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Nur Safirah Bahuriddin
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia

Farzaneh, Hooman
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Muhamad Zameri Mat Saman
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia

Nurhasyimah Mohamed-Ali
Research Management Centre, Universiti Teknologi Malaysia

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Nur Safirah Bahuriddin[1,2], Hooman Farzaneh[2], Muhamad Zameri Mat Saman[1], Nurhasyimah Mohamed-Ali[3]

[1] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

[2]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, 816-8580, Japan

[3]Research Management Centre, Level 1, F54, Building School Graduate Student, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

Corresponding author email: nsafirah5@graduate.utm.my

Abstract: *Malaysia's National Energy Transition Roadmap (NETR) and the Twelfth Malaysia Plan emphasize the importance of low-carbon development and the adoption of clean energy solutions. In this context, the southern region of Malaysia emerges as a strategic location for deploying carbon capture technology, given its high concentration of energy plants. This study evaluates the amount of* CO_2 *emissions captured and the corresponding reduction in* $PM_{2.5}$ *emissions resulting from the implementation of carbon capture units. It then conducts a co-benefit analysis, focusing on the environmental, health, and economic gains associated with reduced* $PM_{2.5}$ *exposure. Additionally, the development of carbon capture infrastructure is expected to stimulate the creation of green jobs. By presenting these findings, the study aims to inform policymaking and underscore the role of carbon capture as a vital tool in supporting Malaysia's transition toward a cleaner, more sustainable future.*

Keywords: Co-benefits; Health impact assessment; Carbon capture

1. INTRODUCTION

1.1 Overview of Carbon Capture in Malaysia

The fast-paced economic expansion in Malaysia has led to a marked increase in energy usage, which is largely dependent on fossil fuels, resulting in a significant rise in CO_2 emissions. According to Othman and Jafari [1], the energy industry accounts for approximately 32% of Malaysia's total CO_2 emissions, highlighting its significant contribution to the nation's carbon footprint. This sector, which encompasses electricity generation and a range of industrial processes, remains a principal source of national emissions.

In response to these challenges, Malaysia has pledged to achieve carbon neutrality by 2050. One important way to support this goal is by implementing carbon capture technology in power plants. Recent studies indicate that carbon capture has the potential to mitigate up to 60% of CO_2 emissions within Malaysia's energy sector, establishing it as a promising approach to achieving the country's climate targets [2].

Carbon capture technology is an approach designed to reduce greenhouse gas emissions. It includes a range of techniques and technologies designed to extract carbon dioxide from flue gases and the atmosphere, subsequently enabling its reuse or secure, long-term storage [3]. This process depends on the capture of carbon dioxide through the use of absorbent materials or membrane-based techniques [4]. To achieve substantial reductions in greenhouse gas emissions and support the decarbonization of the energy sector, carbon capture must be deployed across all fossil-fuel-based power generation facilities nationwide [2].

Besides technological challenges such as significant uncertainties in capture technologies and the questionable reliability of CO_2 storage sites, carbon capture also encounters economic and regulatory barriers. These include insufficient financial incentives, limited engagement from energy sector stakeholders, low levels of public acceptance, and minimal political backing [5]. Addressing these issues is crucial to facilitate large-scale deployment, as overcoming economic constraints and fostering stakeholder collaboration will enhance the feasibility and social acceptance of carbon capture projects, ultimately accelerating progress toward national and global emission reduction targets.

1.2 Research Gap and Contributions

In Malaysia, existing research on carbon capture technologies frequently examines environmental, health, and economic impacts in isolation, lacking a unified analytical framework. This compartmentalized approach hinders a holistic understanding of the interrelated benefits and trade-offs associated with carbon capture deployment. While environmental assessment tools such as Life Cycle Assessment (LCA) are commonly employed, they often omit concurrent evaluations of health and economic outcomes. As shown in [6-7], the emphasis remains largely on CO_2 mitigation, with limited attention to indirect co-benefits, particularly the reduction of co-pollutants such as $PM_{2.5}$ and their associated health impacts. This reveals a significant research gap in capturing the broader implications of carbon capture technologies, underscoring the need for integrated, multi-dimensional methodologies to inform balanced and effective policy development.

This study applies a comprehensive modeling approach, based on the methodologies presented in [8–9]. The co-benefits analysis specifically focuses on energy facilities located in Johor, Melaka and Negeri Sembilan, as these states host the highest concentration of energy plants in the country. This approach aims to provide deeper insights into the often-overlooked benefits that arise when carbon capture is used as a complementary solution to conventional emissions reduction strategies, ultimately enabling policymakers to make more informed decisions when formulating energy and climate-related policies.

Firstly, the net CO_2 captured is estimated from major energy plants located in southern Malaysia. Then, the avoided $PM_{2.5}$ emissions are quantified, and subsequently, $PM_{2.5}$ exposure is determined using a dispersion model. The second part assesses the impact of avoided $PM_{2.5}$ exposure on public health by developing and applying a dynamic dispersion model across the districts using a tool developed by the Energy and Environmental Systems (EES) laboratory at Kyushu University, Japan. Then, the health impact assessment and economic impact assessment are applied to quantify the benefits associated with reduced $PM_{2.5}$ exposure, as well as the corresponding cost savings derived from improved public health outcomes. Finally, the social benefits, which include the creation of green jobs, are also considered as integral components of the co-benefit analysis.

2. METHODS

2.1 Long Short-Term Memory

Long short-term memory (LSTM) is a type of recurrent neural network (RNN) specifically designed to model time-dependent and sequential data by addressing the limitations of traditional RNNs. LSTM is utilized in this study to predict CO_2 emissions in 2030 based on historical energy sector data of Malaysia (1990–2021).

This step is crucial as it provides a data-driven projection of future emissions, serving as a baseline for evaluating the potential environmental and health co-benefits of carbon capture implementation under various policy and technological scenarios. Moreover, projecting CO_2 emissions in 2030 serves as the foundation for quantifying associated reductions in co-emitted air pollutants, particularly $PM_{2.5}$. This integrated approach provides more robust and evidence-based insights for policymakers to justify carbon capture investments not only from a climate perspective but also from public health and socio-economic standpoints.

2.2 Co-benefits Approach

The concept of co-benefits denotes the supplementary community-level advantagesbenefits that arise from climate change mitigation strategies, which surpassthe main goal of lowering carbon emissions [10]. As previously noted, the co-benefits framework provides a more comprehensive perspective by accounting for advantages that extend beyond climate change mitigation, including effects on public health and economic outcomes [11]. In this study, four categories of co-benefits are assessed, all linked to reductions in $PM_{2.5}$ exposure, as shown in Figure 1.

Environmental co-benefits: The first step in this co-benefits approach is to estimate the corresponding reduction in $PM_{2.5}$ emissions resulting from the application of carbon capture technology at the power facility. Carbon capture installations primarily target CO_2 removal from flue gas streams in power generation and do not directly address $PM_{2.5}$ emissions.

However, its long-term implications become substantial, particularly when evaluating the differences between facilities equipped with carbon capture technology and those operating without it. If an equivalent volume of

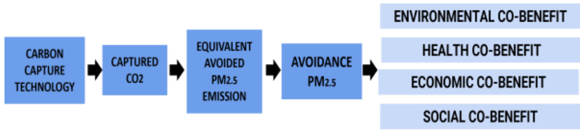

Fig. 1. Co-benefits analysis based on the structured framework developed in [8].

CO_2 were released through fossil fuel combustion in a conventional power plant lacking such technology, it would concurrently result in a corresponding level of $PM_{2.5}$ emissions.

The concept of "equivalent avoided $PM_{2.5}$ emissions" is employed, referring to the estimated volume of $PM_{2.5}$ that would have been discharged if an equivalent quantity of CO_2 had been emitted through fossil fuel combustion in power generation facilities. This concept may be expressed in formal terms as [8]:

$$E_{PM_{2.5(Avoided)}} = \frac{E_{CO_{2(Net\ Captured)}} EF_{PM_{2.5}}}{EF_{CO_2}} \tag{1}$$

$$E_{CO_{2(Net\ Captured)}} = E_{CO_{2(Captured\ from\ power)}} - E_{CO_{2(emitted\ from\ capture\ plant)}} \tag{2}$$

Where $E_{PM_{2.5(Avoided)}}$ denotes the estimated quantity of $PM_{2.5}$ emissions prevented by implementing a carbon capture at the energy facility that would otherwise operate without such a unit [kg/year]; $E_{CO_2(Net\ Captured)}$ refers to the total net CO_2 sequestered, accounting for additional emissions produced during the capture process due to auxiliary steam generation and internal energy consumption [kg/year]. $EF_{PM_{2.5}}$ and ECO_2 represent the emission factors for $PM_{2.5}$ and CO_2, respectively, associated with electricity production [kg/kWh]. Notably, the specific value of $E_{CO_2(Net\ Captured)}$ is determined based on calculations in [8].

Health co-benefits: To quantify the potential health co-benefits resulting from the reduction of $PM_{2.5}$ emissions in power plants equipped with carbon capture systems, it is essential to estimate the pollutant exposure experienced by surrounding populations. This study applies a steady-state Gaussian dispersion model for point sources to simulate hourly concentrations of $PM_{2.5}$ at specified locations. The avoided $PM_{2.5}$ exposure is calculated using the assessment tool developed by the Energy and Environmental Systems (EES) laboratory at Kyushu University, Japan based on [12]. The ground-level dispersion model is employed to project short-term regional concentrations of $PM_{2.5}$ based on the following equation:

$$L = \frac{E_{PM_{2.5(Avoided)}}}{2\pi u_s} \int \frac{Y}{\sigma_y \sigma_Z} \left(erfc\left(\frac{y}{\sigma_y}\right)\right) \tag{3}$$

$$Y = \left(exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + exp\left[\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right) \tag{4}$$

$$\sigma_y = 465.12(x)\, tan(0.0174(\theta - \mu\, ln(x)) \tag{5}$$

$$\sigma_z = \gamma x^{\tau} \tag{6}$$

The parameters σ_y and σ_z denote the lateral and vertical dispersion coefficients, respectively, measured in meters. H indicates the effective height of the emission source, and x refers to the horizontal distance from the emission point, both expressed in meters. The coefficients θ, μ, γ and τ are constants determined by the atmospheric stability class and the wind speed category of the study area. X and y are the downwind and crosswind distances from a hypothetical emission source (stack) situated at the energy plant site.

Given a known exposed population size N, the estimated number of additional cases of mortality or morbidity (ND_i) attributable to $PM_{2.5}$ exposure can be calculated, as outlined in Equation (7) [8]:

$$NDI_i = \left[\left(RR_{i,c} - 1\right) \times P_c\right] / \left[RR_{i,c} \times P_c\right] \times B_i \times N \quad (7)$$

Where, $RR_{i,c}$ refers to the relative risk of all-cause mortality associated with specific health outcomes (i) under a defined exposure condition (c). P_c represents the segment of the population exposed within each defined exposure category. B_i is the baseline incidence rate.

In the equations above, the relative risk (RR) reflects the probability of experiencing negative health effects in populations subjected to elevated levels of air pollution. When measured against those experiencing lower pollutant concentrations, this can be modeled using a linear function [8]:

$$RR = exp\mu(\Delta C) \quad (8)$$

Where μ denotes the factor that measures the sensitivity of a particular health condition to changes in pollutant levels, while ΔC signifies the avoided $PM_{2.5}$ concentration. It is essential to note that when assessing areas with $PM_{2.5}$ concentrations (C) substantially higher than those observed in reference epidemiological studies, it is advisable to utilize effect estimates derived from environmental epidemiology research that associate health impacts with logarithmic changes in $PM_{2.5}$ exposure.

Economic co-benefits: This study utilizes the Value of a Statistical Life (VSL) to estimate the economic burden of premature mortality linked to $PM_{2.5}$ exposure. Due to the limited availability of country-specific VSL data for Malaysia, the VSL for Malaysia was approximated based on existing estimates from the United States, following the adjustment methodology proposed by Viscusi and Masterman [13], such that,

$$VSL_{MY} = VSL_{USA} \times \left(\frac{Y_{MY}}{Y_{USA}}\right)^{\alpha} \quad (9)$$

In this analysis, Y_{MY} and Y_{USA} represent the gross national income (GNI) per capita for Malaysia and the United States, estimated at \$11,710 and \$80,450, respectively, in 2024 [14]. The variables VSL_{USA} and VSL_{MY} correspond to the Value of a Statistical Life for the U.S. and Malaysia for the same year. The U.S. VSL is assumed to be \$9.6 million, as reported by [15]. The term α indicates the income elasticity of VSL, which reflects how VSL changes in response to changes in income. In line with the recommendations for application in lower- and middle-income nations, this study adopts an elasticity value of one, as suggested by [16]. The Cost of Illness (COI) method is used to estimate the financial burden associated with hospitalizations resulting from morbidity outcomes. The cumulative economic benefits derived from reduced mortality and morbidity rates can be estimated using the following approach [8]:

$$C = \sum_i NDI_i \times S \quad (10)$$

Where C indicates the overall economic benefits resulting from avoided mortality and morbidity, and S refers to the per-person valuation using either the Value of Statistical Life (VSL) or Cost of Illness (COI) (refer Table 1).

Table 1. Unit cost of mortality and morbidity per individual

Endpoint	S (\$)	Method
Total mortality	139,339.96	VSL
Lung cancer and bronchus	1,100	COI
COPD	2,206	COI
IHD	2,645	COI
Stroke	4,737	COI

2.3 Data acquisition

Emissions and Air Quality Data: CO_2 emission data for energy plants in Malaysia is obtained from the source referenced in [17].

Health Data: Based on data from the Institute for Health Metrics and Evaluation (IHME) [18], information on Years Lived with Disability (YLDs) and deaths for the states of Malaysia was collected for this study. For mortality, three types of diseases were examined: non-communicable diseases (NCDs), respiratory diseases, and cardiovascular diseases. For morbidity, four specific conditions were considered: bronchus and lung cancer, chronic obstructive pulmonary disease (COPD), ischemic heart disease, and stroke.

3. RESULTS

3.1 Case Study

The LSTM model was developed using monthly CO_2 emission data collected from the energy industry across Malaysia, spanning the period from 1990 to 2021. This extensive historical dataset provided the basis for training and validating the model, ensuring accurate future projections. Based on the output of the LSTM model, the total CO_2 emissions in 2030 are projected to reach approximately 152.30 million metric tons (Mt CO_2) under a baseline scenario. This scenario assumes that no significant changes or enhancements will be made to current emission reduction policies or mitigation strategies, thereby reflecting a continuation of existing trends in energy production and carbon output.

Then, the study examines the implementation of carbon capture technologies at eleven energy plants in Southern Malaysia, located in Johor, Melaka, and Negeri Sembilan. Table 2 presents the technical characteristics of these facilities. The annual amount of CO_2 captured shows significant variation, ranging from approximately 41,72 tonnes of CO_2 per year at the Edra Melaka to more than 1.3 million tonnes annually at the Tanjung bin Power facility. The corresponding avoided $PM_{2.5}$ emissions derived based on the net captured CO_2 are lowest at Edra Melaka and Powertek, with estimated values of 12.46 and

13.38 tonnes per year, respectively, attributed to their comparatively lower electricity generation capacities. Figure 2 presents the amount of CO_2 captured and the corresponding avoided $PM_{2.5}$ emissions at the selected facility.Next, the $PM_{2.5}$ emissions is input into the dispersion model to calculate the corresponding avoided $PM_{2.5}$ exposure linked to the implementation of carbon capture to the energy facility. The spatial distribution of avoided $PM_{2.5}$ exposure from each plant, mapped within a 10 × 10 km² receptor grid, is presented in Table 3.The monthly dispersion patterns in Johor, Negeri Sembilan, and Melaka exhibit seasonal variability, with pollutant plumes typically aligning along the prevailing wind direction, influenced by coastal and inland wind dynamics. The downwind $PM_{2.5}$ concentration was highest at Tanjung Bin Power (1.66 µg/m³) and lowest at Powertek (0.06 µg/m³), influenced by regional wind patterns. The reduction in health burden is contingent upon the population density surrounding each district's plant and the level of avoided $PM_{2.5}$ exposure. Evaluations of yearly reductions in mortality and morbidity attributable to the implementation of carbon capture are detailed in Table 4.

For this study, RR values are based on the meta-analysis conducted in [8]. The results indicate that installing carbon capture systems in southern Malaysia has the potential to lower CO_2 emissions by 5.6 million tons annually, which would correspond to avoiding approximately 1,659 tons of $PM_{2.5}$ emissions each year. The integrated co-benefits analysis reveals significant results, estimating the avoidance of 1,424 deaths and 1,941 illness cases. This reduction in health impacts translates into approximately $190 million in savings for the local government, attributed to lower mortality and morbidity rates. With Johor ($ 102 million), Melaka ($65 million) and Negeri Sembilan ($34 million). In terms of avoided mortality cases, Johor demonstrates the most significant outcome,, with a total of 719 cases prevented. Then, the avoided mortality in Melaka with 462 cases and Negeri Sembilan with 243 cases. A total of 980 morbidity cases were avoided in Johor, marking the highest reduction among the regions, followed by Melaka with 632 cases and Negeri Sembilan with 330 cases.

For the assessment of social co-benefits, this study focuses on the creation of green jobs. The idea of green employment stems partly from a genuine dedication to sustainable development and environmental responsibility [19].

Carbon capture technology offers multiple advantages, including the promotion of low-carbon development, job generation, and support for a just transition within local communities. These social dimensions are integral to understanding the broader implications of implementing carbon capture solutions. Employment projections for implementing carbon capture at power plants indicate that there will be 20.48 job years/MW for construction, installation, and manufacturing (CIM), 0.31 job years per megawatt for operations and maintenance (O&M), and 0.00006 job years/MW for power plant processing (PP)[8]. Table 5 presents figures on potential green job opportunities associated with setting up carbon capture systems in the studied plants.

Environmental, health, and social benefits alone may not convince stakeholders unless they are linked to financial metrics. This comparison bridges technical outcomes

Table 2. Location and specifications of the energy plant

Region	Location	Place	Fuel
Johor	Kukup	Tanjung bin Power	Coal
		Tanjung bin Energy	Coal
	Pasir Gudang	TNB Pasir Gudang	Gas
		Pengerang Power	Gas
		SPGP	Gas
Melaka	Alor Gajah	Powertek	Gas
		Panglima Power	Gas
		Edra Melaka	Gas
Negeri Sembilan	Port Dickson	Jimah Energy	Coal
		Jimah East	Coal
		Port Dickson	Gas

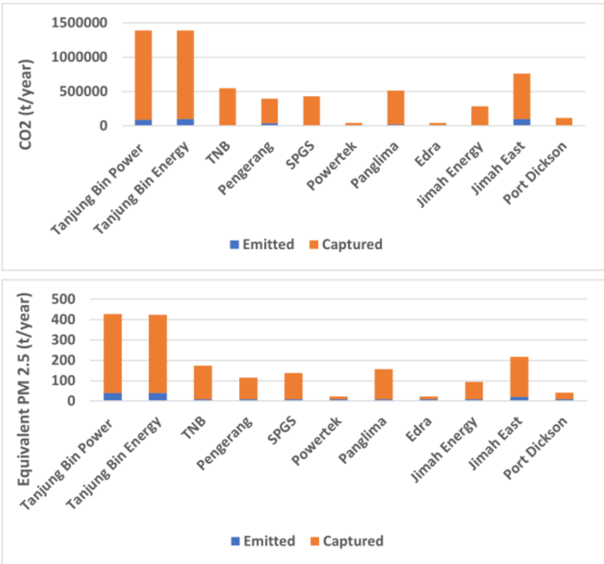

Fig. 2. Captured CO_2 and equivalent avoided $PM_{2.5}$ emissions in the selected energy facilities

Table 3. Average ground level avoided $PM_{2.5}$ exposure (10 x 10 km² area)

Name	Average ground level avoided $PM_{2.5}$ exposure
Tanjung Bin Power	1.66
Tanjung Bin Energy	1.65
TNB	0.7
Pengerang	0.45
SPGS	0.55
Powertek	0.06
Panglima	0.63
Edra	0.05
Jimah Energy	0.37
Jimah East	0.85
Port Dickson	0.14

with economic realities, making the research findings more practical and actionable. In this study, the annualized capital expenditure (CAPEX) is compared with the avoided cost to provide a comprehensive understanding of the technology's cost-effectiveness and economic justification. Annualized CAPEX reflects the yearly financial commitment required to invest in and maintain the carbon capture infrastructure over its operational lifespan.

Table 4. Annual regional benefits from carbon capture in eleven energy plants

Region	Mortalities		Morbidities	
	Avoided case	Avoided cost ($)	Avoided case	Avoided cost ($)
Tanjung Bin Power	26	3.642 M	35	98906.43
Tanjung Bin Energy	25	3.503 M	34	97514.82
TNB Pasir Gudang	221	30.80 M	300	859256.27
Pengerang Power	224	31.14 M	305	10688
SPGP	224	31.14 M	305	878197.10
Powertek	153	21.38 M	210	606417.26
Panglima Power	154	21.52 M	211	10688
Edra Melaka	154	21.52 M	211	10688
Jimah Energy Ventures	81	11.31 M	110	314913.59
Jimah East Power	82	11.46 M	111	316269.88
Port Dickson	79	11.03 M	109	312863.11

Table 5. Green job creations based on this study

District	Operational (MW)	CIM	O&M	PP
Kukup	590	9523	189	341
Pasir Gudang	347	7107	108	190
Alor Gajah	328	8021	122	209
Port Dickson	310	6810	128	250

By contrasting this with the avoided costs, researchers can determine whether the monetary benefits gained from emission reductions and social improvements offset the investment costs.

Table 6 presents a comparison between the avoided cost and the annualized capital expenditure (CAPEX). The total avoided cost for the 11 energy plants in Malaysia amounts to 43.78% of the total annualized capital expenditure (CAPEX), highlighting a significant reduction in investment requirements achieved through optimized operational strategies and cost-saving measures.

This substantial percentage indicates the effectiveness of the implemented technologies and management practices in minimizing upfront financial burdens, thereby enhancing the overall economic feasibility and sustainability of these power generation facilities.

Table 6. Comparison of avoided costs and annualized CAPEX for each plant

Name	Annualize CAPEX	Avoided cost
Tanjung Bin Power	15.21 M	3.74 M
Tanjung Bin Energy	18.08 M,	3.60 M
TNB	68.08 M	31.66 M
Pengerang	55.10 M	31.16 M
SPGS	81.11 M	32.02 M
Powertek	30.38 M	21.98 M
Panglima	32.86 M	21.52 M
Edra	31.90 M	21.52 M
Jimah Energy	42.86 M	11.62 M
Jimah East	35.97 M	11.77 M
Port Dickson	20.42 M	11.34 M

4. DISCUSSSION

4.1 Limitations

One key limitation of this study is its exclusive focus on $PM_{2.5}$ as the primary air pollutant of concern, which overlooks the potential co-benefits associated with reducing other harmful co-pollutants, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ground-level ozone. Additionally, the analysis does not account for non-health-related externalities, such as agricultural productivity losses and ecosystem degradation, which may also be mitigated through the implementation of carbon capture technologies. As a result, the total environmental and societal co-benefits of carbon capture may be underestimated.

4.2 Future Research

Future research could explore how the co-benefits of carbon capture vary across different geographic regions, income groups, and levels of population vulnerability. Populations living near industrial zones or in areas with poor air quality often experience disproportionately higher exposure to air pollutants, making them more likely to benefit from air quality improvements associated with the implementation of carbon capture. Additionally, lower-income or marginalized communities may face limited access to healthcare and greater sensitivity to pollution-related health impacts. By disaggregating co-benefit outcomes by socioeconomic and demographic factors, future studies can help identify environmental justice implications and inform more equitable policy design. Such targeted insights would enable policymakers to prioritize carbon capture deployment in locations where it yields the most excellent health and economic gains for vulnerable populations, thereby maximizing the societal return on investment and advancing the goals of both climate mitigation and social equity.

4.3 Conclusions

Based on projected CO_2 emissions in 2030, the implementation of carbon capture technology has the potential to reduce emissions from Malaysia's energy sector by approximately 7%. While this figure may seem modest, it reflects a realistic and practical target, considering that Malaysia is still in the initial phase of deploying such technology. This estimate is derived from theoretical modeling rather than real-world data, underscoring the need for pilot projects and empirical validation in the future.

The financial gains achieved through the reduction of $PM_{2.5}$ exposure present an opportunity to reinvest in carbon capture initiatives across Malaysia, emphasizing the broad socio-economic value of adopting such technology within the national power industry. These findings highlight the dual advantage of carbon capture systems, offering both environmental improvements and economic relief for Malaysia's energy and industrial sectors.

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