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A Transparent Techno-Enviro-Economic Assessment of a Coal-Fired Power Plant: Integrating Biomass Co-Firing and CO_2 Sequestration Technology in a Carbon-Priced Environment

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ABSTRACT

The integration of carbon capture and storage (CCS) into coal and biomass co-firing systems (CBCCS) offers a promising solution for reducing carbon emissions in electricity generation. This study evaluates hypothetical scenarios in Malaysia and Indonesia, focusing on techno-economic-environmental transparency. The analysis shows a negligible change in plant net efficiency (~1%) across biomass co-firing ratios of 5-20% in both countries. The capture penalty increases at higher biomass ratios, particularly at 20% co-firing, due to higher auxiliary power demands and steam extraction. As biomass share increases, net CO_2 emissions decrease by an average of 43% in Malaysia and 34% in Indonesia. Economic evaluations show a positive revenue increase for Malaysia at a 20% co-firing ratio, while Indonesia faces a revenue deficit (0.6%) under the same condition, mainly due to an unattractive carbon price and feed-in tariff from 2027 onward. Malaysia faces a higher risk of stranded assets due to earlier retirement plans, compared to Indonesia. As the co-firing ratio increases, the risk of stranded assets decreases by 3% in Malaysia and 0.6% in Indonesia. The present work showcases the intricate and synergistic effects of energy and commodity market dynamics from a micro-sector perspective towards plant revenue. This allows both Indonesia and Malaysia to learn from each other in their quest to achieve energy independence and security. Collaboration in tapping renewable sources is one way the two countries can secure energy for their domestic needs while addressing the challenges of carbon lock-in and the impact of stranded assets.

Keywords: Carbon Dioxide Sequestration, Energy, Genetic Algorithm, Matlab, Renewable and Sustainable Energy

INTRODUCTION

The energy sector remains the largest contributor to global greenhouse gas emissions, with coal accounting for approximately 45% of total emissions from fuel combustion [1]. To address this issue, two promising strategies have been identified, which include cofiring coal with biomass for power generation (CB) and retrofitting coal-fired power plants with carbon capture and storage (CCS) technology. According to the Intergovernmental Panel on Climate Change (IPCC), these strategies play a significant role in supporting the Paris Agreement targets [2]. Many studies have been carried out on the performance of biomass cofiring integrated with CCS system (CBCCS), encompassing both technical and environmental perspectives. For instance, Cebrucean et al. [3] identified that biomass co-firing with a supercritical coal plant equipped with a carbon capture system can enhance energy and environmental performance, achieving a 2.4% increase in net efficiency and a 6% reduction in CO_2 emissions compared to conventional subcritical plants. However, at a 30% co-firing ratio, net plant efficiency is reduced by 1%, negatively impacting the plant's economic viability. In another study, approximately a 14% reduction in net plant efficiency was observed at a 10% biomass co-firing ratio. This significant discrepancy is influenced by the type of biomass and coal plant technology. While co-firing ratios exceeding 10% have been shown to result in net negative CO_2 emissions, Yang et al. [4] reported that higher CO_2 capture rates are directly associated with significant declines in net plant efficiency, which typically ranges from 28% to 31%. Despite several studies available on the ground, the global commercialization of CBCCS technology remains sluggish. This can be attributed to factors such as the limited availability of biomass resources, socio-economic barriers, the absence of robust policies and regulatory frameworks, and the risk of stranded assets (SA) faced by coal-fired power plants [5-6]. In this paper, we evaluate the techno-enviro-economic performance of the CBCCS system, taking into account carbon price and the impact of stranded assets on the plant's lifetime operation. This work addresses concerns raised by the International Energy Agency (IEA), emphasizing the need for a reliable framework that ensures transparency to support CBCCS technology as one of the carbon dioxide removal solutions[7].

METHODOLOGY

An improved genetic algorithm (GA) optimization algorithm

Present work adapts and further enhances a previously developed GA optimization algorithm executed in Mathlab software [8]. The enhancement focuses on biomass co-firing in a supercritical power plant (direct co-firing) integrated with CCS system (i.e. monoethanolamine (MEA) – based post combustion carbon capture)). For this study, it is assumed that the coal plant does not require significant modifications for the carbon capture retrofit or biomass co-firing integration. The analysis also includes the cost of stranded assets, evaluated based on both physical and economic lifetimes, alongside the feed-in tariff (FiT). This approach provides new insights into the financial risks and benefits posed by the evolving power sector.

The objective function of the enhanced GA optimization remains focused on maximizing plant revenue from 2024 to 2034 by optimizing the power plant load (PP_N) and CO_2 capture rate. Table 1 presents the details of the optimization enhancements. While this paper presents only significant and new information and approaches, readers can reference previous works for comprehensive background information [9-10].

As referenced in Table 1, the revenue formulation is illustrated in the equation (1).

$$Max(Revenue) = \int E\,(Q_e - Q_p)\,dt - \int C\,(Q_c)\,dt - PP_{op} - CCS_{op} - CCS_{cap} + \int F\,(Q_L)\,dt \quad (1)$$

Where *E, C* and *F* represent the electricity price, carbon price and feed-in-tariff for biomass, while Q_e, Q_p, Q_c, Q_L are power plant net load, total power penalty, CO_2 emissions and proportion of electricity produced from biomass in co-firing power plant. Since biomass is considered as carbon neutral fuel thus burning biomass is not counted for carbon tax[11-12]. In this work, we consider a stringent and extreme condition, where no free allowance provided to the power plant.

Table 1: Detail of the GA optimization enhancement adapted in present study.

Items	Ref work [9]	Present work
Power plant (660 MW)	Subcritical	Supercritical
Non-linear prediction model	Q_{reb} =f(x_i) Aux = f(x_i)	Q_{reb} = -20% *(f(x_i)[3] Aux = - 8* f(x_i) [3]
Objective function	Revenue (without FiT)	Revenue (with FiT and CCS capital cost)
Inequality constraint	c_1:$PP_N < PP_G$	c_1: $PP_N < PP_G$ c_2: $CO_2^E < CO_2^T$
Fuel	Coal	Coal and biomass (palm kernel shell, PKS)
Stranded asset	Not evaluated	Evaluated by the influence of power plant load (x_i)

On top of ensuring that the PP_N of the power plant does not exceed the gross load (PP_G), present work incorporates carbon neutrality and emission constraints into the enhanced optimization algorithm, as follows.

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max_CO₂_threshold = 0.5
c₂ = ((Total_CO₂_Emissions/PP_load) -
max_CO₂_threshold)
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This constraint (c_2) ensures that the CO_2 emissions produced at each interval remain below a specified threshold (max_CO_2_threshold) to align with carbon neutrality/emission reduction goals. While a standard methodology (ISO 14068-1) exists for assessing carbon neutrality [13], no specific emission threshold has been formally established yet. Therefore, this work sets the threshold at 0.5 tonnes CO_2/MWh, based on China's coal benchmarking for power decarbonization from 2018 to 2030. This value aligns with the averaged benchmark outlined in Sustainable Development Goals (SDGs)[14]. For the evaluation of stranded asset (SA), the calculation was adapted from [6] as shown in equation (2).

$$SA = OC_{cap} * K * \left(\frac{L_R}{C_{LT}}\right) * LF \tag{2}$$

Where OC_{cap} is an overnight capital cost (USD/kW), K, L_R and C_{LT} are the plant capacity, remaining lifetime and coal plant lifetime. This work considers SA based on physical (SA_{LP}) and economic lifetimes (SA_{LE}). Where physical lifetime is generally longer (standard/technical lifetime) than the economic lifetime (early retirement). In this work, load factor (LF) is being considered to reflect the operational deficiency over the years of co-firing power plant. The LF is dynamically calculated as in equation (3).

$$LF = \frac{PP_N}{700} \tag{3}$$

While other researchers have used intricate and financially detailed methods to evaluate SA[15], this work considers a simple and tactical method as a preliminary approach.

Scenario setting

Four scenarios representing three ranges of biomass ratios (by low heating value, LHV) are evaluated based on hypothetical situations in Malaysia and Indonesia. As both countries are the major producers of palm oil [16], there is significant potential for the adoption and development of biomass co-firing technology within their energy infrastructure. However, as developing nations with dynamic economic and policy landscapes, both countries face considerable risks of stranded assets and carbon lock-in. Therefore, understanding the technical, environmental and economic implications is critical to effectively evaluate their exposure to stranded asset risks and align with emission reduction targets, particularly for hybrid technologies like the CBCCS system. Table 2 presents the input data used in the enhanced optimization algorithm, including the associated costs for the CBCCS system. Several assumptions were made due to the unavailability of certain data. This study does not consider biomass pre-treatment, assuming that the power plant receives biomass with suitable characteristics for direct use.

Table 2: Input data and costs assumptions of CBCCS plant.

Parameters	Malaysia	Indonesia
Plant commissioning	Tanjung Bin, 2016 [17]	Cirebon, 2012 [18]
PKS ratio (%)	0, 5, 10, 20	
PP_G (MW)	Similar pattern [19]	
FiT (USD/MWh)	62.60[20]	60.00[21]
Electricity price (USD/MWh)	2024: [22] 2025-2034 :10% increment[23]	2024: [24] 2025-2034: 20% increment
Coal price (USD/tonne)	2024 [25] 2025-2034: 12% [26]	2024: [27] 2026 - 2034: Follow MAS
Biomass price (USD/tonne)	2024: 53.50[28] 2029-2034: 300 [28]	2024: 140 2025-2034: 150
OC_{cap} (USD/kW)	6,901 based on 4,759 (2010) [29]	
LHH (MJ/kg)	Coal: 24.4, PKS: 20.09	
EF (kg CO_2/MJ)	Coal: 0.0959, PKS: 0.112	
CB_{Lp}	35 [6]	
CB_{LE}	2044 [30]	2035 [31]
CB operating cost (USD)	1,733,000	
CCS capital cost (USD)	10,420,657 [8]	
CO_2 price (USD/tonne)	8.00 [32]	2.10 [33]
MEA price (USD/tonne)	1,940[34]	
Transportation and storage (USD)	25[35]	

RESULTS AND DISCUSSION

Technical transparency

The net plant efficiency is a critical indicator of the energy conversion performance of a system. According to Table 3, the analysis reveals a marginal efficiency variation from 29.8% to 31% across the co-firing spectrum (0–20%) for both countries, with an approximate difference of 1% point. This noteworthy phenomenon is attributed to the sensitivity and flexibility of the optimization algorithm, which requires the power plant load to dynamically meet the objective function while adhering to the constraint (c_1) at each time interval. This finding is distinct with existing literature, where increasing the biomass co-firing ratio typically leads to a decline in net plant efficiency. Such depreciation is often directly related to the high CO_2 capture rate, commonly set at 90% [4]. In contrast, the current work considers a dynamic capture rate influenced by carbon pricing and emission constraints (c_2), which we believe more accurately reflects real-world flexible CBCCS operations. This aligns with the findings of [3], which showed that the net efficiency of power plants increases when the capture efficiency is reduced from 90% to 50%. This improvement is primarily due to the reduced steam extraction from the steam cycle to meet the heat requirements of the capture unit, allowing more steam to be available for power generation. Additionally, operating the power plant in a base-load scenario may not generate significant revenue for plant owners. The CO_2 capture energy penalty exhibits an upward trajectory for both nations, with Malaysia's requirements increasing from 9.66 to 11.53 MJ/kg CO_2 and Indonesia's from 9.24 to 11.51 MJ/kg CO_2 as the biomass ratio escalates. This range is technically accepted since maximum energy penalty associated with MEA-capture system (retrofit with coal plant) can reach up to maximum 8.00[36] to 10.23 MJ/kg CO_2 [37]. Where, this escalation in energy penalty is consistent with the technical challenges including increased parasitic loads from auxiliary equipment and reboiler duty from the steam extraction/solvent regeneration [3,38]. Based on the optimization results presented in this study, it is suggested that retrofitting carbon capture technology into a supercritical plant with a co-firing ratio of 5–20% does not impose a significant efficiency penalty, provided the plant is allowed to operate flexibly. This technical transparency highlights a critical trade-off between achieving higher biomass co-firing ratios for enhanced carbon reduction and maintaining optimal plant performance, particularly in the context of emerging economies transitioning to low-carbon energy systems

Table 3: Technical performance of CBCCS system under the carbon price regime.

Co-firing ratio		**0**	**5**	**10**	**20**
Net plant	MAS	29.8%	30.6%	30.9%	31.0%
eff. (LHV %)	IND	30.5%	30.5%	30.5%	31.0%
$CC_{penalty}$	MAS	9.66	9.76	10.30	11.53
(MJ/kg CO_2)	IND	9.24	9.78	10.23	11.51

Environmental transparency

The environmental performance analysis of the CBCCS system reveals distinct CO_2 emission patterns across varying co-firing ratios, demonstrating the system's potential for carbon mitigation. As shown in Figure 1, increasing the co-firing ratio results in a notable reduction in net CO_2 emissions. At 20% biomass co-firing, the net CO_2 emissions account for 43% and 34% of the total CO_2 emissions from co-firing plant in Malaysia and Indonesia, demonstrating a trend similar to that observed in [3]. Without co-firing, coal plants generate an average of 65% net CO_2 emissions, emphasizing the significant contribution of biomass co-firing to CO_2 emission mitigation. However, the total CO_2 emissions from the biomass combustion of a biomass co-firing plant increase by 17% compared to a coal plant due to the adoption of co-firing. Since CO_2 emissions from biomass combustion are sequestered as biomass regrows, sustainably managed biomass is considered carbon neutral. These findings underscore the effectiveness of biomass co-firing in reducing fossil-based CO_2 emissions by substituting a portion of fossil carbon with a renewable carbon source. The total captured CO_2 exhibits slight variation across different co-firing ratios, reflecting the complex interaction between maintaining CO_2 emissions below a specified threshold (c_2) and maximizing plant revenue. This observation aligns with [39] , which identified that biomass co-firing ratios significantly influence carbon capture performance due to variations in fuel composition and combustion characteristics. Notably, under higher carbon pricing scenarios, CBCCS plants in Malaysia tend to reduce their total capture percentage to optimize economic outcomes. The dynamic interplay between these emission components highlights the potential of CBCCS as a viable negative-emission technology, particularly in regions with access to sustainable biomass resources and existing coal power infrastructure.

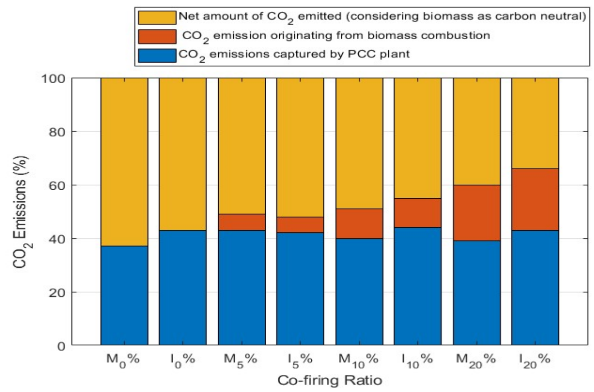

Figure 1. Environmental performance of CBCCS system under at various biomass co-firing ratio under carbon price regime

Economic transparency

Figure 2 illustrates the economic performance of the CBCCS system, focusing on plant revenue, CO_2 emission costs, and stranded assets (SA) in Malaysia and Indonesia. In Malaysia, revenue increases modestly from USD 3 billion to USD 3.5 billion as co-firing ratios rise to 20%, while Indonesia sees higher revenue due to its higher electricity prices and low carbon price. Both countries show exponential growth in FiT rates, highlighting the need for financial incentives to offset higher operational costs. The CO_2 emission costs decline with higher co-firing ratios, with Malaysia consistently having higher costs due to its higher carbon price. For stranded assets under the physical lifetime, Malaysia shows a higher baseline (USD 2.1 billion) compared to Indonesia (USD 1.8 billion), but both exhibit a slight decline with higher co-firing, suggesting biomass integration helps hedge against future carbon regulations. The economic lifetime SA risk remains stable, though Malaysia consistently faces higher risks. These results indicate that CBCCS systems, while requiring significant initial investment and policy support, offer substantial benefits in reduced carbon costs and stranded asset risk. The differences system, while requiring significant initial investment policy support, offer substantial benefits in reduced and

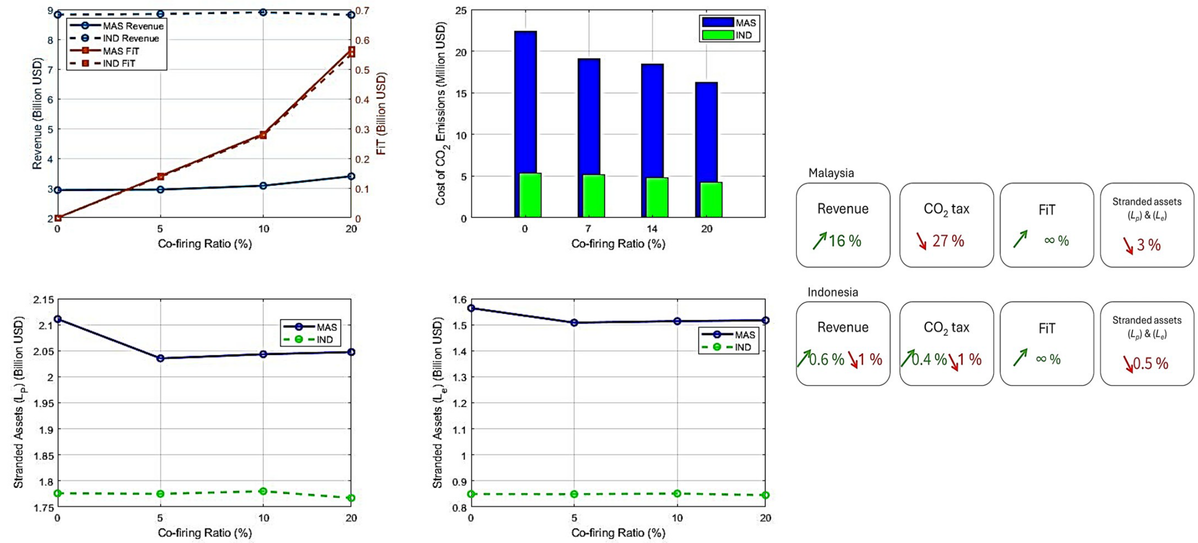

Figure 2. Economic performance of CBCSS system at various biomass co-firing ratio under the carbon price regime**.**

between Malaysia and Indonesia are mainly due to infrastructure age, policy frameworks, and market dynamics. The comparative dashboard (Figure 2, right) provides a scalable performance overview from 2024 to 2034, serving as a guideline for future implementation.

CONCLUSION

Biomass co-firing (5-20%) in Malaysia and Indonesia shows minimal impact on plant efficiency (~1%) but manage to reduce net CO_2 emissions (43% Malaysia, 34% Indonesia). At 20% co-firing, Malaysia sees revenue growth even under the high carbon price, while Indonesia faces deficit. This preliminary work shows that Malaysia has higher stranded asset risk, though increased co-firing slightly reduces this risk in both countries**.**

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