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Harnessing Carbon Trading and Life Cycle Assessments for Renewable Energy Transition in Southeast Asia

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Abstract

The climate crisis, caused by fossil fuel dependence and deforestation, poses significant socio-economic and environmental challenges for Southeast Asia, including reduced agricultural productivity and increased health risks. While previous studies have explored renewable energy development in the region, limited research has systematically examined how renewable energy adoption, carbon trading, and life cycle assessments (LCA) can work together to accelerate the energy transition. To address this gap, our study assesses the potential of renewable energy in mitigating these challenges and examines the key mechanisms needed to support a sustainable transition. Through a structured review of peer-reviewed articles, government reports, and data from intergovernmental organizations, we analyzed renewable energy potential and the roles of carbon trading and life cycle assessments (LCA) as enabling mechanisms in Southeast Asia. Our findings reveal that, despite projected increases in CO_2 emissions from 1.4 gigatons (Gt) in 2018 to nearly 2.4 Gt by 2040, Southeast Asia has set ambitious targets to reduce energy consumption by 23% and increase renewable energy to 22.1% within the same timeframe. Achieving these goals will require robust, adaptive policies that incentivize renewable investment and promote regional cooperation. Carbon trading and LCA are identified as pivotal tools, providing financial motivation for emission reductions and offering frameworks to assess the environmental impacts of energy projects. In conclusion, this study suggests that Southeast Asia's renewable energy adoption, supported by sustainable practices like carbon trading and LCA, could significantly advance both global climate mitigation and socio-economic resilience within the region.

Keywords:
carbon trading, CO_2 emission, life cycle assessments, renewable energy, Southeast Asia.

1. Introduction

Climate change is one of the most urgent challenges of our time, primarily driven by human activities such as fossil fuel combustion and deforestation (Huang et al., 2016). Since the pre-industrial era, global temperatures have risen by approximately 1.1 °C, leading to more frequent and intense weather events, rising sea levels, and disruptions to ecosystems (Tollefson, 2021). This global warming is closely tied to the increase in atmospheric greenhouse gases (GHGs)—particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—emitted through industrial, transportation, and agricultural activities (Abbass et al., 2022; Jones et al., 2023; Sovacool et al., 2021). These emissions have accelerated the natural greenhouse effect, intensifying global warming and its widespread impacts.

The health impacts associated with climate change are equally severe. Rising temperatures and shifting weather patterns facilitate the spread of vector-borne diseases, such as malaria and dengue fever (Campbell-Lendrum et al., 2023; Uji, 2012; United Nations Framework Convention on Climate Change [UNFCCC], 2007; Ryan et al., 2021). Vulnerable populations, including the elderly, children, and individuals with pre-existing conditions, are particularly at risk (Zhou & Wang, 2024). Addressing these multifaceted challenges necessitates a comprehensive and integrated approach (Wang et al., 2022).

The energy sector is a major contributor to GHG emissions, with fossil fuel combustion accounting for approximately 73% of global emissions (Ritchie, 2020). As reliance on fossil fuels increases, their burning generates significant CO_2 emissions and leads to air and water pollution, posing serious health and environmental risks (Campbell-Lendrum et al., 2023; Khine & Langkulsen, 2023; Uji, 2012). Therefore, transitioning to sustainable energy sources is critical for mitigating climate change and promoting long-term environmental health (Attanayake et al., 2024; Gielen et al., 2019; Qazi et al., 2019).

Southeast Asia, rich in renewable resources such as solar, wind, hydro, and geothermal energy, has significant potential to contribute to the global energy transition. However, unlocking this potential requires overcoming substantial challenges, including financial constraints, technological gaps, and regulatory complexities (Handayani et al., 2022; Pereira & Shaw, 2022; Sakti et al., 2023). Additionally, the region's rapidly growing energy demand—driven by urbanization and economic development—underscores the need to shift toward cleaner, sustainable energy sources that align with environmental and socio-economic goals (Handayani et al., 2022).

The socio-economic impacts of climate change are particularly pronounced in Southeast Asia. The region is heavily dependent on climate-sensitive sectors such as agriculture, fisheries, and coastal resources, which are increasingly vulnerable to changing climate patterns (Dong et al., 2024). For instance, the agricultural sector faces threats from altered precipitation, soil degradation, and increased pest infestations, all of which could compromise food security (Habib-ur-Rahman et al., 2022; Zambrano-Medina et al., 2024). Additionally, rising sea levels and more frequent extreme weather events, such as floods and typhoons, contribute to displacement, environmental degradation, and social challenges (Chen et al., 2020). These extreme weather events and their associated impacts underscore the urgent need for climate resilience. Major cities in the region, including Jakarta and Manila, are particularly susceptible to flooding, highlighting the necessity for significant investments in resilient infrastructure to support their growing populations (Holden & Marshall, 2018). Moreover, biodiversity loss due to habitat degradation further destabilizes ecosystems, compounding the risks faced by local communities (Eekhout & De Vente, 2022).

Previous studies have focused on specific aspects of renewable energy in ASEAN, such as hydrogen technology (Kumaraswamy et al., 2024), electricity market design (Nepal et al., 2024), and the export of renewable energy (Mubarok & Kartini, 2023). Our study fills a critical gap by offering the first comprehensive evaluation of renewable energy feasibility across six ASEAN nations, with a unique focus on integrating carbon trading and life cycle assessments (LCA). This dual focus not only extends the current discourse on energy transition pathways (Fahim et al., 2023; Handayani et al., 2022), but establishes a novel, actionable framework to support ASEAN's sustainable energy goals (Hu & Weng, 2024; Yusoff et al., 2024). By combining these mechanisms, our research identifies viable pathways that support climate mitigation, socio-economic growth, and enhanced energy security.

2. Methods and Materials

This study employed a structured literature review to evaluate pathways toward achieving Net Zero Emissions (NZE) in the Association of Southeast Asian Nations (ASEAN) region, focusing on renewable energy transition, carbon trading mechanisms, and LCA. The primary data sources included

peer-reviewed journal articles, government reports, and reports from intergovernmental organizations. Databases such as Web of Science, Scopus, and Google Scholar were utilized to retrieve peer-reviewed articles, while government and intergovernmental reports were accessed through their respective websites and repositories. Key reports included documents from the United Nations Development Programme (UNDP), the Malaysian Investment Development Authority (MIDA), ASEAN Member States (AMS), the United Nations Framework Convention on Climate Change (UNFCCC), the International Renewable Energy Agency (IRENA), the ASEAN Center for Energy (ACE), the Intergovernmental Panel on Climate Change (IPCC), and the International Energy Agency (IEA).

The selection of studies and reports adhered to specific inclusion criteria to ensure quality and relevance. To be included, a source had to meet four criteria. The first criterion was relevant to the research question, focusing on renewable energy potential, energy transition, carbon trading, and LCA in Southeast Asia. The second criterion was the credibility of the publication, which was limited to peer-reviewed journals and reports from reputable organizations. The third criterion required the availability of both qualitative and quantitative data, providing either empirical evidence or in-depth theoretical analyses. The final criterion was a geographic focus on the ASEAN region or the inclusion of AMS in global energy transition models. To ensure that the analysis reflected the most recent developments in the field, only studies and reports published within the last decade (2013–2024) were included. Exclusion criteria eliminated non-peer-reviewed articles, opinion pieces, and studies lacking rigorous methodological frameworks.

Both qualitative and quantitative analyses were conducted to provide a comprehensive understanding of the data. Each source was critically assessed to identify discrepancies, gaps in existing research, and areas requiring further investigation. Studies were cross-referenced with government and intergovernmental reports to validate key findings and ensure consistency in the analysis. Potential biases were carefully considered, particularly in reports sponsored by private entities or governmental bodies with vested interests in specific energy policies. The collected data were organized into the following thematic categories: (i) impacts of climate change on Southeast Asian energy systems; (ii) renewable energy potential (solar, wind, hydroelectric, geothermal); (iii) challenges and opportunities in energy transition (technological, economic, and policy-related); (iv) carbon trading systems and their implications for reducing emissions; and (v) the role of LCA in renewable energy projects and policy planning.

The findings from the literature review were synthesized into coherent themes, providing a structured overview of the energy transition landscape in Southeast Asia. This synthesis highlighted the current state of renewable energy adoption, the socio-economic and environmental challenges faced by AMS, and the potential for carbon trading and LCA to accelerate the transition to NZE. Results were presented through a combination of textual analysis, tables, and figures, ensuring that key insights were effectively communicated. The analysis also emphasized future scenarios for achieving regional and global climate goals by 2050.

3. Results and Discussions

3.1 Climate Change Threats in Southeast Asia

Our review found that fossil fuel combustion is the primary source of GHG emissions, significantly contributing to global warming (Huang et al., 2016; Magnan et al., 2021). This widespread consensus underscores the urgent need for immediate, collective action to address these harmful impacts (Thompson, 2010). In Southeast Asia, the situation is exacerbated by rampant deforestation, which reduces the number of trees that can absorb CO_2 and disrupts local ecosystems. Forest depletion raises atmospheric CO_2 levels, increasing the region's vulnerability to climate change.

Recognizing these critical issues, ASEAN has integrated climate change and disaster risk management into its core strategic plans, aligning with the United Nations' 2030 Agenda for Sustainable

Development. All AMS have committed to the Paris Agreement, aiming to limit the increase in global temperature. While efforts to cap global warming at 1.5 °C can help avert the more severe impacts associated with a 2 °C rise, Southeast Asia remains highly vulnerable to risks such as more extreme weather events and ecological disruption (Pereira & Shaw, 2022; Tollefson, 2021).

Aligned with these climate goals, the Stated Policies Scenario (STEPS) in the World Energy Outlook presents an alarming outlook for ASEAN. Projections indicate that emissions in the region could increase from approximately 1.4 gigatons (Gt) of CO_2 in 2018 to nearly 2.4 gigatons by 2040 (IEA, 2019). Although ASEAN's share of global emissions was relatively modest at about 4.3% in 2018, it is expected to grow to 6.5% by 2040 (IEA, 2019). Given the region's rapidly expanding population of nearly 696 million and one of the world's fastest-growing economies, with a GDP of around USD 3.5 trillion, energy demand and emissions are anticipated to continue their upward trend (Handayani et al., 2022; IEA, 2019).

Rising emissions exacerbate existing climate-related issues affecting diverse sectors, including agriculture. In rainfed agricultural areas such as Thailand, Cambodia, and Myanmar, prolonged droughts have severely impacted crop yields (Ha et al., 2023). Conversely, Indonesia, the Philippines, and Malaysia have faced increased flooding, with significant effects on agriculture and infrastructure (Chen et al., 2020; Venkatappa et al., 2021). Between 2015 and 2019, these extreme weather events led to the loss of approximately 20.6 million tons of crop production across ASEAN (Venkatappa et al., 2021). These climate-related challenges highlight the varied environmental difficulties across the region, with some countries struggling with drought and water scarcity while others contend with flooding and its detrimental effects on agriculture (Venkatappa et al., 2021).

Carleton and Hsiang (2016) emphasize the urgent need for targeted adaptation measures to protect ASEAN communities, such as strengthening healthcare infrastructure, developing early warning systems for extreme weather events, and adopting sustainable agricultural practices (Abbass et al., 2022; Khine & Langkulsen, 2023). Renewable energy utilization has the potential to support sustainable agriculture and to improve community health by providing long-term environmental benefits and reducing pollution (Chopra et al., 2022; Seddighi et al., 2023).

3.2 Southeast Asia's Energy Dependency on Fossil Fuels

The reliance on fossil fuels presents a major obstacle to achieving regional and global climate goals. In Southeast Asia, the reliance on non-renewable energy is particularly pronounced. While countries in the region have made commitments under the Paris Agreement, the continued expansion of fossil fuel infrastructure makes it difficult to meet these targets. Many countries are investing in new coal plants and oil refineries, which could remain operational for decades, thus locking in emissions and making it harder to transition to cleaner energy sources.

Thus, fossil fuels are expected to dominate the energy landscape in the region for decades to come, even as renewable energy sources slowly increase their share (ACE, 2020). In a baseline scenario, total final energy consumption (TFEC) is projected to rise by 38% by 2025 and a staggering 146% by 2040. Despite growing efforts to invest in cleaner energy alternatives, fossil fuels—including oil, coal, and natural gas—are still expected to account for two-thirds of TFEC over this period.

One of the most concerning aspects of this trend is the substantial portion of fossil fuels that are consumed by the industrial sector. The industrial sector alone is responsible for around 58% of fossil fuel demand, not including the fossil fuels used for electricity production (ACE, 2020). The continued growth of energy-intensive industries such as manufacturing, mining, and construction in Southeast Asia has driven up demand for coal and oil, further entrenching fossil fuels in the region's energy mix. This not only increases GHG emissions but also prolongs the region's dependence on unsustainable energy practices.

3.3 ASEAN Member States (AMS) Target Scenario for Energy Transition

Countries investing heavily in renewable energy infrastructure, particularly solar and wind, have seen notable reductions in emissions (Gielen et al., 2019). Solar power, for instance, generates electricity without CO_2 emissions, and wind farms offer a zero-emission alternative to coal or natural gas. These cleaner sources improve air quality by reducing harmful pollutants such as SO_2 and NOx, which are linked to respiratory and other health issues (Bertrand, 2021; Gielen et al., 2019).

The AMS Target Scenario represents a unified effort across ASEAN to meet energy demands while cutting GHG emissions by improving energy efficiency and expanding renewable energy use. The scenario projects energy efficiency improvements that could reduce TFEC by 8% by 2025 and 23% by 2040 compared to baseline projections (ACE, 2020). A key element of the scenario is the ambitious adoption of renewable energy, with goals to raise its contribution to 17.7% of the region's energy supply by 2025 and 22.1% by 2040 (ACE, 2020). This shift toward renewables aligns ASEAN with broader global efforts to transition to low-carbon systems, decrease fossil fuel dependence, and achieve international climate goals (ACE, 2020; Handayani et al., 2022).

To achieve the AMS Target Scenario, solar energy, in particular, has immense potential in Southeast Asia due to the region's abundant sunshine (Dalapati et al., 2023). Countries like Vietnam, Thailand, the Philippines, and Malaysia have made significant strides in solar energy development, with Vietnam emerging as a regional leader in solar capacity (Do et al., 2021; Dalapati et al., 2023). Similarly, wind energy, though geographically constrained, holds potential in countries with suitable coastal areas or elevated terrains, such as Vietnam and Indonesia (Chang & Phoumin, 2021; Do et al., 2021; Sakti et al., 2023). The installation of wind turbines along coastlines and in rural areas has already proven effective in reducing carbon footprints while supplying electricity to remote communities (Attanayake et al., 2024).

Moreover, Indonesia and the Philippines have substantial geothermal energy potential, offering a unique opportunity for these nations to diversify their energy mix and reduce their dependence on fossil fuels (Gutiérrez-Negrín, 2024; Pambudi & Ulfa, 2024). Geothermal energy is a stable and reliable energy source, providing a continuous power supply independent of weather conditions. This characteristic makes geothermal energy particularly valuable in regions like Southeast Asia, where intermittency remains a significant challenge for renewable energy integration.

The deployment of hydropower has also been significant in Southeast Asia, except in Singapore. Hydropower offers a reliable, large-scale renewable energy source, contributing significantly to the region's electricity generation (Handayani et al., 2022). Meanwhile, biomass energy presents another renewable option, particularly in countries with large agricultural sectors, such as Indonesia (Handayani et al., 2022). By utilizing these organic materials for energy, AMS can not only reduce waste but also decrease their reliance on fossil fuels (IRENA & ACE, 2022).

3.4 Challenges and Fundamental Pathways to Energy Transition in ASEAN

Figure 1 illustrates a comprehensive energy transition scheme, highlighting the shift from fossil fuels to renewable energy sources. This scheme positions energy projects as a foundational platform, supported by low-carbon policies (such as carbon tax and carbon market) and LCA, with the goal of achieving NZE in the region. However, a successful transition should address a multifaceted array of challenges, including financial, technological, policy, social, and dependency issues, even though investments in renewable energy technologies hold the potential to create new industries and job opportunities while decreasing the region's reliance on imported fossil fuels (Attanayake et al., 2024). Financial constraints still pose a significant barrier, as substantial investments are required to develop renewable energy infrastructure. Governments must implement policies that encourage clean energy projects, such as subsidies and carbon pricing mechanisms that render fossil fuels less economically attractive (Handayani et al., 2022; Zheng & Khoo, 2022).

Southeast Asia faces several challenges in expanding its clean energy infrastructure and technology advancement (Aleluia et al., 2022; Handayani et al., 2022). One of the primary hurdles is the intermittency of renewable energy sources, particularly solar and wind power. Unlike fossil fuels, which provide a constant energy supply, renewable sources depend on environmental conditions. Solar energy generation fluctuates with daylight hours and weather, while wind energy varies with wind patterns, which can be unpredictable (Tong et al., 2021). This intermittency creates gaps in the energy supply, making it challenging to rely solely on renewables without substantial advancements in energy storage technologies.

Advancements in energy storage, grid modernization, and energy efficiency are necessary to lower costs and enhance the reliability of renewable energy sources (Qazi et al., 2019; Seddighi et al., 2023). For instance, improvements in battery technology can facilitate the storage of excess energy generated from intermittent sources like wind and solar (Ajibade et al., 2024). Furthermore, modernizing the energy grid will help integrate renewable sources into the existing infrastructure.

Geophysical limitations further complicate renewable energy adoption (Tong et al., 2021). The availability of wind and solar resources is uneven across the region. For instance, Vietnam boasts extensive coastal areas suitable for wind farms, whereas other nations may lack the geography for large-scale wind power implementation. Similarly, regions experiencing monsoons can face challenges in solar energy generation.

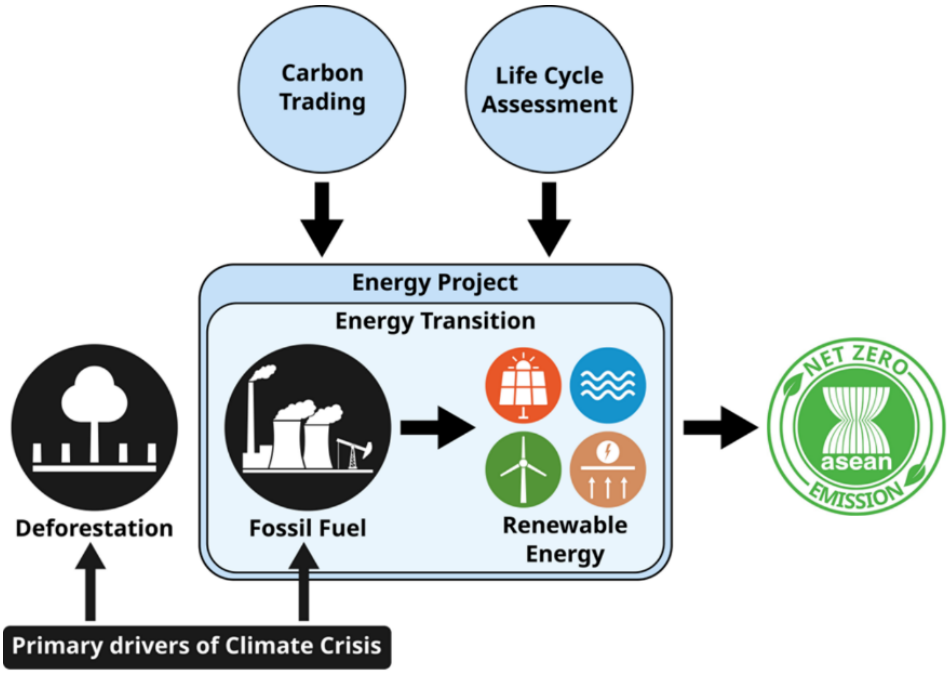

Figure 1. Scheme of energy transition to address the climate crisis and the challenge of NZE.

Moreover, social issues also play a vital role in the transition process. Public acceptance of renewable energy initiatives can significantly influence their success. Communities may have concerns about land use and the impact of renewable projects on local ecosystems (Van De Ven et al., 2021). Furthermore, transitioning away from fossil fuels can disrupt existing industries and livelihoods.

The dependency on fossil fuels remains a formidable challenge, particularly in regions where economies are built around fossil fuel extraction and consumption (IEA, 2019). To successfully navigate the energy transition, a concerted effort is required among governments, industries, and communities to implement supportive policies, invest in clean energy technologies, and address both the social and economic implications of this significant transformation. Given these bottlenecks, our research underscores the

urgent need for regional cooperation in technology development and the standardization of renewable energy policies across Southeast Asia. Subsequently, collaborative efforts are essential for facilitating cross-border energy projects, which can maximize the benefits of the energy transition (credible, efficient, and robust) (Figure 2).

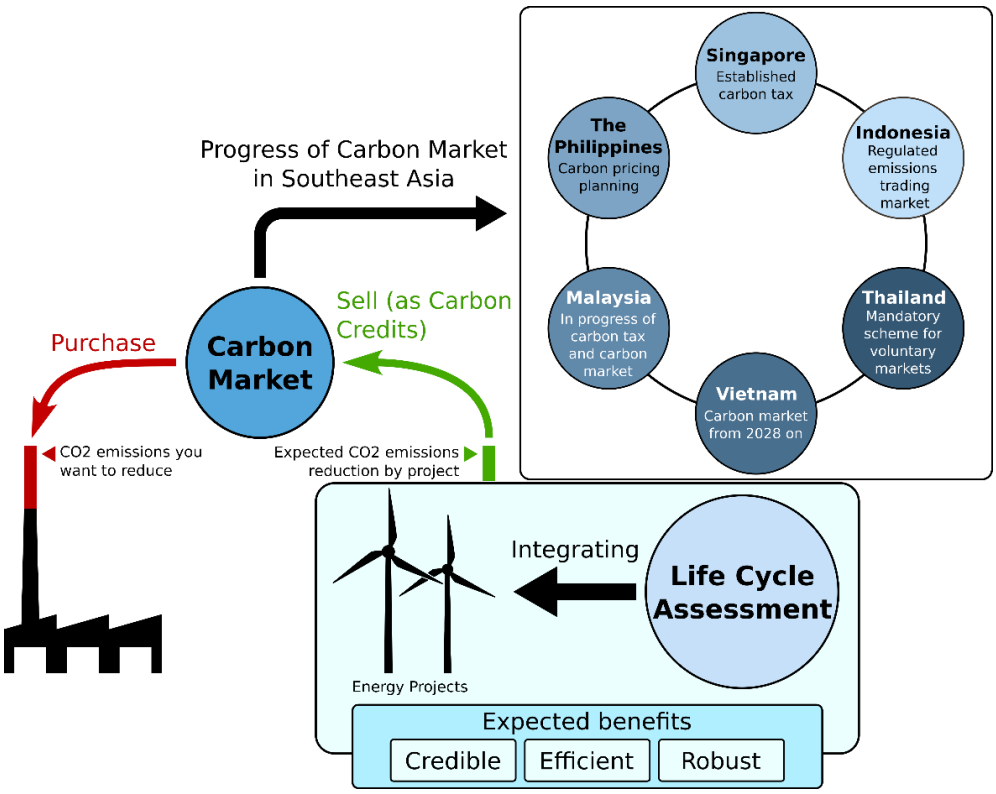

Figure 2. Overview of carbon market, progress of carbon market in Southeast Asia, and key role of LCA in establishing carbon market.

3.5 Carbon Trading and LCA as Game Changers in ASEAN Energy Transition

Renewable energy could play a transformative role in achieving the goals of the Paris Agreement (Gielen et al., 2019; Hassan et al., 2024). With the right international policies and investments in carbon markets (Michaelowa et al., 2019, 2022) and LCA (Caetano et al., 2024; Turconi et al., 2013), renewable energy can drastically lower global emissions while providing a sustainable and reliable energy supply (Erdiwansyah et al., 2019; Handayani et al., 2022). A critical element in the global energy transition is the implementation of the carbon market, also known as the carbon trading or emission trading system (ETS). By putting a price on carbon emissions, carbon markets provide economic incentives for companies to reduce their carbon footprint, encouraging the adoption of cleaner technologies and renewable energy sources. These markets can facilitate international cooperation and help countries achieve their emissions targets in cost-effective ways (Michaelowa et al., 2022). The success of carbon markets is largely contingent on well-regulated systems that ensure transparency, accountability, and effectiveness (Michaelowa et al., 2019, 2022). Well-structured carbon markets could help finance renewable energy projects, especially in developing regions like Southeast Asia, where the initial costs of clean energy technologies can be prohibitive.

In conjunction with carbon markets, LCA is crucial for evaluating the environmental impact of different energy systems, from production to disposal. LCA helps quantify the total emissions associated with energy sources, including the hidden emissions that occur during the extraction, manufacturing, and transportation phases (Caetano et al., 2024; Sun et al., 2022). For instance, while renewable energy sources like wind and solar have minimal emissions during operation, the production of solar panels

and wind turbines involves energy-intensive processes that must be accounted for to ensure the overall sustainability of these technologies. LCA provides a holistic framework for policymakers to assess the long-term environmental benefits of transitioning to renewable energy, helping them make informed decisions that consider the entire energy supply chain (Caetano et al., 2024; Turconi et al., 2013).

3.5.1 Low-carbon policy development and energy transition commitment in six ASEAN countries

Low-carbon policies include a carbon tax and carbon market, in which carbon tax is more direct but less comprehensive than the carbon market to reduce carbon emissions (Zavyalova & Li, 2024). Our study focuses on the development of carbon markets and the integration of LCA in energy projects (Figure 2) in six AMS—Singapore, Indonesia, Thailand, Vietnam, Malaysia, and the Philippines. These countries, which have experienced substantial economic growth in recent years, represent a significant portion of the Southeast Asian market and possess considerable potential for adopting clean and renewable energy sources (Bakhtyar et al., 2013).

Despite collective commitments to the Paris Agreement, AMS show varied progress in adopting renewable energy technologies (IRENA & ACE, 2022; Sakti et al., 2023). As CO_2 emissions in ASEAN reached 1.74 billion metric tons in 2021, with Indonesia being the largest emitter, the region's response to mitigating these emissions has become increasingly urgent (Statista, 2023). However, Indonesia, together with Singapore, are relatively optimistic about meeting their renewable energy targets (100%) by 2050 and 2060, respectively (Zheng & Khoo, 2022). Table 1 illustrates that six AMS have already established low-carbon policies or carbon markets, starting in different years, with Singapore emerging as a pioneer in this direction starting in 2019 (Lawson et al., 2023).

Table 1. The progress of carbon trading, NZE commitment, and energy transition of six south east Asian countries.

Parameters	Singapore	Indonesia	Thailand	Vietnam	Malaysia	The Philippines
CO_2 emission (million metric tons)	32.51	619.28	278.5	326.01	256.05	144.26
NZE commitment	2050	2060	2050	2050	2050	Not yet
Renewable energy share by net zero-year (%)	100	100	50	59.8	70	50
Low-carbon policy start year	2019	2021	2021	2020	2022	2023
Mechanism of low-carbon policy (E/I/P)*	• Carbon tax (E) • Carbon market (I)	• Carbon market (E) • Carbon tax from 2025 (P)	• Carbon tax from 2025 (P)	• Carbon tax (E) • Carbon market from 2028 (P)	• Carbon tax (I) • Carbon market (I)	• Carbon tax (P) • Carbon market (P)

*E =established, I= in progress, P = plan/ expected

The diversity in policy approaches and adoption rates reflects the complex dynamics shaping each country's energy transition. Comparative analysis reveals that economic, political, and social factors significantly influence the growth of renewable energy in AMS (Handayani et al., 2022). The pace of development in this sector is uneven, with some countries making substantial progress while others lag behind (Lawson et al., 2023; Sakti et al., 2023; Zheng & Khoo, 2022).

One of the critical factors influencing the uneven growth of renewable energy in ASEAN is the economic condition of each nation. Wealthier countries, such as Singapore, have more financial resources to invest in cutting-edge technologies and infrastructure, allowing for more rapid deployment of renewable energy systems. Singapore's forward-looking policies have enabled it to invest heavily in solar energy and energy-efficient technologies, which are projected to play a central role in its energy mix by 2050 (Zheng & Khoo, 2022). Additionally, Singapore's carbon policy is multifaceted, integrating direct taxation and providing assistance to industries and households as they shift towards a low-carbon economy (Rakhiemah et al., 2024).

Indonesia has significant renewable energy potential, especially in geothermal and hydropower. However, its reliance on coal presents a major challenge to reducing emissions (Pambudi & Ulfa, 2024). The country has announced ambitious plans to phase out coal plants by 2050, but the economic and social implications of this transition, particularly for communities dependent on the coal industry, complicate its energy transition. To overcome these challenges, Indonesia has started focusing on expanding its renewable energy capacity, particularly in geothermal energy, which it holds one of the largest potentials in the world (Gutiérrez-Negrín, 2024). By continuing to invest in renewable technologies and developing a more comprehensive carbon pricing mechanism (Rakhiemah et al., 2024), Indonesia could shift toward a more sustainable energy mix.

Government policies also play a crucial role in determining the pace of renewable energy development. Countries with strong regulatory frameworks and incentives for renewable energy development have seen more significant progress than those lacking such measures. Thailand's success in promoting solar energy, for instance, can be attributed to its feed-in tariff (FiT) system, which incentivizes households and businesses to install solar panels by guaranteeing a fixed price for the electricity they generate (Odermatt, 2023). This policy has helped Thailand become a regional leader in solar energy capacity.

In Vietnam, rapid economic growth has fuelled energy demand, leading to increased reliance on fossil fuels. However, Vietnam has become a rising star in the renewable energy sector, particularly in solar energy, where it has experienced an unprecedented boom (Do et al., 2021; Sakti et al., 2023). Vietnam's success in scaling up solar energy capacity has been driven by favourable government policies, such as the introduction of feed-in tariffs and power purchase agreements, which have attracted both domestic and international investments.

While Malaysia is still in the progress of the carbon tax and carbon market (Figure 2), the country has made considerable progress in integrating renewable energy into its national grid. MIDA has introduced policies aimed at boosting investment in solar, wind, and biomass energy projects and targeted the renewable energy capacity at 70% by 2050 (MIDA, 2023).

The Philippines is also making strides in its renewable energy sector, particularly through its geothermal energy capacity, one of the largest in the world (Pambudi & Ulfa, 2024). Despite this, challenges remain in scaling up other renewable sources, such as solar and wind, due to the high cost of technology and lack of investment in energy infrastructure. The Philippines' participation in regional carbon markets could help bridge this investment gap.

The need for regional cooperation and knowledge sharing is evident from the literature. AMS can benefit significantly from pooling its resources and expertise to accelerate the adoption of renewable energy technologies. Regional cooperation on projects such as cross-border electricity trade can help countries with surplus renewable energy capacity, like Laos, export clean electricity to neighbouring countries, reducing overall emissions across the region (Handayani et al., 2022). Initiatives like the ASEAN Plan of Action for Energy Cooperation (APAEC) provide a framework for collaboration on energy efficiency and the deployment of renewables, aiming to increase the region's share of renewable energy in the total energy mix (IRENA & ACE, 2022).

3.5.2 LCA's potential for evaluating the environmental impact of energy projects

Carbon trading enables industries to reduce emissions through financial rewards, fostering cleaner production processes and encouraging investment in renewable energy technologies. This mechanism aligns market forces with climate objectives, promoting a more sustainable energy landscape. Simultaneously, LCA provides a comprehensive framework for assessing the overall environmental effects of energy projects, ensuring that the long-term impacts of technologies are considered, from production through disposal.

Establishing effective and standardized LCA protocols should adopt four foundational principles (Müller et al., 2020). The first principle emphasizes aligning LCA guidelines with International Organization for Standardization (ISO) standards. This ensures global consistency and fosters adherence to best practices. Incorporating energy audits and promoting transparency within the process also helps verify data accuracy and enhances compliance (Badiola et al., 2017; Müller et al., 2020). Transparency is especially important in maintaining public trust and ensuring that all stakeholders, especially policymakers and industry leaders, can access and understand the results.

The second principle involves the integration of LCA with techno-economic assessments (TEA). By combining environmental and economic factors, this approach offers a more comprehensive evaluation of energy projects. TEA provides insight into the financial feasibility of energy technologies, while LCA ensures that environmental performance is prioritized. Developing guidelines that link LCA and TEA helps decision-makers balance environmental sustainability with economic viability, thus promoting investments in cost-effective renewable energy technologies that also minimize environmental harm (Müller et al., 2020; Sun et al., 2022).

The third principle stresses that both the environmental and cost impacts should be optimized (Müller et al., 2020; Sun et al., 2022). Energy projects must demonstrate a clear reduction in environmental damage while maintaining cost competitiveness. This balance is essential for broader adoption, as renewable energy options must compete with traditional fossil fuels not only in terms of emissions but also in affordability. Through such evaluations, stakeholders can identify technologies that offer the greatest environmental benefits at the lowest cost.

Lastly, one of the key challenges in LCA implementation is the complexity of the reports generated. These reports, while thorough, are often dense and difficult for practitioners in the field to interpret. As such, the fourth principle calls for LCA practitioners to develop simplified methods for writing clear and concise reports tailored to specific audiences (Chau et al., 2015; Müller et al., 2020). Streamlining communication not only makes LCA findings more accessible to policymakers, project managers, and investors but also helps translate scientific data into actionable insights. Finally, the practitioner should also ensure that reports are understandable and can facilitate better decision-making at all levels of project implementation and policy development.

3.6 A Role of Government Policies Towards Energy Transition in ASEAN

The successful implementation of the AMS Target Scenario requires technological innovation, substantial financial investments, and supportive policy frameworks (ACE, 2020; Handayani et al., 2022; Sakti et al., 2023). Transitioning to renewable energy and achieving energy efficiency targets by 2025 and 2040 will require public and private sector funding (ACE, 2020). ASEAN governments must prioritize investments in renewable projects, including solar farms, wind parks, hydropower plants, energy storage, and grid modernization. These investments depend on both domestic resources and international financial support, especially in developing countries where upfront costs can be high.

In addition to financial backing, robust policy support is essential. Governments should implement policies that incentivize renewable energy adoption, such as feed-in tariffs, tax breaks, and subsidies for clean energy projects (Odermatt, 2023; Sakti et al., 2023). Low-carbon policies (carbon tax and

carbon market) can further promote the shift away from fossil fuels by increasing their cost relative to renewable alternatives. Countries that have adopted these mechanisms have witnessed accelerated renewable energy adoption as the economic benefits of clean energy become clearer.

International cooperation is crucial in supporting the ASEAN region's energy transition. Collaborative efforts among AMS, along with partnerships with external organizations, can facilitate knowledge sharing and technology transfer. Such collaborations help countries overcome technical and financial barriers. In this light, initiatives like APAEC provide a framework for coordinated efforts in promoting energy efficiency and renewable energy adoption (Rakhiemah et al., 2024).

Political stability and the rule of law in ASEAN play a crucial role in shaping the region's energy transition by providing a foundation for long-term planning, investment security, and regulatory consistency, which in turn attracts investors and accelerates the deployment of renewable energy (Aleluia et al., 2022). For instance, in Vietnam and Thailand, government-backed feed-in tariff programs have played a crucial role in promoting solar energy growth. In Vietnam, attractive tariff rates have led to a significant increase in solar installations, positioning the country as one of the fastest-growing solar markets globally (Do et al., 2021; Odermatt, 2023; Sakti et al., 2023). Similarly, Thailand has leveraged financial incentives for renewable energy to expand its solar power sector (Odermatt, 2023; Sakti et al., 2023).

However, the energy transition in other AMS faces challenges. While Vietnam and Thailand have taken significant measures, others are left behind due to political and regulatory inconsistencies. Countries without a clear legal framework for renewable energy often struggle to attract the necessary investments (Erdiwansyah et al., 2019). Political instability can undermine efforts to implement energy policies, as fluctuating agendas disrupt energy priorities. This emphasizes the need for harmonizing regulations across the region to ensure that all AMS progress toward their renewable energy targets consistently (Handayani et al., 2022).

Furthermore, regional cooperation in standardizing renewable energy policies could facilitate cross-border energy trade, allowing countries with surplus renewable capacity to support those with deficits. This would enhance energy security across ASEAN while advancing collective climate goals. Intergovernmental organizations, such as ACE, are crucial in fostering dialogue and cooperation among member states to promote renewable energy and efficiency. Through the APAEC, ACE supports integrating renewable energy goals into national plans and encourages the sharing of best practices (Handayani et al., 2022).

4. Conclusions

This study underscores the strategic importance of renewable energy in Southeast Asia's pathway toward net-zero emissions (NZE), leveraging the region's abundant solar, wind, hydro, and geothermal resources. Addressing a significant gap in the literature dominated by single-technology studies, our research uniquely contributes a holistic evaluation of renewable energy potential by integrating carbon trading mechanisms with life cycle assessment (LCA) in the ASEAN context. This combined approach provides an original, comprehensive strategy to drive sustainable energy transitions, facilitating strategic planning for net-zero emissions while considering economic and environmental sustainability.

Carbon trading offers financial incentives that attract investment in cleaner technologies, while LCA ensures that renewable energy projects are environmentally sustainable. Together, these mechanisms contribute a robust framework for advancing ASEAN's renewable energy agenda, positioning them as foundational tools for climate resilience. For policymakers, our findings point to the need for adaptive regulatory frameworks that support carbon markets and incorporate LCA insights. Subsequently, regional cooperation is vital to align standards, foster knowledge exchange, and build joint initiatives, such as a shared carbon market across ASEAN, to strengthen the region's capacity for sustainable energy.

Future research should prioritize case studies from AMS that are leaders in low-carbon policies or have significant renewable energy capacity. These studies would help evaluate the reduction of carbon emissions and assess the application and effectiveness of carbon trading mechanisms and LCA in driving sustainable energy transitions. Research using country-specific data could provide practical insights into how these tools support emissions reduction targets and improve renewable energy implementations.

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