JTE
HCM-UTE
ISSN: 2615-9740

JOURNAL OF TECHNICAL EDUCATION SCIENCE
Ho Chi Minh City University of Technology and Engineering
Website: https://jte.edu.vn
Email: jte@hcmute.edu.vn

Evaluating the Technical, Economic and Environmental Efficiencies of Biomass Co-firing Technology in Coal Thermal Power Plants in Vietnam

Kien Quoc Vo
Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, Vietnam

Corresponding author. *Email: vkquoc@hcmut.edu.vn*

ARTICLE INFO

Received:	18/08/2025
Revised:	04/05/2026
Accepted:	09/06/2026
Online First:	17/06/2026
Published:	

KEYWORDS

Co-firing;
Power plant;
CO_2 emissions;
Economy;
Environtment;
Biomass.

ABSTRACT

This paper presents the results of theoretical research on co-firing technology in coal power plants. In this paper, co-firing technologies were evaluated. The results show that, in Vietnam's conditions, with operating power plants, direct co-firing technology is the most suitable. Besides, the effects of co-firing have also been analyzed based on the operating experience of plants that have applied co-firing technology in the world. In addition, the assessment of the economic and environmental benefits of co-firing technology have also been carried out based on theoretical calculations for the 600 MW unit of Song Hau power plant. The results show that with the price difference between coal and biomass being insignificant and the CO_2 emissions trading market not yet approved, co-firing will not be economically beneficial. However, the additional cost per GWh of electricity is negligible and acceptable. The advantage of co-firing technology is that it always has environmental and social benefits that do not depend on fuel costs.

Doi: https://doi.org/10.54644/jte.2026.1986

1. Introduction

Environmental pollution and climate change are increasingly posing serious threats to human living conditions, making sustainable development a globally shared priority. This commitment has been clearly demonstrated through international frameworks such as the COP26, in which Vietnam is an active participant. In alignment with its pledge to achieve net-zero greenhouse gas emissions by 2050, Vietnam requires a coherent set of policies and immediate implementation of practical solutions, executed in a structured and timely manner.

Among various emission sources, coal-fired power plants remain one of the largest contributors to greenhouse gas emissions, significantly exacerbating environmental pollution and climate change. While many developed countries have progressively phased out coal in favor of renewable energy, coal-fired power generation continues to play a dominant role in Vietnam’s energy mix. In recent years, the rapid expansion of renewable energy sources, particularly wind and solar power, has contributed to reducing the operational burden on coal-fired plants and lowering overall emissions. However, despite their advantage of near-zero greenhouse gas emissions during operation, renewable energy systems still present certain environmental and technical challenges that need to be carefully considered.

According to the International Energy Agency (IEA), by 2023 coal-fired power plants in Vietnam generated approximately 122,646 GWh of electricity, with the majority still operating on subcritical technology, resulting in relatively low thermal efficiency. The average CO_2 emission factor is about 1.141 t CO_2/MWh, significantly higher than the global average of 0.962 t CO_2/MWh, leading to total annual emissions of nearly 140 million tons of CO_2. This situation highlights the urgent need for emission reduction solutions in the coal-fired power sector.

Efficiency improvement measures such as supercritical and ultra-supercritical technologies can enhance energy performance, while alternative approaches such as carbon capture and storage (CCS) and biomass co-firing are considered promising decarbonization options. However, CCS remains constrained by high costs and technological immaturity. In contrast, biomass co-firing has been widely implemented due to its high feasibility. This technology has been applied for more than two decades in approximately 150 coal-fired power plants worldwide (50–700 MW), demonstrating both economic and environmental benefits [1].

Vietnam possesses substantial biomass potential due to abundant agricultural and forestry residues, while coal import demand (30–50 million tons/year) increases costs and energy dependency. In this context, biomass co-firing offers integrated benefits in terms of economics (reducing fuel and import costs), environment (lowering emissions and utilizing residues), and society (developing supply chains and creating jobs). Nevertheless, its large-scale deployment remains limited. Pilot tests, such as those at the Ninh Binh coal-fired power plant, indicate that boiler efficiency can improve by about 1% at co-firing ratios of 15–20%, confirming its practical potential. However, domestic studies are still limited and mainly focus on overall techno-economic and environmental assessments [2], [3], where environmental benefits are evident but economic performance remains modest.

Recently, a collaborative project between the Vietnamese Ministry of Industry and Trade and GIZ has provided a comprehensive evaluation of co-firing technologies, identifying direct co-firing as the most suitable option under Vietnamese conditions. On a global scale, biomass–coal co-firing has been extensively studied as a key pathway for low-carbon energy transition. These studies can be broadly classified into four main research directions.

The first group focuses on supply chain optimization and life cycle assessment (LCA), emphasizing the importance of biomass availability and logistics in determining overall system performance. It has been reported that emission reductions can be achieved even at low co-firing ratios; however, the overall effectiveness remains strongly dependent on biomass supply, underscoring the importance of resource planning [4].

The second group investigates combustion characteristics, emissions, and operational issues. Studies have shown that increasing biomass ratios can improve combustion performance but may introduce challenges such as slagging and fouling [5]. Other works confirm that stable operation can be maintained under appropriate operating conditions [6], while research on torrefied biomass indicates its potential to enhance fuel properties and reduce emissions [7], [8]. Large-scale studies further demonstrate that co-firing can improve burnout and reduce NO_x emissions, albeit with some trade-offs in heat transfer performance [9], [10].

The third group addresses system optimization and techno-economic-environmental assessment, often using multi-objective approaches. These studies highlight the influence of economic factors such as fuel prices, subsidies, and carbon pricing on the feasibility of co-firing [11]–[14], as well as the importance of policy mechanisms in supporting its deployment.

The fourth group explores advanced technologies and future trends, including gasification-based co-firing, torrefaction, and integration with carbon capture systems. These approaches aim to further enhance efficiency and achieve deep emission reductions, with some studies indicating the potential to reach net-zero emissions under specific conditions [15], [16].

Despite extensive research, comprehensive and context-specific assessments for Vietnam integrating technical, economic, and environmental aspects under realistic conditions remain limited, constraining informed decision-making for large-scale deployment. Therefore, this study evaluates the techno-economic and environmental performance of biomass co-firing in coal-fired power plants in Vietnam, providing an integrated basis to support emission reduction strategies and sustainable energy transition.

2. Biomass co-firing technologies and technical issues

2.1. Biomass co-firing technologies

There are three main technologies for co-firing biomass with coal, as follows:

Direct co-firing: Biomass is directly mixed with coal and combusted together in the same burner or in separate burners. If a shared burner is used, biomass must be pre-mixed with coal and processed through the same mill. If separate burners are used, biomass does not need to be mixed with coal and can be processed through a separate mill. Each method has its own advantages and disadvantages. Direct co-firing with a shared mill utilizes existing infrastructure without requiring additional investment; however, it faces challenges in achieving uniform blending of coal and biomass and may experience nozzle clogging. In contrast, co-firing technology using separate burners requires modifications to the boiler and additional investment in biomass milling and storage systems. However, operation is easier to manage, as it allows better control over the coal-to-biomass ratio**.** Therefore, direct co-firing with a shared burner can be applied to existing power plants, whereas direct co-firing with separate burners may be more suitable for new plants. The main advantage of direct co-firing is its low initial investment cost and ease of implementation without significantly affecting boiler operation**.** However, the shared burner configuration may limit the proportion of biomass that can be blended with coal due to the design of the boiler combustion chamber, which is primarily intended for coal as the main fuel.

Indirect co-firing: Biomass is converted into another type of fuel, such as gas or solid fuel (e.g., bio-coal), and is then fed into the furnace through separate burners. The advantage of indirect co-firing is that the biomass co-firing ratio can be increased, and the combustion process is more stable compared to raw biomass. However, the drawbacks include the high cost of fuel conversion, the need for boiler retrofitting, and more complex operation**.** Therefore, indirect co-firing is generally suitable only for newly constructed plants.

Parallel co-firing: Biomass is burned in a separate boiler, and the steam generated from the coal-fired boiler and the biomass-fired boiler is then combined. The main advantage of parallel co-firing is that there is no limitation on the biomass co-firing ratio. However, it is more expensive than direct co-firing because it requires entirely new infrastructure for the separate boiler. Thus, parallel co-firing is also only suitable for newly constructed plants.

2.2. Technical issues of biomass to burning characteristics

2.2.1 Characteristics of biomass

Biomass is highly diverse, although its chemical composition is relatively similar. The primary elements in biomass are carbon, hydrogen, nitrogen, and oxygen. In addition, biomass contains minor elements in small proportions, such as P, K, Ca, Mg, S, Zn, Cu, Fe, Mn, B, Mo, and Cl. Biomass exhibits significantly different characteristics compared to coal **,** with greater variability in these properties compared to conventional coal, as shown in Table 1.

Table 1. *Characteristics of coal and some types of biomass [17].*

	Hard coal	Brown coal	Wood	Straw	RDF	Dried sewage sludge
LHV, raw, MJ/kg	28	9	12.4	15	23.5	10.6
Moisture, raw, %	5.1	50.4	33	10.6	4.1	3
Volatile matter, dry, %	34.7	52.1	83.2	74.4	82.6	49.5
Ash, dry, %	8.3	5.1	0.34	6.1	12.2	45.1
Fixed C, dry, %	57.1	42.8	16.5	19.9	5.2	2.4
C, dry, %	72.5	65.9	48.7	47.4	56.8	25.0
H, dry, %	5.6	4.9	5.7	4.5	7.9	4.9
N, dry, %	1.3	0.69	0.13	0.4–0.78	0.74	3.2
S, dry, %	0.94	0.39	0.05	0.05–0.11	0.25	1.1
Cl, dry, %	0.13	<0.1	<0.1	0.4–0.73	0.82	<0.1
O, dry, %	11.1	23	45	40.4	21.3	17.7
Ash fusion temperature, °C	1,250	1,050	1,200	850	1,120	1,200

The heating value of biomass is typically about 50% of that of coal, and its density is significantly lower. Biomass properties vary widely, with ash content ranging from 1% to over 20% and moisture content commonly between 25% and 50%. While nitrogen content is relatively low (0.1–1%), sulfur content is negligible.

Compared to coal, biomass presents challenges in handling and combustion preparation due to its low density, high moisture content, and hygroscopic nature. It is also more difficult to grind into fine particles. These characteristics increase transportation and storage challenges. Additionally, long-term storage may lead to issues such as spontaneous combustion, decomposition, and the release of flammable gases.

2.2.2. Coal and biomass exhibit significantly different combustion characteristics.

Biomass has higher volatile matter content but lower heating value of volatiles compared to coal. Volatile combustion contributes about 70% of the total heat release in biomass, versus 30–45% in coal. During co-firing, biomass releases volatiles earlier and burns more rapidly, losing 90–95% of its mass, while coal typically loses only 55–60%. As a result, a large fraction of biomass is entrained in the flue gas.

Due to its low density, higher oxygen content, and porous structure, biomass ignites and oxidizes faster than coal. However, a large particle size or high moisture content may lead to incomplete combustion.

Biomass combustion also alters flue gas characteristics. Per unit of energy, biomass can produce higher flue gas volumes, affecting heat transfer in the boiler. In co-firing conditions, especially with multiple or separate burners, non-uniform mixing of flue gases may occur, leading to uneven combustion zones. This can influence ash behavior and increase the risk of localized fouling.

2.2.3. Effect of biomass type on grinding process and burner

Most coal mills rely on the brittleness of coal particles to function effectively. In contrast, biomass, often in a coarse form, is resistant to milling using the same mechanisms as coal. If biomass does not meet the required fineness, it can lead to a reduced combustion rate.

Biomass has a high moisture content, tends to agglomerate, and can cause biomass buildup in the mill. Additionally, when milling high-moisture biomass alongside coal, the moisture content of coal after milling can increase, and the fineness of coal can decrease. Furthermore, biomass has a tendency to release volatile matter inside the mill at lower temperatures, which is why safety concerns regarding combustion and explosion risks during the co-milling of coal and biomass need to be addressed.

2.2.4. Effect of biomass type on slag and deposit

The extent of slagging and fouling depends on the local flue gas temperature, tube wall temperature, temperature differences, tube orientation, local heat flux, and fuel composition. Regarding fuel composition, the formation of slagging and fouling depends on chemical reactions involving chlorine, sulfur, aluminum, silicates, and alkali metals during combustion. Biomass fuel can contain a higher proportion of alkali metals than coal, and these elements tend to vaporize during combustion, resulting in a lower melting point for biomass ash compared to coal. As a result, biomass is more prone to slagging issues.

2.2.5. Effect of biomass type on corrosion and erosion

Co-firing biomass can increase both high- and low-temperature corrosion rates in boilers. At high temperatures, corrosion is exacerbated due to changes in the chemical composition of the ash deposits on the boiler surfaces. This alteration in ash chemistry is a result of the vaporization and condensation of alkali metals during biomass co-firing. Most biomass fuels are relatively rich in alkali metals, especially potassium, and in some cases, phosphorus. Additionally, some biomass fuels have relatively high chlorine concentrations, which can reach up to 1%, and are released as HCl in the flue gas, causing low-temperature acid corrosion. Biomass ash contains elevated levels of potassium and a relatively high chloride/sulfate ratio. This can significantly impact corrosion, particularly at high metal temperatures on superheater surfaces.

2.3. Theoretical basis of co-firing

Overall efficiency of the power plant:

$$\eta_o = \frac{P}{Q} \tag{1}$$

Where:

P: is the capacity of the power plant (MW).

Q: is the total heat energy supplied to the plant (MW).

The overall efficiency of the power plant depends on the efficiency of the boiler (η_b) and the energy conversion efficiency of other devices (η_a) in the cycle. So that, it can be rewritten as follows:

$$\eta_o = \eta_b \text{ x } \eta_a \tag{2}$$

The volume of coal consumed by the power plant in 1 year (kg/year) is determined according to the following formula:

$$M_c = \frac{3600 \text{ x } Q \text{ x } 10^3}{LHV_c} \tau \tag{3}$$

Where:

LHV_c: is the low heating value of coal (kJ/kg).

τ: is the number of working hours of the power plant in 1 year (hours/year).

The mass of coal replaced by biomass ΔM_{coal} (kg/year) when co-burning is determined according to the following formula:

$$\Delta M_c = \frac{LHV_b \text{ x } M_b}{LHV_c} \tag{4}$$

Where:

LHV_b: is the low heating value of biomass (kJ/kg).

M_b: is the amount of biomass replaced (kg/year).

The percentage of co-fired biomass mass is determined using the following formula:

$$B = \frac{M_b}{(M_c - \Delta M_c) + M_b} 100 \tag{5}$$

According to the experimental results at Tillman power plants [18], the reduction in boiler efficiency when co-firing biomass is expressed through the following equation:

$$\Delta\eta = 0.0044B^2 + 0.0055 \tag{6}$$

The total electric power output of the power plant when co-firing biomass is expressed by the following equation:

$$P_{co} = Q(\eta_b - \Delta\eta)\eta_a \tag{7}$$

Operating costs: include the cost of purchasing biomass, the transportation cost of biomass, and additional investment costs.

Cost for biomass C_b (USD/year):

$$C_b = SC_b \text{ x } M_b \tag{8}$$

Where: SC_b is the cost of biomass (USD/kg).

Biomass transportation costs C_{TR} (USD/year):

$$C_{TR} = D_{TR} \text{ x } SC_{TR} \tag{9}$$

Where:

D_{TR}: is the total distance transporting biomass from the raw material area to the power plant (km/year).

SC_{TR}: is the cost of transporting biomass for 1km including fuel, vehicles, labor, tolls, ... (USD/km).

The total biomass transportation distance depends on the biomass distribution density DD_b in kg/(km^2.year) and the payload capacity of each transport vehicle VC in kg/vehicle, as described by Caputo [19]. The total biomass transportation distance is determined by the following equation:

$$D_{TR} = \frac{4}{3}\left(\frac{M_b}{\pi \text{ x } DD_b}\right)^{0.5}\left(\frac{M_b}{VC}\right) \tag{10}$$

The required investment costs for implementing biomass co-firing in an existing coal-fired boiler depend on various factors. However, according to cost analyses from demonstration plants, the primary investment costs largely depend on whether biomass is milled with coal or milled separately. Additionally, the additional investment costs for co-firing also strongly depend on the biomass co-firing ratio. If the biomass portion exceeds a certain threshold, a separate fuel supply system for biomass is generally required [18]. It is not necessary to install a separate fuel supply system when the biomass-to-coal mass ratio (B) is ≤ 4%. A separate fuel supply system must be installed if the co-firing biomass ratio exceeds this threshold. For low co-firing ratios, biomass can be directly blended with coal without significant modifications, resulting in an additional investment cost of approximately 50–100 USD/kW [20]. Therefore, the estimated additional investment cost for co-firing biomass using an existing fuel supply system (B ≤ 4%) is:

$$CI_L = 50 \text{ x } 1000\ \frac{M_b \text{ x } LHV_b}{(M_c - \Delta M_c)LHV_c} P_{co} \tag{11}$$

When the biomass-to-coal mass ratio (B) exceeds 4%, it is necessary to install in a separate fuel supply system for biomass. In this case, the investment costs are significantly higher compared to the previous case. The investment costs for this case include investments in biomass storage facilities (CI_{BS}), biomass handling (CI_{BH}), blowers, and dryers (CI_{CD}). The costs for each of these components depend on the power output attributed to biomass. These investment costs have also been reported by Caputo [19] according to the following relationships:

$$CI_{BS} = 136578\left[\frac{M_b \text{ x } LHV_b}{(M_c - \Delta M_c)LHV_c} P_{co}\right]^{0.5575} \tag{12}$$

$$CI_{BH} = 55780\left[\frac{M_b \text{ x } LHV_b}{(M_c - \Delta M_c)LHV_c} P_{co}\right]^{0.9554} \tag{13}$$

$$CI_{CD} = 13646\left[\frac{M_b \text{ x } LHV_b}{(M_c - \Delta M_c)LHV_c} P_{co}\right]^{0.5575} \tag{14}$$

The total additional investment cost when co-firing with a biomass mass ratio B>4% is:

$$CI_H = CI_{BS} + CI_{BH} + CI_{CD} \tag{15}$$

For investment projects financed through loans, the investor must repay an amount that includes both the principal and interest, which are distributed evenly over the loan period, with an annual fixed interest rate of IR (% per year), and a loan term of N (years). The Capital Recovery Factor (CRF) for the borrowed capital is determined using the following formula:

$$CRF = \frac{A_{CI}}{CI} = \frac{IR(1+IR)^N}{(1+IR)^N - 1} \tag{16}$$

Where: A_{CI} is the annual payment amount (USD/year).

The additional annual fuel cost AAC_f (USD/year):

$$AAC_f = C_b + C_{TTR} - (\Delta M_c \text{ x } SC_c) \tag{17}$$

Where: SC_c is cost of coal (USD/kg).

Additional cost per unit of electricity (USD/GWh):

$$ACE = \frac{A_{CI} + AAC_f}{P_{co} \text{ x } \tau \text{ x } 3600} 1000 \tag{18}$$

Carbon oxidation reaction:

$$\begin{gathered} C + O_2 = CO_2 \\ 12 + 32 = 44 \\ 1 + 2.67 = 3.67 \end{gathered} \tag{19}$$

1 kilogram of carbon, when burned, will generate 3.67 kilograms of CO_2. Therefore, the reduction in CO_2 emissions (in tons of CO_2 per year) when co-firing is:

$$\Delta M_{CO2} = \frac{3.67(\Delta M_c \text{ x } fc)}{1000} \tag{20}$$

Where: fc is the mass fraction of Carbon in coal (%).

The additional cost to reduce emissions per ton of CO_2 is AC_{CO2} (USD/ton CO_2):

$$AC_{CO2} = \frac{A_{CI} + AAC_f}{\Delta M_{CO2}} \tag{21}$$

3. Results of case studies and assessment of economic and environmental efficiency in Vietnamese conditions

The economic performance of biomass co-firing mainly depends on the price difference between biomass and coal, as well as transportation costs. Minimizing transportation distances requires locating power plants near biomass resources. In Vietnam, biomass is abundant but unevenly distributed; therefore, regional assessments are necessary to identify suitable plants for co-firing.

Rice husk is a major biomass resource concentrated in the Mekong Delta, where three power plants are in operation: O Mon (Can Tho), Song Hau, and Duyen Hai (Tra Vinh). Among these, the Duyen Hai Thermal Power Plant is less favorable due to its greater distance from biomass resources. Therefore, the Song Hau Thermal Power Plant is selected as the case study for evaluating the economic and environmental performance of co-firing technology.

Table 2. *Technical parameters and actual conditions of Song Hau thermal power plant.*

Parameters	Value
Power plant capacity: P (MW)	600
Biomass in fuel mix: B (%)	0-15
Specific price of biomass: SC_b (USD/ton)	100

Specific price of coal: SC_c (USD/ton)	150
Biomass distribution density: DD_b (ton/(km^2.year))	5.6
Remaining power plant life: N (year)	20
Market price of electricity: (USD/kWh)	0.08
Boiler efficiency: η_b (%)	88.75
Energy conversion efficiency of the plant: η_a (%)	46.2
Operating hours of the plant: τ (hours/year)	6500
Vehicle capacity: VC (ton/vehicle)	15
Transportation costs: SC_{TR} (USD/km)	2.25
Effective rate of interest on borrowed capital: INT (%/year)	10

Table 3. *Characteristic of coal and biomass.*

Charateristics of fuels (%)	**Import coal**	**Biomass (Rice hust)**
Moisture	8.4	10.53
Ash, dry	10.17	11.72
Fixed carbon, dry	37.13	16.15
Volatile matter, dry	32	61.6
Ultimate analysis (%)		
C	53.13	39.37
H	3.62	4.87
N	1.24	0.3
S	0.62	0.04
O	11.22	33.13
Ash	10.17	11.72
Low heating value (kJ/kg)	20270	14001

To select a suitable co-firing technology, specific technical evaluation criteria are required. According to the International Renewable Energy Agency (IRENA) [21], there are six criteria for assessing co-firing technologies, which include the level of CO_2 emission reduction (high or low), impact on the existing system, ease of operation (difficult or easy), variability in plant performance (high or low), economic efficiency (high or low), and the co-firing ratio (high or low). Based on these criteria, under current conditions in Vietnam, direct co-firing technology appears to be the most appropriate compared to other technologies as it satisfies the majority of the criteria outlined above.

Drawing on the theoretical foundation presented above, in conjunction with the practical operational conditions of a specific power plant, the Song Hau Thermal Power Plant, as presented in Table 2 and Table 3, the calculation results are presented in the following graphs.

3.1. Effect of co-firing ratio on boiler efficiency

The calculation results in Figure 1 demonstrate that as the biomass co-firing ratio increases, the boiler's efficiency decreases slightly, but this change is not significant. The primary reason for this reduction is the decrease in the boiler heat transfer coefficient during co-firing. Biomass contains various alkali metals with low vaporization temperatures, which can lead to their deposition on heat exchange surfaces, resulting in increased ash fouling. Additionally, uneven mixing between coal and biomass can alter the flame center position and affect the boiler's heat transfer capability. Furthermore, the combustion characteristics of biomass can also influence the boiler's efficiency.

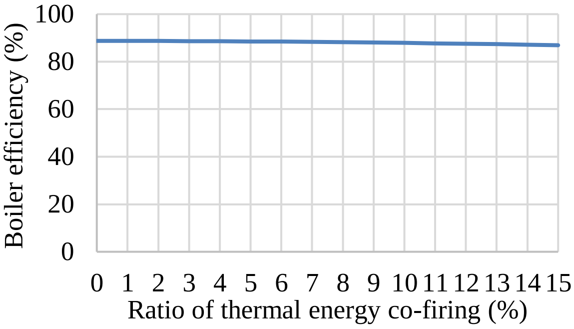

Figure 1. *Effect of co-firing ratio on boiler efficiency.*

3.2. Effect of co-firing ratio on CO_2 emissions

Biomass is considered a CO_2-neutral fuel; therefore, co-firing can reduce CO_2 emissions. As shown in Figure 2, emissions decrease approximately linearly with increasing co-firing ratio. Although the absolute reduction depends on the carbon content of coal, the reduction rate remains proportional to the biomass fraction.

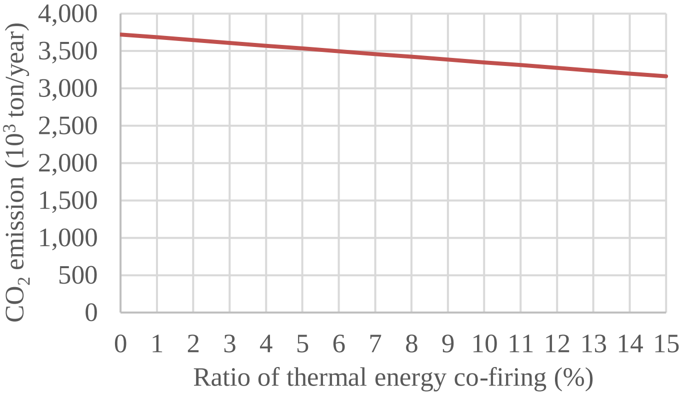

Figure 2. *Effect of co-firing ratio on CO_2 emissions.*

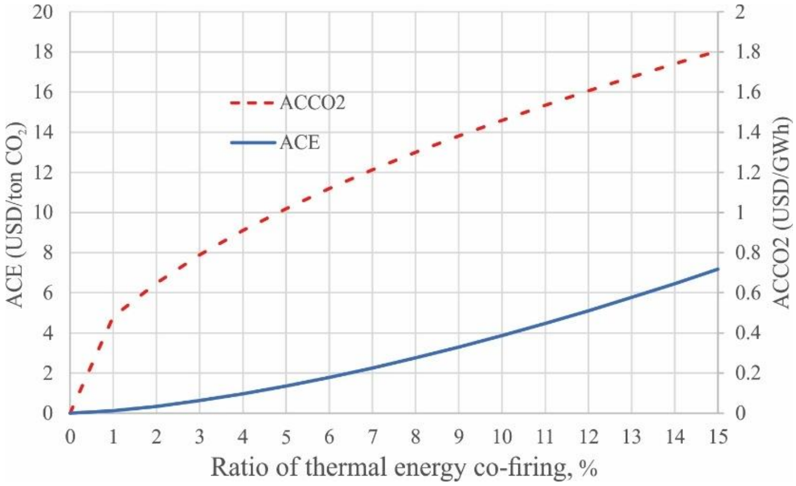

***Figure 3**. Effect of co-firing ratio on the cost of reducing CO_2 emissions and increasing electricity prices.*

While co-firing provides clear environmental benefits, its economic performance depends on fuel price differences. When the price gap between coal and biomass is small, emission reduction may incurs additional costs. However, these costs can be offset through carbon markets. According to the International Renewable Energy Agency (IRENA), carbon prices range from 40–50 USD/tCO_2. Under current conditions, the mitigation cost remains below 40 USD/tCO_2 for co-firing ratios below 10% (Figure 3), indicating economically acceptable performance. Although higher co-firing ratios increase costs, the resulting increase in electricity generation cost per GWh is negligible. These costs mainly include biomass supply, transportation, additional investment, and efficiency losses during co-firing.

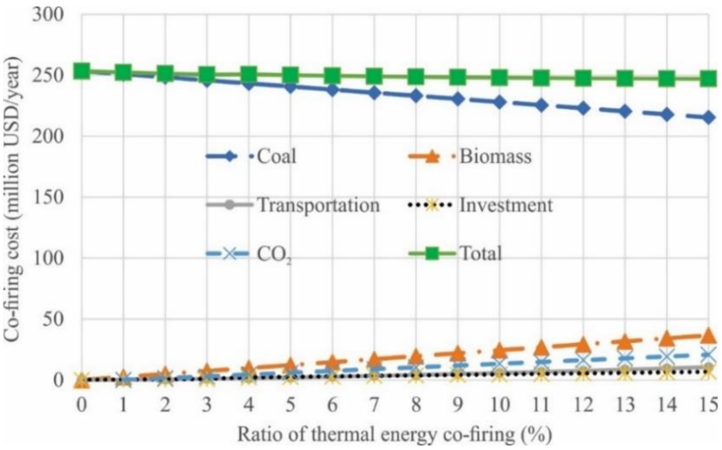

Figure 4. *Effect of co-firing ratio on operating costs.*

The results in Figure 4 indicate that, with coal priced at 150 USD/ton and biomass at 100 USD/ton, the annual fuel cost for a 600 MW unit exceeds 250 million USD. When co-firing is applied, the total cost includes coal, biomass, transportation, and additional investment for handling and combustion systems. Although coal consumption decreases with increasing co-firing ratio, the total fuel cost remains nearly unchanged due to the relatively small price difference and lower heating value of biomass. Moreover, transportation and investment costs increase with higher biomass ratios, making co-firing less attractive from a purely economic perspective.

However, the environmental benefits are significant. Increasing the co-firing ratio leads to greater economic gains from CO_2 emission reduction, particularly under carbon trading mechanisms. At low co-firing levels ($B < 4\%$, equivalent to ~3% energy share), additional investment is minimal, making this range the most economically feasible for practical implementation.

4. Conclusions

Co-firing technology for reducing CO_2 emissions has been implemented in some developed countries. The environmental benefits of this technology are the most apparent. However, its economic benefits depend significantly on the price difference between coal and biomass. In recent years, the fossil fuel market has experienced significant fluctuations, impacting electricity production costs. To promote the application of co-firing technology in power plants, there needs to be mechanisms and policies supported by the government aimed at reducing CO_2 emissions, contributing to Vietnam's commitment to the 26th UN Climate Change Conference of the Parties (COP26).

In addition to the economic challenges mentioned earlier, there are also some potential barriers to co-firing biomass, such as:

- The biomass supply must ensure stable quality, moisture content, and energy density.

- Mixing coal with biomass must be uniform, even though they have different densities.

- Fly ash from coal combustion is used in construction materials, while biomass ash is used as fertilizer. The fly ash from co-firing cannot be used for these purposes.

Overall, co-firing biomass has positive environmental and societal benefits, but it can also pose technical challenges and potential economic drawbacks. Sustainable development is a common goal for the world. Therefore, technical and economic obstacles should not be considered insurmountable. Co-firing at high ratios may require more caution, but co-firing at lower ratios can be implemented immediately in power plants to gain operational experience and address potential technical issues. Subsequently, the co-firing ratio can be gradually increased, allowing better mastery of the technology.

Acknowledgement

We acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

Conflict of Interest

We declare that there are no conflicts of interest in this paper.

REFERENCES

[1] P. Basu, J. Butler, and M. A. Leon, "Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants," *Renewable Energy*, vol. 36, no. 1, pp. 282-288, 2011.

[2] T. A. Ha, "Potential and socio-economic & environmental impacts of co-firing technology in Vietnam," University of Science and Technology of Hanoi, 2020.

[3] A. H. Truong, M. Ha-Duong, and H. A. Tran, "Economics of co-firing rice straw in coal power plants in Vietnam," *Renewable and Sustainable Energy Reviews*, vol. 154, p. 111742, 2022.

[4] A. A. R. Setiawan *et al.*, "Optimizing biomass supply for cofiring at power plants to minimize environmental impact: A case of oil palm empty fruit bunches in West Java," *Fuel*, vol. 367, p. 131359, 2024.

[5] Hariana, Prabowo, E. Hilmawan, F. Milky Kuswa, A. Darmawan, and M. Aziz, "A comprehensive evaluation of cofiring biomass with coal and slagging-fouling tendency in pulverized coal-fired boilers," *Ain Shams Engineering Journal*, vol. 14, no. 7, p. 102001, 2023.

[6] P. R. Wander, F. M. Bianchi, N. R. Caetano, M. A. Klunk, and M. L. S. Indrusiak, "Cofiring low-rank coal and biomass in a bubbling fluidized bed with varying excess air ratio and fluidization velocity," *Energy*, vol. 203, p. 117882, 2020.

[7] C. Ndibe, J. Maier, and G. Scheffknecht, "Combustion, cofiring and emissions characteristics of torrefied biomass in a drop tube reactor," *Biomass and Bioenergy*, vol. 79, pp. 105-115, 2015.

[8] Z. Liang, Y. Hou, F. Yang, and H. Tan, "The characteristics of biomass torrefaction and nitrogen oxide emission during co-firing with coal," *Fuel*, vol. 425, p. 139382, 2026.

[9] A. A. Z. Rohmah, W. Meka, A. B. K. Putra, A. Altway, A. Nugroho, and T. Widjaja, "Engineering study of coal co-firing based on biomass mixture and slagging-fouling control in the steam power plant," *South African Journal of Chemical Engineering*, vol. 55, pp. 191-221, 2026.

[10] L. Chen, M. Wang, and X. Wu, "Numerical research on coal-biomass co-firing in a 1000 MW tangential-fired tower boiler for flexible operation under wide range of load conditions," *Fuel*, vol. 425, p. 139454, 2026.

[11] M. Wu, Y. Zhang, and Y. Liu, "Sustainable energy development of biomass-coal co-firing power generation system under ambiguous distribution information," *Renewable Energy*, vol. 257, p. 124757, 2026.

[12] Y. L. Zhang *et al.*, "Economic feasibility assessment of coal-biomass co-firing power generation technology," *Energy*, vol. 296, p. 131092, 2024.

[13] Q. Huang and Q. Feng, "A bi-level model for coal power decarbonization via biomass co-firing considering CO2 emission trading system," *Energy*, vol. 305, p. 132385, 2024.

[14] L. Sun, X. Zheng, Z. M. Harris, X. Xu, F. He, and L. Liu, "National-level evaluation of the economic and environmental advantages of retrofitted biomass-coal co-firing power plants," *Renewable Energy*, vol. 265, p. 125586, 2026.

[15] X. Lu, L. Sun, Y. Li, H. Xuan, and R. Zheng, "Technical, Economic, and Environmental Analysis of Coal Co-firing with Biomass: A Comparative Study of Gasification Co-firing, Torrefaction Co-firing, and Direct Co-firing," *Energy*, p. 141194, 2026.

[16] W. Wu and H. Zhai, "Life cycle assessment of co-firing biomass at coal-fired power plants with carbon capture and storage toward net-zero emissions," *International Journal of Greenhouse Gas Control*, vol. 153, p. 104653, 2026.

[17] Hein K R G, Scheurer W, "Co-combustion of biomass, wastes and residues with coal". *In: EU seminar on the use of coal in mixture with wastes and residues II, Cottbus, Germany*, 19-20 Oct 2000, pp 31-40, 2000.

[18] D. A. J. B. Tillman and bioenergy, "Biomass cofiring: the technology, the experience, the combustion consequences," *Biomass and Bioenergy*, vol. 19, no. 6, pp. 365-384, 2000.

[19] A. C. Caputo, M. Palumbo, P. M. Pelagagge, F. J. B. Scacchia, and Bioenergy, "Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables," *Biomass and Bioenergy*, vol. 28, no. 1, pp. 35-51, 2005.

[20] L. J. F. Baxter, "Biomass-coal co-combustion: opportunity for affordable renewable energy," *Fuel*, vol. 84, no. 10, pp. 1295-1302, 2005.

[21] *Biomass co-firing: Technology brief*, International Renewable Energy Agency IRENA Press, 2013.

Kien Quoc Vo graduated with a Bachelor's degree in Energy Mechanical Engineering in 2003, a Master's degree in Thermal Engineering in 2007, and a Ph.D. in Thermal Technology and Equipment from the University of Technology – Vietnam National University, Ho Chi Minh City, in 2018. He published 20 scientific papers in national and international journals and conferences, including 16 as the first author and 2 in SCIE journals. Since 2003, has been working in the Department of Thermal and Refrigeration Engineering, Faculty of Mechanical Engineering, University of Technology – Vietnam National University, Ho Chi Minh City. Research field: Energy saving and efficient energy use, humidification – dehumidification desalination, and renewable energy.

Email: vkquoc@hcmut.edu.vn. ORCID: https://orcid.org/0000-0003-1977-1748