

Stoichiometric Combustion Modeling and Regulatory Compliance Assessment of Indonesian Sub-bituminous Coal: Implications for Clean Coal Technology Deployment

Robekca Purba* and Nyimas Ulfatry Utami

Department of Mining Engineering, Faculty of Engineering, Universitas Sriwijaya Jln. Raya Palembang Prabumulih KM 32 Indralaya Ogan Ilir

*Corresponding Author: robekcapurba2@ft.unsri.ac.id

Abstract

Coal is an important energy source, but its utilization must consider quality and environmental aspects for sustainability. This study aims to characterize coal from Muara Enim Regency and to evaluate its energy utilization potential. A 2.365 kg coal sample was analyzed at Geoservice laboratory, Bandung. Proximate analysis results showed total moisture 6.26%, ash content 10.63%, volatile matter 37.84%, and fixed carbon 47.71%. Ultimate analysis revealed carbon 68.56%, hydrogen 5.12%, nitrogen 1.42%, oxygen 13.71%, and sulfur 0.56%. The calorific value is 6,900 kcal/kg with fuel ratio 1.26. These parameters classify the coal as Sub-bituminous B with good combustion characteristics. Stoichiometric calculations determined theoretical air requirements of 2.24 kg/kg coal, producing 2.51 kg CO₂, 0.46 kg H₂O, 0.0009333 kg NO₂ and 0.0112 kg SO₂. Theoretical SO₂ emissions (1.557 mg/Nm³) exceed Indonesian regulations, requiring Flue Gas Desulfurization (FGD) installation. The coal has good energy potential with low sulfur content, suitable for power generation with proper emission control technology. This study provides a database for optimizing energy systems and clean coal technologies..

Keywords: coal characterization; calorific value; combustion stoichiometry; clean coal technology, coal chemistry

Article Info

Received 19 November 2026
Received in revised 25 February 2026
Accepted 26 February 2026
Available Online 28 February 2026

Abstrak (Indonesian)

Batubara merupakan sumber energi penting, namun pemanfaatannya harus mempertimbangkan aspek kualitas dan lingkungan demi keberlanjutan. Penelitian ini bertujuan untuk mengkarakterisasi batubara dari Kabupaten Muara Enim serta mengevaluasi potensi pemanfaatan energinya. Sampel batubara seberat 2,365 kg dianalisis di laboratorium Geoservice, Bandung. Hasil analisis proksimat menunjukkan total kelembaban 6,26%, kadar abu 10,63%, zat terbang 37,84%, dan karbon tetap 47,71%. Analisis ultimat mengungkapkan kandungan karbon 68,56%, hidrogen 5,12%, nitrogen 1,42%, oksigen 13,71%, dan sulfur 0,56%. Nilai kalor batubara adalah 6.900 kkal/kg dengan rasio bahan bakar 1,26. Parameter-parameter ini mengklasifikasikan batubara sebagai Sub-bituminous B dengan karakteristik pembakaran yang baik. Perhitungan stoikiometri menentukan kebutuhan udara teoritis sebesar 2,24 kg/kg batubara, menghasilkan 2,51 kg CO₂, 0,46 kg H₂O, 0,0009333 kg NO₂, dan 0,0112 kg SO₂. Emisi SO₂ teoritis (1,557 mg/Nm³) melebihi regulasi Indonesia, sehingga memerlukan pemasangan instalasi Flue Gas Desulfurization (FGD). Batubara ini memiliki potensi energi yang baik dengan kandungan sulfur rendah, cocok untuk pembangkit listrik dengan teknologi pengendalian emisi yang tepat. Studi ini menyediakan basis data untuk optimasi sistem energi dan teknologi batu bara bersih

Kata Kunci: karakterisasi batubara; nilai kalor; stoikiometri pembakaran; teknologi batubara bersih; kimia batubara

INTRODUCTION

Coal originates from accumulated organic materials deposited over geological time scales, undergoing biochemical and geochemical transformations that enhance its energy density. Indonesia remains a key global coal producer, with South Sumatra particularly Muara Enim Regency contributing significantly to national output. Despite the global shift toward renewables, coal still supplies approximately 36% of global electricity, especially in developing economies where it supports energy security and industrial growth [1].

To evaluate coal suitability for energy conversion and environmental compliance, proximate and ultimate analyses are essential standard procedures [2, 3]. Proximate analysis quantifies moisture, ash, volatile matter, and fixed carbon parameters that directly influence combustion behavior, boiler efficiency, and handling characteristics [2], [3]. Ultimate analysis determines elemental composition (C, H, N, S, O), which is critical for stoichiometric modeling of combustion, emission prediction, and carbon accounting [5].

Recent advances in coal characterization emphasize integration with predictive modeling and emission control strategies, especially for sub-bituminous coals, which exhibit higher moisture and lower calorific value but are abundant in Indonesia [6, 7]. Clean coal technologies (CCTs), such as fluidized bed combustion and flue gas desulfurization (FGD), rely heavily on accurate proximate/ultimate data to optimize performance and meet environmental regulations [8, 9]. This study aims to: (1) characterize the quality and rank of sub-bituminous coal from Muara Enim, South Sumatra, through standardized proximate and ultimate analyses (ASTM methods), and evaluate its suitability for thermal power generation based on combustion behavior and energy content; and (2) assess its environmental impact by quantifying theoretical CO₂ and SO₂ emissions, and evaluate compliance with Indonesian emission regulations to inform clean coal technology deployment.

MATERIALS AND METHODS

Materials

A representative 2.365 kg coal sample was collected from Muara Enim, South Sumatra, using the ASTM D2234 incremental sampling method [8] to ensure homogeneity. The sample was stored in hermetically sealed vessels to avoid oxidation and the absorption or loss of water before it was analyzed at

PT. Geoservice (Bandung), an ISO/IEC 17025 accredited laboratory.



Figure 1. Coal Sample

Method

Proximate and Ultimate Analysis

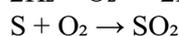
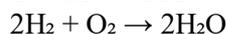
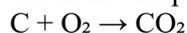
Proximate and Ultimate Analysis. All analyses followed current ASTM standards (Table 1) as validated in modern coal characterization protocols [11, 10].

Table 1. Proximate and ultimate analysis standard method

Analyses	Methods
Total Moisture	ASTM D3302/D3302M-22a
Moisture in the analysis sample	ASTM D3173/D3173M-17a
Ash Content	ASTM D3174-12(2018) e1
Volatile Matter	ASTMD3175.20
Fixed Carbon by difference	ASTM D3172-13(202r) e1
Total Sulphur (Instrument method)	ASTM D4239 Method.A-2018e1
Gross Calorific Value	ASTM D5865/D55865M-19
Ultimate Analysis (CHN Instrument)	ASTM D5373-21 Metode A

Combustion Stoichiometry Calculations

Theoretical air and emission calculations were based on complete combustion reactions [5], [10].



Air was assumed to contain 23.15% O₂ and 76.85% N₂ by mass. CO₂ and SO₂ emissions were expressed in kg/kg coal and normalized to kWh using a base plant efficiency of 35%.

RESULTS AND DISCUSSION

Proximate and Ultimate Analysis

The coal exhibits characteristics typical of Sub-bituminous B rank (ASTM D388-23) [11].

Table 2. Proximate and ultimate analysis result

Parameter	Unit	Basis	Result
Total Moisture	%	ar	6.26
Moisture in the analysis sample	%	adb	3.82
Ash Content	%	adb	10.63
Volatile Matter	%	adb	37.84
Fixed Carbon by difference	%	adb	47.71
Total Sulphur (Instrument method)	%	adb	0.56
Gross Calorific Value	kcal/kg	adb	6900
Carbon	%	adb	68.56
Hydrogen	%	adb	5.12
Nitrogen	%	adb	1.42

These properties align with sub-bituminous coals studied in Southeast Asia, which show high volatile content and moderate ash, making them suitable for pulverized coal and circulating fluidized bed (CFB) systems [6]. The total moisture of 6.26% (ar) represents the overall water content in the sample as received from the field, while moisture in the analysis sample of 3.82% (adb) shows the water content after air drying (**Table 2**). This difference indicates surface water loss of 2.44% during the air-drying process, which is standard practice in coal sample preparation for laboratory analysis [2]. The total moisture of 6.26% is within the acceptable range for sub-bituminous coal and indicates proper storage and handling. High moisture content (>15%) can significantly reduce effective calorific value and increase transportation costs, while very low moisture content (<3%) can increase the risk of spontaneous combustion, which is very dangerous in storage processes [12]. The observed total moisture indicates an optimal balance between storage stability and energy efficiency. The moisture in the analysis sample of 3.82% shows that after air drying, the sample still retains inherent moisture content, which is a natural characteristic of sub-bituminous coal [7].

The ash content of 10.63% is considered moderate for thermal coal types. High ash can cause operational problems such as slagging and fouling on boiler heating surfaces, reduce heat transfer efficiency, and increase disposal costs [13]. Conversely, low ash content (<6%) is optimal for power plants as it minimizes maintenance and maximizes combustion efficiency. Compared to Banten PLTU 3 specifications with maximum coal ash content at 6% (adb), this coal does not meet those requirements. However, it meets the requirements of Paiton PLTU

(max. 15%), Suralaya (max. 12%), and Cilacap (max. 18%). The observed ash content is suitable for various combustion technologies while maintaining good calorific value [14].

Fuel ratio is an important parameter for assessing coal quality and combustion behavior. The ratio of fixed carbon to volatile matter (fuel ratio) is calculated as follows:

$$\text{Fuel Ratio (FR)} = \frac{\text{Fixed Carbon (FC)}}{\text{Volatile Matter (VM)}} \dots \dots \dots (1)$$

The fuel ratio indicates a balance between rapidly combustible components (VM) and stable combustion components (FC). The FR in this study is 1.26, indicating balanced combustion characteristics. A fuel ratio between 1 and 3 generally indicates good ignition ease and flame stability. Coal with a fuel ratio <1.0 is easily ignited but has a short flame, while those with a fuel ratio >3.0 are difficult to ignite but provide stable and long-lasting flames [3]. The observed fuel ratio indicates that this coal will show good ignition characteristics with stable combustion, making it suitable for pulverized coal combustion systems and fluidized bed boiler technology [8].

Ultimate analysis revealed the following elemental composition on an air-dried basis: carbon 68.56%, hydrogen 5.12%, nitrogen 1.42%, oxygen 13.71% (by difference), and sulfur 0.56%. The high carbon content directly contributes to calorific value, as carbon combustion ($C + O_2 \rightarrow CO_2$) releases 8,100 kcal/kg carbon, representing the main energy contribution in coal [5].

Hydrogen content of 5.12% is within the typical range for sub-bituminous coal. Hydrogen combustion ($2H_2 + O_2 \rightarrow 2H_2O$) releases approximately 34,000 kcal/kg hydrogen, contributing about 7–8% to total calorific value despite its relatively small mass fraction [5]. However, hydrogen combustion produces water, which reduces net calorific value due to latent heat of vaporization (approximately 600 kcal/kg H_2O) [15].

Nitrogen content of 1.42% is typical for coal and generally does not contribute to calorific value but is important for environmental considerations. During combustion, fuel nitrogen can be partially converted to nitrogen oxides (NO_x), which are regulated air pollutants. Bound nitrogen in coal generally produces 20–40% NO_x conversion depending on combustion conditions [16].

Oxygen content of 13.71% is also typical for sub-bituminous coal. Oxygen in coal does not contribute to calorific value and actually reduces it

because some oxygen is already combined with hydrogen and carbon in the coal molecular structure. Coal with higher oxygen generally has lower calorific value compared to coal with higher carbon at the same rank [15].

Coal Quality Evaluation Based on Proximate and Ultimate Analysis

Coal quality evaluation was conducted comprehensively based on proximate and ultimate parameters that have been analyzed. From the proximate aspect, coal shows medium-high quality characteristics with a calorific value of 6,900 kcal/kg, indicating adequate energy content for thermal applications [11, 14]. Total moisture of 6.26% is at an optimal level that maintains balance between energy efficiency and storage safety [12]. Fuel ratio of 1.26 indicates balanced combustion characteristics, combining ignition ease from volatile matter (37.84%) with combustion stability from fixed carbon (47.71%) [3].

Ash content of 10.63% becomes a critical parameter in quality evaluation. This value is in the medium category and becomes a limiting factor for certain applications. Comparison with PLTU specifications shows that this coal meets the requirements of Paiton PLTU (max. 15%), Suralaya (max. 12%), and Cilacap (max. 18%), but does not meet the specifications of Banten PLTU 3, which requires maximum ash content of 6% [17]. This indicates that the coal is suitable for power plants with medium ash tolerance but requires adequate ash handling systems [7].

Evaluation based on ultimate parameters shows favorable composition for energy conversion. Carbon content of 68.56% is the main energy-forming component and is at a good level for sub-bituminous coal [2]. Sulfur content of 0.56% is a major advantage of this coal, classifying it as low-sulfur coal (<1% S), which is environmentally friendly [7]. The H/C ratio of 0.075 and oxygen content of 13.71% indicate a coal maturity level consistent with sub-bituminous classification [15].

Coal classification based on ASTM D388-23 [11] places this sample in the Sub-bituminous B coal category, with a calorific value of 6,900 kcal/kg slightly above the typical range of 5,833–6,389 kcal/kg for this rank, likely due to sampling or regional variation, which is common in Indonesian deposits [11, 14]. Overall, quality evaluation places this coal at a medium-good grade, with main advantages in low sulfur content and balanced combustion characteristics, and limitations in moderate ash content. This coal is feasible for

utilization in power plants and industries that have adequate ash handling infrastructure [6].

Potential for Energy Generation Utilization

Based on the evaluated characteristics, this coal has wide utilization potential for energy generation. The main application is for coal-fired power plants (PLTU) with pulverized coal combustion technology. A calorific value of 6,900 kcal/kg meets minimum requirements for efficient PLTU operation, with power generation potential of approximately 0.8–1.0 MWh per ton of coal at plants with 32–35% efficiency [1].

Besides power plants, this coal also has potential for industrial applications requiring steam or process heat. Cement, fertilizer, paper, and textile industries can utilize this coal as industrial boiler fuel with a capacity of 10–100 tons/hour [6]. Low sulfur content (0.56%) becomes a competitive advantage, reducing investment and operational costs for desulfurization systems [17]. Ash content of 10.63% is still acceptable for industrial applications, with potential utilization of ash as cement raw material or construction aggregate [13].

Energy efficiency potential that can be achieved depends on the technology used. For conventional subcritical power plants (steam pressure <22 MPa), net thermal efficiency that can be achieved is 32–35%. Supercritical technology (steam pressure 22–25 MPa, temperature 540–565°C) can increase efficiency to 38–40% (**Figure 2**). For ultra-supercritical technology (pressure >25 MPa, temperature >580°C), efficiency potential can reach 42–45% [8, 9]. Use of co-firing technology with biomass is also possible to increase sustainability and reduce carbon emission intensity [13, 8].

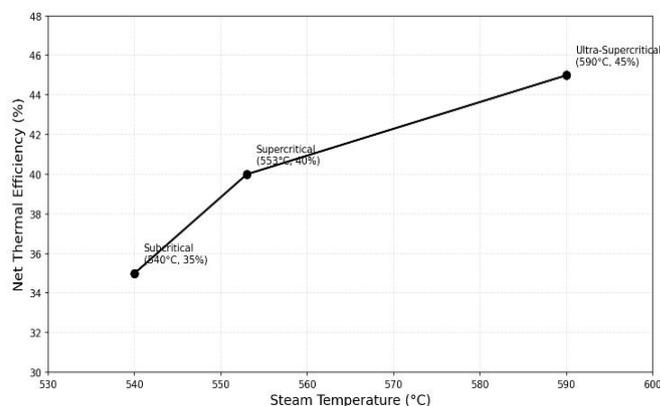


Figure 2. Correlation Between Steam Temperatur (°C) and Net Thermal Efficiency(%)

Advantages of this coal for energy utilization include: (1) adequate calorific value for efficient

power generation, (2) low sulfur content minimizing emission control system complexity, (3) balanced combustion characteristics for stable operation, and (4) good fuel ratio for ignition ease and flame stability [3, 5]. The main limitation is moderate ash content, requiring adequate ash handling systems and higher cleaning frequency to prevent slagging and fouling on boiler heating surfaces [7].

From a technical operational perspective, this coal has good feasibility for large-scale energy utilization. Stable combustion characteristics enable continuous operation with minimal load fluctuations [5]. Low sulfur content reduces the need for complex desulfurization systems, simplifying emission control system design [17]. Potential coal consumption for 100–200 MW capacity power plants is estimated at 500,000–1,000,000 tons per year, depending on plant efficiency and operating capacity factor [1].

Environmental and Emission Assessment

In this study, the oxygen content of the coal was not measured directly and therefore had to be determined indirectly using the following mass balance equation:

$$O = 100\% - (C + H + N + S + \text{ash} + \text{moisture}) \dots \dots \dots (2)$$

Based on this calculation, the oxygen content was found to be 9.89% adb.

The ultimate and proximate analyses of the coal sample were reported on a per-kilogram basis. The mass of each elemental component was then calculated using Equation (3), with results summarized in **Table 3**.

$$\text{Massa unsur} = \% \text{ unsur} \times 1000 \text{ g} \dots \dots \dots (3)$$

Table 3. Elemental composition of coal

Component	% Element (adb)	Mass (kg)
Carbon (C)	68.56	0.6856
Hydrogen (H)	5.12	0.0512
Nitrogen (N)	1.42	0.0142
Sulphur (S)	0.56	0.0056
Oxygen (O)*	9.89	0.0989
Ash	10.63	0.1063
Moisture	3.82	0.0382

To determine the theoretical oxygen (and air) requirement, predict combustion products, and evaluate energy efficiency, a stoichiometric combustion analysis was conducted assuming

complete combustion of all combustible elements [4]. The governing reactions are as follows [5]:

1. Carbon (C)
 $C + O_2 \rightarrow CO_2$
 $m_{O_2} = m_C \times (MO_2 / MC) \dots \dots \dots (4)$
2. Hydrogen (H)
 $2H_2 + O_2 \rightarrow 2H_2O$
 $m_{O_2} = m_{H_2} \times (MO_2 / 2MH_2) \dots \dots \dots (5)$
3. Sulfur (S)
 $S + O_2 \rightarrow SO_2$
 $m_{O_2} = m_S \times (MO_2 / MS) \dots \dots \dots (6)$
4. Nitrogen (N)
 $N + O_2 \rightarrow NO_2$
 $m_{O_2} = m_N \times (MO_2 / MN) \dots \dots \dots (7)$

After determining the oxygen required for each element, the mass (in kg) of the combustion products is subsequently calculated.

1. CO₂
 $m_{CO_2} = m_C \times \frac{M_{CO_2}}{M_C} \dots \dots \dots (8)$
2. H₂O
 $m_{H_2O} = m_H \times \frac{M_{H_2O} \times 2}{M_{H_2} \times 2} \dots \dots \dots (9)$
3. SO₂
 $m_{SO_2} = m_S \times \frac{M_{SO_2}}{M_S} \dots \dots \dots (10)$
4. NO₂
 $m_{NO_2} = m_N \times \frac{M_{NO_2}}{M_N} \dots \dots \dots (11)$

The mass of each combustion product was subsequently calculated using analogous stoichiometric relationships (Equations 8–11). Critically, only 2% of the fuel-bound nitrogen is assumed to be converted to NO_x (reported as NO₂ equivalent), consistent with empirical data from coal combustion studies [16]. The results of the stoichiometric calculations are presented in **Table 4**.

Table 4. Stoichiometric oxygen demand and combustion product yields

Input Component	Input mass (kg)	O ₂ Required (kg)	Product	Product Mass (kg)
Carbon (C)	0.6856	1.8283	CO ₂	2.5139
Hydrogen (H)	0.0512	0.4096	H ₂ O	0.4608
Nitrogen (N)	0.0142	0.000649	NO ₂	0.000933
Sulphur (S)	0.0056	0.0056	SO ₂	0.0112

The resulting combustion product masses (in kg) were converted to concentration units (mg/Nm³) to

enable direct comparison with the emission limits stipulated in Indonesian Minister of Environment and Forestry Regulation No. P.15/MENLHK/SETJEN/KUM.1/4/2019 concerning Emission Standards for Thermal Power Plants [17].

In the context of environmental impact assessment for fossil fuel-based thermal processes, accurate quantification of flue gas volume is fundamental to determining atmospheric pollutant concentrations. This study adopts the dry flue gas basis—excluding water vapor—as the reference standard for evaluating CO₂, SO₂, and NO₂ emissions from coal combustion. This approach aligns with international conventions and national regulatory requirements, including the aforementioned Indonesian regulation, which mandates emission reporting on a dry basis [17].

Based on the coal's ultimate analysis, the total dry flue gas volume was calculated as 7.194 Nm³ per kg of coal, comprising CO₂, SO₂, NO₂, and nitrogen from combustion air, with water vapor excluded. This volume serves as the critical denominator for converting pollutant masses (in milligrams) into standard concentration units (mg/Nm³). The resulting concentrations and their comparison with regulatory limits are shown in Table 5.

Table 5. Emission concentrations vs. regulatory limits for coal-fired steam power plants

product	Dry flue gas volume (Nm ³)	Concentration (mg/ Nm ³)	Emission limit (mg/ Nm ³)
NO ₂	7.194	130	200
SO ₂	7.194	1.557	200

Flue gas emission characterization is a critical step in evaluating the environmental performance of coal-fired power generation. Based on stoichiometric combustion modeling of a representative high-volatile bituminous coal (C: 68.56 wt%, S: 0.56 wt%, N: 1.42 wt%), the dry flue gas volume was determined to be 7.194 Nm³ per kg of coal burned (**Table 5**). Assuming a 2% conversion of fuel-bound nitrogen to NO_x (reported as NO₂-equivalent), the predicted emission concentrations are 130 mg/Nm³ for NO₂ and 1,557 mg/Nm³ for SO₂, referenced to dry gas conditions at standard temperature and pressure [4, 16].

When benchmarked against the emission limits in Regulation No. P.15/2019 for existing steam power plants (PLTU), a clear regulatory divergence emerges [17]. The calculated NO₂ concentration (130 mg/Nm³) remains below the statutory threshold of 200 mg/Nm³,

indicating compliance with national standards for nitrogen oxides. In contrast, the SO₂ emission (1,557 mg/Nm³) exceeds the permitted limit of 200 mg/Nm³ by nearly eightfold, signaling non-compliance in the absence of post-combustion emission controls. High SO₂ emissions cause equipment corrosion, as SO₂ reacts with water vapor to form sulfuric acid (2SO₂ + O₂ + 2H₂O → 2H₂SO₄), a well-documented issue in boiler systems [5], [17].

This elevated SO₂ emission is directly attributable to the coal's sulfur content (0.56%), which—moderate by global standards—is incompatible with stringent emission limits without flue gas desulfurization (FGD) technology [17]. These findings underscore the necessity of deploying advanced air pollution control systems, particularly wet or dry scrubbers, for sulfur mitigation in coal-fired power plants utilizing medium to high-sulfur coals [8]. Conversely, NO_x emissions—governed by fuel-bound nitrogen and thermal formation mechanisms—remain within allowable ranges under the assumed 2% conversion factor, suggesting that selective noncatalytic reduction (SNCR) or combustion optimization may suffice for future compliance should conversion rates increase [16].

This analysis highlights the critical role of fuel composition, conversion efficiency assumptions, and regulatory benchmarking in emission forecasting. It further emphasizes that compliance strategies must be pollutant-specific: while NO_x management may be achievable through combustion tuning, SO₂ control unequivocally requires end-of-pipe treatment to meet contemporary environmental standards [6, 17].

The CO₂ emission intensity expressed as kg CO₂ per kWh of electricity generated—was calculated using fundamental coal properties: carbon content (68.56%) and gross calorific value (GCV = 6,900 kcal/kg). Based on stoichiometric combustion, the theoretical CO₂ yield from 1 kg of coal was determined to be 2.514 kg CO₂/kg coal. To derive the electricity output per kilogram of coal, the following equation was used:

$$\text{CO}_2 \text{ emission intensity} = \frac{m_{\text{CO}_2}}{E_{\text{electrical}}} \dots\dots\dots(12)$$

The CO₂ emission intensity was then calculated using:

$$E_{\text{electrical}} \text{ conversion factor} = \text{GCV} \times \eta_{\text{plant}} \times \dots\dots(13)$$

CO₂ emission intensity in this study is 0.921 kg CO₂/kWh. This value is representative of sub-bituminous coals globally (typically 0.85–0.95 kg/kWh) and serves as a baseline for decarbonization

strategies [1]. For context, upgrading to supercritical technology ($\eta \approx 40\%$) would reduce this to 0.78 kg/kWh, while co-firing with 20% biomass could lower it to 0.72 kg/kWh, and ultra supercritical could lower it to 0.70 kg/kWh [8, 9] as shown in **Figure 3**.

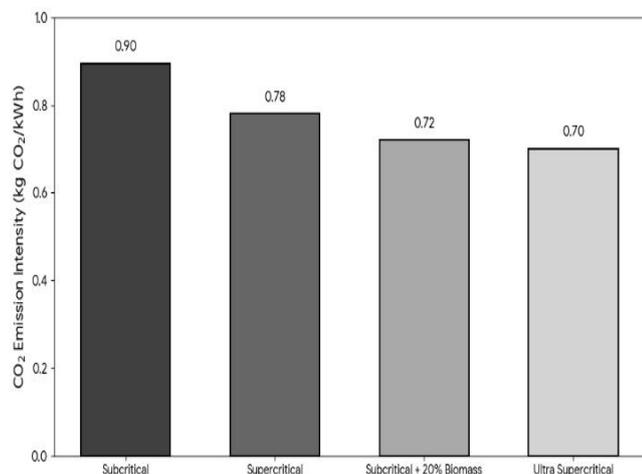


Figure 3. Comparative analysis of CO₂ emission intensity under different technology scenarios

Recommendations for environmental impact mitigation include: (1) SO₂ mitigation: Installation of a flue gas desulfurization (FGD) system is mandatory for regulatory compliance if used in power generation [17]; (2) CO₂ mitigation: Adoption of supercritical/ultra-supercritical boilers and/or co-firing with biomass can significantly lower emission intensity [8, 9]

CONCLUSION

This study provides a comprehensive characterization and stoichiometric assessment of sub-bituminous B coal from Muara Enim, South Sumatra, Indonesia, demonstrating its viability for thermal power generation while highlighting critical environmental challenges. Proximate and ultimate analyses revealed favorable combustion properties, including a gross calorific value of 6,900 kcal/kg, moderate ash content (10.63% adb), and low sulfur (0.56% adb), classifying the coal as suitable for pulverized coal and fluidized bed systems [11, 2]. Stoichiometric modeling indicated theoretical oxygen demand of 1.585 kg O₂/kg coal and combustion products comprising 2.514 kg CO₂/kg coal, 0.011 kg SO₂/kg coal, and minimal NO₂ (0.0009 kg/kg coal, assuming 2% fuel-N conversion), yielding a dry flue gas volume of 7.194 Nm³/kg coal [4, 5, 16]. Emission evaluations against Indonesian regulatory standards (Regulation No.

P.15/MENLHK/SETJEN/KUM.1/4/2019) showed compliance for NO₂ (130 mg/Nm³ < 200 mg/Nm³ limit) but significant exceedance for SO₂ (1,557 mg/Nm³ > 200 mg/Nm³ limit), underscoring the necessity for flue gas desulfurization (FGD) systems [17]. The calculated CO₂ emission intensity of 0.921 kg CO₂/kWh aligns with global benchmarks for sub-bituminous coals, with potential reductions to 0.70–0.78 kg/kWh through supercritical/ultra-supercritical technologies or biomass co-firing [1, 8, 9].

These findings affirm the coal's potential for energy security in Indonesia's developing economy, provided clean coal technologies (CCTs) are deployed to mitigate SO₂ and CO₂ impacts [6]. Future research should incorporate empirical combustion tests under varying excess air ratios and integrate life-cycle assessments to optimize CCT implementation, ensuring sustainable coal utilization amid global decarbonization efforts [7, 1].

REFERENCES

- [1] International Energy Agency, *Coal 2023: Analysis and forecast to 2026*. Paris, France, 2023.
- [2] D. Racero-Galaraga, J.D. Rhenals-Julio, S. Sofan-German, J. M. Mendoza, and A. Bula-Silvera, "Proximate analysis in biomass: Standards, applications and key characteristics," *Results in Chemistry*, vol. 12, p. 101886, 2024.
- [3] R.D. Riski, A. Octova, Y.M. Anaperta Anaperta, M.H.M. Hashim, P. Razi, "Proximate analysis, sulfur, and calorific value in determining coal quality," in *Advances in Geoscience and Remote Sensing Technology*, 2024, pp. 15-27.
- [4] H. Binous and A. Bellagi, "Calculations of complex chemical reaction equilibria using stoichiometric and non-stoichiometric approaches in combination with arc-length continuation," *Engineering Reports*, vol. 4, p. e12506, 2022.
- [5] S.R. Turns, *An Introduction to Combustion: Concepts and Applications, 3rd ed.* New York, NY, USA: McGraw-Hill, 2012.
- [6] R. Clark, N. Zucker, and J. Uperlainen, "The future of coal-fired power generation in Southeast Asia," *Renewable and Sustainable Energy Reviews*, vol. 121, p. 109650, Apr. 2020.
- [7] J.C. Hower, R.B. Finkelman, C.F. Eble, and B.J. Arnold, "Understanding coal quality and the critical importance of comprehensive coal analyses," *International Journal of Coal Geology*, vol. 263, p. 104120, 2022.

- [8] B. Tramošljika, P. Blecich, I. Bonefačić, and V. Glažar, "Advanced ultra-supercritical coal-fired power plant with post-combustion carbon capture: Analysis of electricity penalty and CO₂ emission reduction," *Sustainability*, vol. 13, no. 2, p. 801, 2021.
- [9] J. Wang, L. Duan, J. Yang, M. Yang, Y. Jing, and L. Tian, "Energy-saving optimization study on 700°C double reheat advanced ultra-supercritical coal-fired power generation system," *Journal of Thermal Science*, vol. 32, no. 1, pp. 30-43, 2023.
- [10] ASTM International, Annual book of ASTM standards: Volume 05.06 - Coal and coke, 2024 ed.
- [11] ASTM International, ASTM D388-23: Standard classification of coals by rank. West Conshohocken, PA, 2023.
- [12] N. Fernandez-Anez, B. C. Hagen, I. Amez, and B. Castells, "Assessing fire and explosion hazards in biomass: Insights and emerging challenges," *Journal of Physics: Conference Series*, vol. 2885, no. 1, p. 012002, 2024.
- [13] K. Švičkienė, P. Baltrėnas, and T. Januševičius, "Medical peat waste upcycling to carbonized solid fuel in the torrefaction process," *Energies*, vol. 14, no. 19, p. 6053, 2021.
- [14] A.R. Haqiqie and A. Husni, "Penentuan kualitas batubara dengan menggunakan analisis proksimat di PT Bukit Asam Tbk site Tanjung Enim, Sumatera Selatan," *Pondasi: Journal of Applied Science Engineering*, vol. 4, no. 2, pp. 72-81, 2024.
- [15] A. Volborth, "Problems of oxygen stoichiometry in analyses of coal and related materials," in *Analytical Methods for Coal and Coal Products*, B. R. K. Rao, Ed. New York: Academic Press, 1979, vol. III, pp. 543-583.
- [16] G.J. Roeder, J. Haimerl, Y. Chen, M. Gaderer, S. Fendt, and H. Spliethoff, "Measurements of NO_x emissions from biomass combustion in small to large-scale power plants," *Fuel*, vol. 397, p. 135801, 2025.
- [17] Ministry of Environment and Forestry, *Republic of Indonesia, Regulation No. 15 of 2019 on emission standards for thermal power plants*. Jakarta, 2019.