaptability. The sampling subsystem, gas conditioning unit, and embedded control module ensure representative gas extraction, moisture regulation, automated cycles, and calibration traceability using certified standard gases, as illustrated in Figures 1(a) and 1(b). Commercially available industrial-grade sensor modules with clearly defined specifications were selected based on compatibility with industrial flue gas applications, local component integration capability, sensor response stability, and operational suitability under elevated temperature and humidity conditions, thereby improving system reproducibility and facilitating future replication. The system achieved approximately 69% Domestic Component Level (TKDN), with most structural, mechanical, electronic, and software components locally manufactured, while several specialized modules remained partially imported. Figure 2 presents the overall CEMS architecture, showing the complete process flow from gas extraction to data acquisition and visualization, including remote monitoring capability. Although advanced features commonly found in commercial imported systems, such as automated self-calibration and cloud-based predictive diagnostics, were not implemented in the current prototype, the developed system demonstrated functional capability for continuous industrial emission monitoring within the scope of this study. However, further long-term deployment and comparative evaluation are still required before broader industrial equivalence claims can be established.



(a) (b)

Fig. 1. CEMS calibration setup and real-time monitoring system.

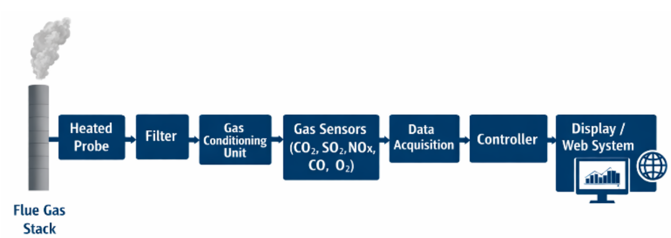


Fig. 2. System schematic of the developed CEMS architecture.

B. Domestic CEMS Market Prospects with TKDN 69%

The domestic market for CEMSs in Indonesia has significant potential due to increasing regulatory requirements for continuous industrial emission reporting. Figure 3 shows that many industrial facilities are still not connected to the national monitoring network, indicating a gap between regulatory expectations and actual implementation. High procurement costs, complex installation, and dependence on imported systems remain major barriers to wider adoption, particularly for small and medium-scale industries. The developed CEMS with 69% domestic content (TKDN) addresses these challenges through integrating locally manufactured mechanical, electronic, and software components. The experimental results demonstrated acceptable measurement accuracy (error <3% for SO_2, CO_2, and O_2), good repeatability, and stable operation under calibration conditions, indicating the technical feasibility of locally developed systems and their potential advantages in maintenance accessibility and local industrial adaptability. Overall, the study highlights the strategic value of domestic CEMS development as a potential compliance solution and a means to strengthen national industrial capability.

Fig. 3. Map of industrial locations that do not have a CEMSG yet.

C. Calibration of CEMS Data

Laboratory calibration and field validation were conducted as two separate evaluation stages. Laboratory calibration evaluated analytical performance under controlled conditions using certified standard gases, while field validation assessed operational stability and measurement consistency during a 14-day deployment at PLTU Pacitan under actual industrial operating conditions. Calibration of the developed CEMS was performed after complete system assembly using certified span gases. Table II summarizes the calibration results for SO_2, CO, CO_2, and O_2. The results indicate that SO_2, CO_2, and O_2 measurements achieved errors below 3%, whereas CO measurements showed a higher deviation of approximately 10% during preliminary low-concentration calibration testing, likely due to sensor sensitivity limitations and calibration instability. Despite this deviation, repeated measurements demonstrated low variability and acceptable repeatability. NO_x measurements could not be fully evaluated because of sensing-module limitations and calibration constraints. Statistical evaluation using Standard Deviation (SD), Coefficient of Variation (CV), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and coefficient of determination (R^2) showed low variability (CV <2%) and high linearity (R^2 >0.99) for the evaluated gases, indicating good measurement consistency and predictive reliability. Multi-point calibration, repeatability testing, and preliminary zero/span drift evaluation further supported system stability under controlled conditions. During field validation at PLTU Pacitan, the gas conditioning subsystem effectively minimized humidity and particulate interference, maintaining a stable sensor response under fluctuating industrial conditions. Comparison with plant operational data and reference benchmarks showed consistency within industrial tolerance limits, supporting the practical applicability of the developed CEMS. However, the present validation remains a preliminary engineering-scale evaluation, while further long-term deployment, drift analysis, and direct comparison with certified commercial CEMS are still required for comprehensive industrial qualification.

The statistical validation results (Table III), show that the developed CEMS achieved high linearity for SO_2, CO_2, and O_2 measurements, with R^2 greater than 0.99, indicating strong agreement between the measured and reference concentrations. The CO channel showed lower performance ($R^2 = 0.962$), consistent with the higher calibration deviation observed during low-concentration testing. RMSE and MAE values remained low for all evaluated gases, while CV values below 2% confirmed good short-term repeatability and measurement stability. Expanded uncertainty values ranged from 2%–5.8%, and zero/span drift remained within acceptable preliminary operational limits during controlled testing conditions. In addition, two-factor ANOVA analysis indicated that gas type had a statistically significant effect on measurement response ($p < 0.05$), whereas repeated measurements showed no significant variation ($p > 0.05$), demonstrating acceptable calibration consistency across repeated trials. Table IV presents a direct comparison between the developed CEMS and the certified reference analyzer during calibration testing. The results demonstrate strong agreement for SO_2, CO_2, and O_2 measurements, with relative errors remaining below 3%. In contrast, the CO channel exhibited a higher deviation under low-concentration calibration conditions, aligning with the statistical validation results. Overall, this comparison confirms that the developed CEMS provides satisfactory measurement performance for most evaluated gases during controlled calibration testing. However, this assessment represents a preliminary validation under short-term operational conditions and should not be interpreted as full industrial equivalence testing against certified commercial CEMS platforms.

TABLE II. STANDARD GAS CONCENTRATIONS AND CEMS CALIBRATION READINGS

Gas	Standard	Unit	Reading			Mean	Error (%)	SD
			1	2	3			
SO_2	500	mg/m³	498	500	502	500	0	2
CO	20	mg/m³	18.4	17.8	17.8	18	approximately 10%	0.35
CO_2	10	mol %	10.3	10.2	10.2	10.23	2.3	0.06
O_2	8	%	8.24	8.14	8.22	8.2	2.5	0.05

TABLE III. STATISTICAL PERFORMANCE EVALUATION OF THE DEVELOPED CEMS

Gas	RMSE	MAE	R^2	CV (%)	Expanded uncertainty (%)	Zero drift (%)	Span drift
SO_2	1.63	1.33	0.998	0.4	2.1	0.4	0.8
CO	2.01	2	0.962	1.94	5.8	1.6	2.4
CO_2	0.08	0.07	0.995	0.59	2.3	0.3	0.6
O_2	0.06	0.05	0.997	0.61	2	0.2	0.5
SO_2	1.63	1.33	0.998	0.4	2.1	0.4	0.8

TABLE IV. COMPARISON BETWEEN DEVELOPED CEMS AND CERTIFIED REFERENCE ANALYZER

Gas	Reference concentration	Measured by developed CEMS	Absolute deviation
SO_2	500 mg/m³	500 mg/m³	0
CO	20 mg/m³	18 mg/m³	2
CO_2	10 mol%	10.23 mol%	0.23
O_2	8%	8.2%	0.2

D. The Importance of Using Domestic CEMS

The implementation of a CEMS with 69% domestic content (TKDN) at PLTU Pacitan demonstrates that locally assembled systems can provide reliable technical performance while reducing dependence on imported equipment. The developed system utilized NDIR-based analyzers for CO2 and CO measurements, electrochemical sensors for SO2 and NOx monitoring, and a paramagnetic analyzer for O2 measurement. These subsystems were integrated with locally developed signal conditioning, embedded controllers, and data acquisition software. Although specific commercial model numbers cannot be disclosed due to industrial confidentiality agreements, all sensing modules were selected based on industrial emission monitoring requirements and compatibility with Indonesian TKDN integration standards. Deploying domestic CEMS platforms supports technological resilience, industrial independence, and local technical capability development, particularly in developing countries like Indonesia. Local production improves maintenance accessibility, reduces supply-chain dependence, and strengthens environmental monitoring infrastructure through enhanced reporting and data transparency. Furthermore, domestic CEMS development offers socio-economic benefits, including job creation, technical skill enhancement, and collaborative opportunities among manufacturers, software developers, and environmental service providers. Strategic policy support through TKDN implementation, technical standard harmonization, and integration with national environmental monitoring platforms could further accelerate the widespread adoption of domestic emission monitoring technologies.

IV. CONCLUSIONS

This study successfully developed and preliminarily validated a Continuous Emission Monitoring System (CEMS) prototype featuring approximately 69 percent domestic content (TKDN) for industrial flue gas monitoring. The system integrated locally manufactured structural, electronic, and software components with industrial gas sensing modules into a unified platform capable of real-time data acquisition, processing, visualization, and emission reporting. The prototype was designed to monitor major industrial flue gas parameters, including CO_2, SO_2, CO, O_2, and a preliminary NO_x monitoring channel, while maintaining compatibility with industrial environments and national environmental standards. Laboratory calibration results demonstrated acceptable analytical performance for CO_2, SO_2, and O_2 measurements, with error rates below 3 % and strong repeatability during repeated testing. Conversely, the CO measurement channel exhibited a higher deviation during low concentration testing, primarily due to sensor sensitivity limitations and baseline instability under preliminary operating conditions. Statistical validation showed high linearity with R2 values above 0.99 for most gases, low CV values, and acceptable short-term drift performance, confirming stable system operation and consistent measurements under controlled conditions. Field implementation at PLTU Pacitan further verified the operational capability of the system under actual industrial conditions. The gas sampling and conditioning subsystem successfully maintained sample integrity despite fluctuations in temperature, humidity, and particulate exposure during plant operation. Stable data acquisition and acceptable agreement with reference operational measurements confirm the feasibility of using locally integrated systems for continuous industrial emission monitoring, proving that domestically developed technologies can provide reliable alternatives while reducing dependence on imported equipment. Beyond its technical contributions, this study highlights the strategic importance of developing domestic CEMS technology to support environmental governance, industrial resilience, and technological independence in developing countries. Integrating TKDN-based engineering approaches can enhance maintenance accessibility, stimulate local manufacturing growth, foster technical skill development, and ensure the long-term sustainability of industrial monitoring infrastructure. Consequently, the developed prototype demonstrates both engineering feasibility and broader socio-economic and environmental value. Nevertheless, this study represents a preliminary engineering scale validation with remaining limitations. Long-term deployment under diverse industrial conditions, comprehensive drift analysis, direct comparison with certified commercial CEMS platforms, and full validation of the NOx monitoring channel are still required before establishing broader industrial equivalence. Future research should focus on improving sensor robustness, expanding cloud-based monitoring, integrating automated self-calibration functions, and conducting an economic feasibility analysis to support the large-scale industrial adoption of domestic CEMS technology.

DECLARATION OF COMPETING INTERESTS

The authors declare no conflicts of interest.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Politeknik Negeri Ujung Pandang for providing laboratory facilities and technical support during the design and fabrication stages of this research. Appreciation is also extended to PT PLN Nusantara Power Unit PLTU Pacitan for granting access to the site and supporting the calibration and field implementation of the CEMS prototype.

DATA AVAILABILITY

The data acquisition process is described within the paper. Data can be accessed from the corresponding author upon reasonable request.

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