

Supporting ASEAN Energy Decarbonisation through Bespoke Decision-support Software



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Executive Summary

The Southeast Asian region is the fifth largest global economy and fuelled predominantly by conventional (i.e., fossil-based) energy resources. The region faces escalating emissions and resource depletion due to rapid economic growth and urbanisation, posing significant challenges such as deforestation, natural disasters, energy crises and global warming, necessitating urgent policy measures to enhance energy security and sustainability. Despite commitments (net-zero, NDC, etc.), ASEAN (Association of Southeast Asian Nations) countries struggle to meet decarbonisation targets, with the region projected to lose up to 35% of its gross domestic product (GDP) by 2050 due to climate change impacts if climate issues remain unmanaged ('Open Access Government', 2021). Effective solutions include potentially developing a regional integrated energy market, fostering bioenergy with carbon capture and storage (BECCS) or bioenergy with carbon capture, utilisation, and storage (BECCUS), deploying low-emitting technologies, commissioning climate mitigation measures / technologies, and implementing carbon trading markets to drive decarbonisation. Long-term and short-term policies, alongside grassroots decarbonisation activities, are crucial for transitioning to a clean energy future and ensuring economic stability.

The RIDA (Research and Innovation for Development in ASEAN) project was initiated to address the pressing challenges linked to climate change and energy security within the ASEAN region. Recognising the heavy reliance on fossil fuels among ASEAN countries, the project aims to develop an optimisation-based decision-making framework for policymakers that supports the transition to sustainable energy systems while reducing greenhouse gas (GHG) emissions. Building on the DECarbonisation Options Optimisation (DECO2) software (Bhasker Nair et al., 2023), developed through a British Council-funded initiative, this RIDA project further enhances the model with carbon trading mechanisms, amongst other enhancements, to aid decarbonisation efforts. The primary motivation behind this initiative is to equip ASEAN policymakers with robust tools and strategies to help them achieve their climate targets, ensure energy security, and foster economic growth. The developed decision-making software was case-tested on the power sectors of Peninsular Malaysia and the Luzon grid of the Philippines, aiming to optimise energy planning and carbon trading within those power sectors to expedite ASEAN's transition to low-carbon energy systems. By addressing key questions (around techno-economic analysis) both quantitatively and qualitatively, the study explored the impact of carbon trading on technology selection, average electricity prices, and emissions reduction, and identified suitable carbon (i.e., emission rights) prices for different stakeholders (such as government and power plants) under minimisation of budget and maximisation of profits scenarios. Additionally, it assessed the feasibility of BECCS / BECCUS, examined the role of the bioeconomy in driving decarbonisation, and evaluated optimal energy mixes providing feasibility / infeasibility evidence for different energy policies. The findings culminate in policy recommendations for integrating carbon trading and low-carbon technologies for two major ASEAN economies (Malaysia and Philippines), indicating the scalability of the project across different regions and countries within ASEAN.

The methodology employed by the project is comprehensive and multifaceted. It begins with data collection, gathering extensive data on energy generation, consumption, existing and planned power plants, emission mitigation technologies, and emissions for the case studies on Malaysia and Philippines. The DECO2 software (an open-source mixed-integer linear programming, MILP, energy planning framework) based on deterministic optimisation is

integrated with a mixed-integer non-linear emissions trading model (Hameed et al., 2023). The resulting mixed-integer non-linear programming (MINLP) model is enhanced, incorporating a range of power plant types, emission reduction technologies, energy prices, budget targets, and emission goals to optimise energy systems and carbon trading. The MINLP model simulates the stakeholders of the power sector (the government and power plants) to participate in two businesses: carbon trading and selling electricity. The updated model allows profits from carbon trading to potentially lower electricity prices and taxes, incentivising power plants to reduce emissions, and supporting companies working on low-carbon or emission reduction technologies. The tool's comprehensive approach supports ASEAN countries in independently achieving sustainable and secure energy futures through integrated models encompassing energy system design, average electricity pricing, emissions trading, bioeconomy, and policy frameworks, by providing policy recommendations around optimal energy planning to meet decarbonisation targets. Despite significant fossil fuel subsidies in ASEAN countries (such as Malaysia), the developed framework promotes strategic shifts to low-carbon technologies, helping policymakers assess challenges and opportunities. Malaysian and the Philippines' case studies demonstrate the tool's potential in predicting pathways to meet net-zero targets. Furthermore, stakeholder engagement (from Malaysia and the Philippines) was a critical component, involving policymakers, industry experts, and other stakeholders through workshops and seminars to ensure the model's relevance and applicability.

The first case study focuses on the power sector of Peninsular Malaysia, involving 107 existing and planned power plants to meet power demands from 2024 to 2054. Two scenarios, budget minimisation and profit maximisation, were optimised with and without carbon trading to align with Malaysia's net-zero emissions target by 2050. Results indicate that appropriate carbon pricing and trading policies incentivise cleaner technologies and operational efficiencies, favouring renewable energy over carbon capture and storage (CCS) and negative emission technologies (NETs), and generating additional carbon trading revenue. Higher carbon prices promote renewable energy, while lower prices prefer fossil fuels. Despite the expansion of renewables, CCS and carbon capture, utilisation, and storage (CCUS) remain necessary due to the significant role of natural gas (NG) in the future energy systems as per the optimisation results. Malaysia's fossil fuel subsidies pose a threat to achieving its renewable energy goals. It is inevitable to decommission old fossil plants to avoid capacity payments and enhance renewable contributions to generation mix, which stands at 19% in 2023. Results suggest that carbon trading and gradual fossil phase-out are essential for Malaysia to meet its target of 29% renewable energy by 2030. The National Energy Transition Roadmap (NETR) aims to reduce coal capacity to 0% by 2050, increasing renewables to 70%. However, Malaysia lacks a clear post-2035 plan for achieving these targets as depicted by the gathered data. Solar growth is a key strategy (as suggested by the results) to achieve net-zero by 2050, and as some scenarios deploy afforestation and enhanced weathering NETs, therefore, maintaining 50% forest cover will require stringent regulations on palm plantations. BECCS is also deployed making it an important future low-carbon technology. The comprehensive approach and policies highlight the leadership potential of Malaysia to sustainably decarbonise its power sector through balanced policy and market strategies and help other developing countries in their decarbonisation efforts.

The second case study optimised the Philippines' Luzon grid, which comprises of 133 existing and planned power plants (including coal, oil, NG, biomass, geothermal, solar, hydro, and wind). Coal, followed by NG, holds the highest installed capacity among fossil fuels, while

hydropower leads among renewables. To achieve emission reduction targets of 77 Mt/y by 2024-2028 and 0 Mt/y by 2049-2053, budget minimisation and profit maximisation scenarios were optimised with and without carbon trading. Results indicate that a mix of low-emitting power, emission reduction technologies, CCS / CCUS, and alternative fuels (AFs) is essential for meeting emission targets. While CCS deployment is limited to a capture capacity of 251 Mt (available after 2030) as estimated by Asian Development Bank (ADB), results suggest that carbon trading, renewable energy expansion, fossil plant decommissioning, and emission reduction technologies, including afforestation, can help achieve net-zero. The Philippines' National Renewable Energy Program (NREP) aims for 35% renewable power by 2030 and 50% by 2035, but detailed expansion plans are lacking as per data and the results. Policymakers are urged to set clear, achievable goals for the power sector. The updated Nationally Determined Contribution (NDC) aims for a 75% reduction in GHG emissions from 2020 to 2030, mostly conditional on foreign support. Results suggest that government and plants can generate substantial revenue from carbon trading mechanism, that could reduce Philippines' dependence on foreign investments for its decarbonisation activities. Achieving net-zero by 2060 is possible but it will require aggressive goals, strict regulations, promotion of emerging technologies, and a robust carbon trading mechanism.

The project's outcomes hold substantial implications for ASEAN policymakers, industries, and the broader public. The innovations and methodologies developed through this RIDA project are highly scalable across the ASEAN region. The adaptability of the developed framework to local data and conditions ensures that any emerging nation can utilise the software while maintaining control over their energy policies. By offering a clear pathway for integrating carbon trading into national and regional energy planning and policies, software can be case-tested on other ASEAN countries (an MSc student at the University of Surrey is currently implementing the framework on Thailand's power sector), and the project supports the economic viability testing of low-carbon technologies and reduces reliance on foreign aid / investments. The policy recommendations, which include setting aggressive unconditional goals and promoting a diversified energy mix, are crucial for ASEAN countries to meet their climate targets by maintaining their economic growth and contribute to global decarbonisation efforts. The project has established a foundation for long-term collaborations (between the universities in the UK and the ASEAN region) and future extensions of this work, including detailed modelling of consumer behaviour, uncertainty analysis, energy subsidies, and bi-level optimisation. Potential partnerships with international research institutions and funding bodies are anticipated to further expand the project's impact, promoting sustainable energy transitions throughout ASEAN and other developing regions. This RIDA project represents a significant advancement in energy planning and policy optimisation including carbon trading for ASEAN and other emerging countries. The project provides a viable pathway to achieving sustainable and low-carbon energy systems, advancing economic growth, and guaranteeing environmental sustainability in the region.

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1. Introduction

The Southeast Asian region has seen a remarkable economic growth to become the fifth largest economy in terms of GDP as of 2020 and is projected to become fourth by 2030 (Heidari et al., 2015). This, combined with an increasing population (third largest after India and China), has brought with it escalating emissions and resource depletion, primarily driven by the surging demand for fossil fuels (Heidari et al., 2015) primarily driven by the surging demand for fossil fuels (Heidari et al., 2015). Moreover, the rise of the working and the middle class has led to rapid urbanisation and industrialisation. These trends impact the Association of Southeast Asian Nations (ASEAN) region and its neighbouring countries resulting in a range of interconnected issues such as deforestation, natural disasters, reduced agricultural yields, and global warming (Kabanov et al., 2022). These challenges, including inflation, poverty, and energy crises, are inextricably linked to energy markets and emissions as shown in Figure 1 (Lau, 2022). A recent report highlighted that up to 35% of ASEAN’s GDP could be lost by the year 2050 due to the impacts of climate change (‘Open Access Government’, 2021). If climate change is overlooked, ASEAN’s progress in poverty reduction over the past 30 years could be jeopardised in a short period (Jacob, 2021) and as much as 96% of the region is projected to experience draught, with a further 64% being impacted by extreme drought (‘Open Access Government’, 2021). Recently, serious floods are also resulting because of climate change, more extreme floods are expected in the near future if climate issue is overlooked (Babel, 2016). Acceptable, affordable and applicable solutions implemented via progressive policy measures are needed to move ASEAN towards a sustainable and secure future in terms of energy (Tongsopit et al., 2016).

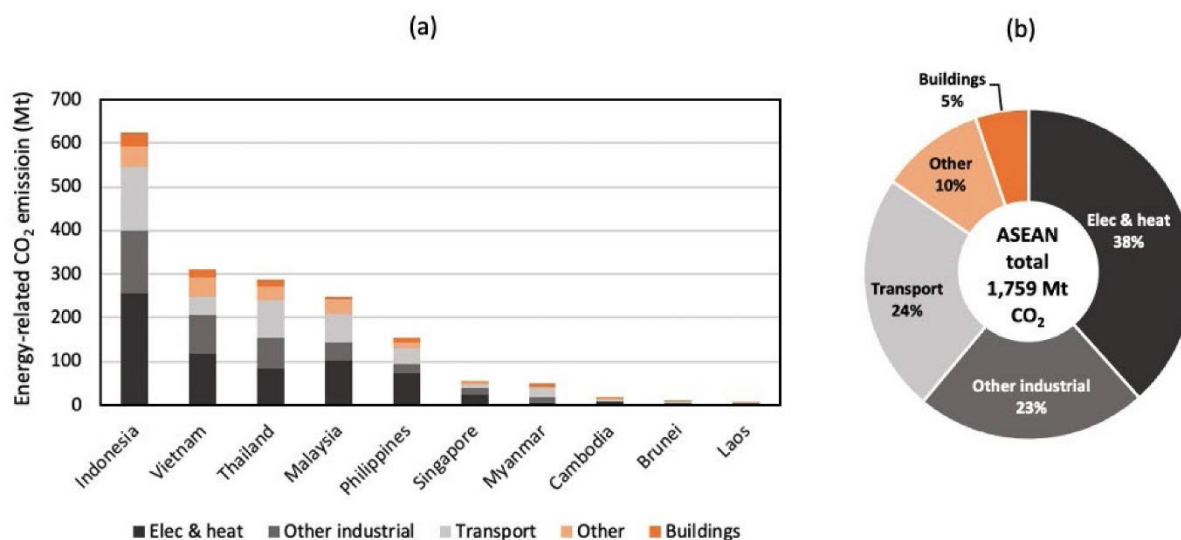


Figure 1. CO₂ emissions (a) by countries and (b) by sectors for ASEAN region, 2019 (Lau, 2022)

At the current pace, ASEAN countries are unlikely to reach their committed future renewable energy share (Overland et al., 2021). They have also been slow in adopting electric vehicles (EVs) and ramping down deforestation (Overland et al., 2021). Deep decarbonisation of transportation using EVs in the future is predicated on the availability of a clean electricity mix with a large share of renewables (Safrina & Utama, 2023). On the other hand, grassroots level nature-based decarbonisation activities have not been reflected adequately in national and regional policies (Hibi & Dublin, 2023). Growing energy demand (projected to grow at 2.4% per annum between 2015 and 2050), reliance on fossil fuels and uneven distribution of energy

resources within ASEAN will necessitate the import of fuels in the future. This, despite uncertainty in fuel prices due to global geopolitics, inciting policymakers to address regional energy concerns, emphasising the urgency of revising and formulating long-term policies to enhance energy supply security (Mat Sahid et al., 2019).

In addition to long-term policymaking, short-term policies are also crucial to ensure the smooth transition towards renewable energy resources and emission reduction technologies to sustain economic growth at both local and national levels while contributing to global sustainability targets (Wu et al., 2021). Moreover, it has been pointed out that establishing a regional integrated energy market in Southeast Asia is key to achieving the ASEAN Economic Community (AEC), ensuring a steady energy supply to meet rising demand and support anticipated economic growth in the region (Indeo, 2019). The role of carbon trading markets in improving developing economies has also been proven (Hameed et al., 2023), but it has not been specifically studied for ASEAN countries. Particularly, dynamic participation of industries and power plants in carbon markets will catalyse the decarbonisation journey towards net zero without relying too heavily on public financing / taxation (Safrina & Utama, 2023). Despite the potential of bioenergy as basis for large-scale low- or negative emission electricity generation in some ASEAN countries, none of their national climate mitigation policies practically include BECCS or BECCUS (Handayani et al., 2022). Lack of public and governmental support has impeded their integration into policies, rendering investments in BECCS / BECCUS politically and financially risky. The sluggish growth in decarbonisation investments puts the region at risk of multi-decade technological lock-in which will hinder the eventual phase-out of fossil fuels. Therefore, besides overcoming technical constraints, recognising (through case studies) and rewarding negative emissions (via emissions trading) with investments in emissions trading schemes are keys to underpinning the BECCS / BECCUS deployment. Hence, improvements in regulatory, policy and capital market frameworks considering grassroot level negative emission activities, simultaneous long- and short-term realistic goals, emissions trading schemes and investments in them, taxation and analysis / implementation of BECCS / BECCUS are necessary to accelerate the transition towards clean energy in the ASEAN region.

2. Proof of Concept

The DECO2 software (web version: <https://deco2.nottingham.edu.my/>) is an open-source energy planning framework based on deterministic optimisation, having recently been developed during a British Council-funded Trilateral Research Initiative project (Bhasker Nair et al., 2023). The superstructure-based mixed-integer linear DECO2 framework encompasses a range of power plant types, general technologies, and considers factors like energy prices, budget targets, and emission goals to meet energy demands. A mixed-integer non-linear emissions trading model has been proposed and integrated within the DECO2 techno-economic energy planning model, using a novel optimisation-based approach (Hameed et al., 2023). As a part of this RIDA project, we have developed an energy planning and policymaking tool, building upon DECO2 and the new optimisation methods for design and operation of emissions trading schemes. This project involves an improved version of the previously published emissions trading mechanism (Hameed et al., 2023), where a portion of profits from the trading may possibly be used to lower electricity prices and a portion of profits reduces the carbon prices. Profit may also be used to lessen general public tax as well. The new model provides indirect incentives, allowing power plants to obtain profit from emissions trading apart from their core energy operations. Therefore, the ratio of earnings from carbon trading to profits from selling electricity is presented, to compare the economic competitiveness of different technologies in the future when carbon trading policy will be in place globally. As a result, energy policies for developing nations will be steered in the direction leading to sustainability and energy security. When carbon prices are high, plants may opt to install emission reduction technologies to consume fewer emission rights than they have purchased and sell surplus / unused rights to generate revenue and to offset the costs of emission reduction technologies.

Moreover, the DECO2 framework is tailored as per case studies by adding new energy resources and emission mitigation technologies. The new tool can comprehensively assess and provide recommendations to address the pressing concerns in the ASEAN region, by providing simultaneous optimal energy planning with identifying opportunities within the ASEAN energy markets and proposing pragmatic scenarios and policies for a transition towards low-carbon energy sources and a sustainable environment. ASEAN countries will be able to use these bespoke tools independently ensuring the governance-related sovereignty of each ASEAN country. The new tool is based on an integrated optimisation model that encompasses critical and complex aspects for realistic energy planning such as energy system design, average electricity pricing, taxation on emissions-intensive fuels, carbon emissions trading and market design, bioeconomy (consisting of cogeneration of existing assets with bio-derived fuels, as well as BECCS / BECCUS, and carbon markets), natural climate solutions (such as afforestation), and policy frameworks. While fossil-based energy currently receives subsidies in the ASEAN region to boost GDP, i.e., 35 billion USD for fossil fuels (OECD/IEA, 2019) as compared to 7 billion USD investment in renewable energy (Ajadi, 2019) sector in 2018 (Overland et al., 2021), our approach provides a comprehensive techno-economic-based decision-making framework to strategically shift support towards low-carbon technologies through mechanisms like adjusted average electricity pricing, emissions trading, taxation (the model can use these values, but we have not considered them for the case studies) and optimised energy system design as shown in Figure 2. These interconnected financial, technical and consumer-related components will assist the analysis of long-term energy systems transitions. Emerging economies have dynamic energy systems with requirements to sustain both economic growth and energy security, and hence the model can help to assess policies, uncover potential challenges and opportunities for their power sectors. Financial entities within the developed energy planning model are shown in Figure 3.

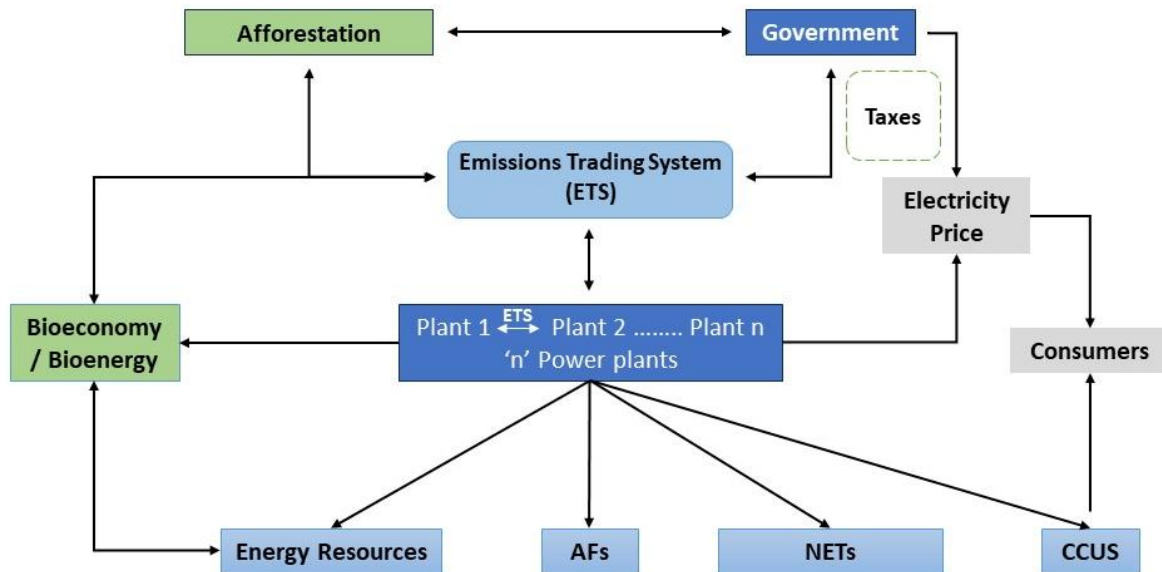


Figure 2. Conceptual framework of software tools developed within the RIDA project

The approach involving simultaneous optimisation of carbon prices and caps for each period is used to model carbon trading mechanism (Hameed et al., 2023). A four-stage carbon trading model as in Eq. (1) is implemented as shown in Figure 3. Stage 1 refers to the cost paid to the government (or carbon bank) to buy emission rights (which are left unused in the previous time-period). Stage 2 involves the cost paid to the government to buy emission rights for the current time-period. In stage 3, cost incurred, or revenue generated as a result of buying emission rights from or selling emission rights to other plants is evaluated. Finally, in stage 4, cost incurred, or revenue generated because of producing more emissions than the bought emission rights or because of the award / price given to the plant by the government as a result of some emission rights left unused by a plant, is estimated.

$$\begin{aligned}
 & \text{Total Carbon Trading Income} && (1) \\
 & = \text{Per Unit Emissions Price} \\
 & \times ((\text{Emissions Bought from the Previous Period or Stage 1}) \\
 & + (\text{Emissions Bought from the Government or Stage 2}) \\
 & - (\text{Emissions Traded within the Plants or Stage 3}) \\
 & - (\text{Emissions Left to Trade in the next Period or Stage 4}))
 \end{aligned}$$

The net income from carbon trading can either be positive (cost) or negative (revenue) depending on carbon prices and the volume of emission rights traded in the final two stages of carbon trading. In the initial two stages, purchasing emission rights from the government adds to plant costs, contributing to government profits. In the third stage, a plant incurs cost when it acquires emission rights from another plant, while it generates revenue if it sells emission rights. It is worth noting that in the same period, one plant may earn revenue while another incurs costs. In the last stage, if a plant consumes more emission rights than it purchases, it pays a cost to the government. If the plant has unused emission rights, the government will pay the plant to buy back the unused rights, resulting in revenue for the plant. These rights bought by the government will be available for trading in the next period. Consequently, some plants may generate revenue, while others may incur costs in the fourth stage. The mathematical model is available on GitHub (<https://github.com/gulhameed361/DECO2-2023v.git>).

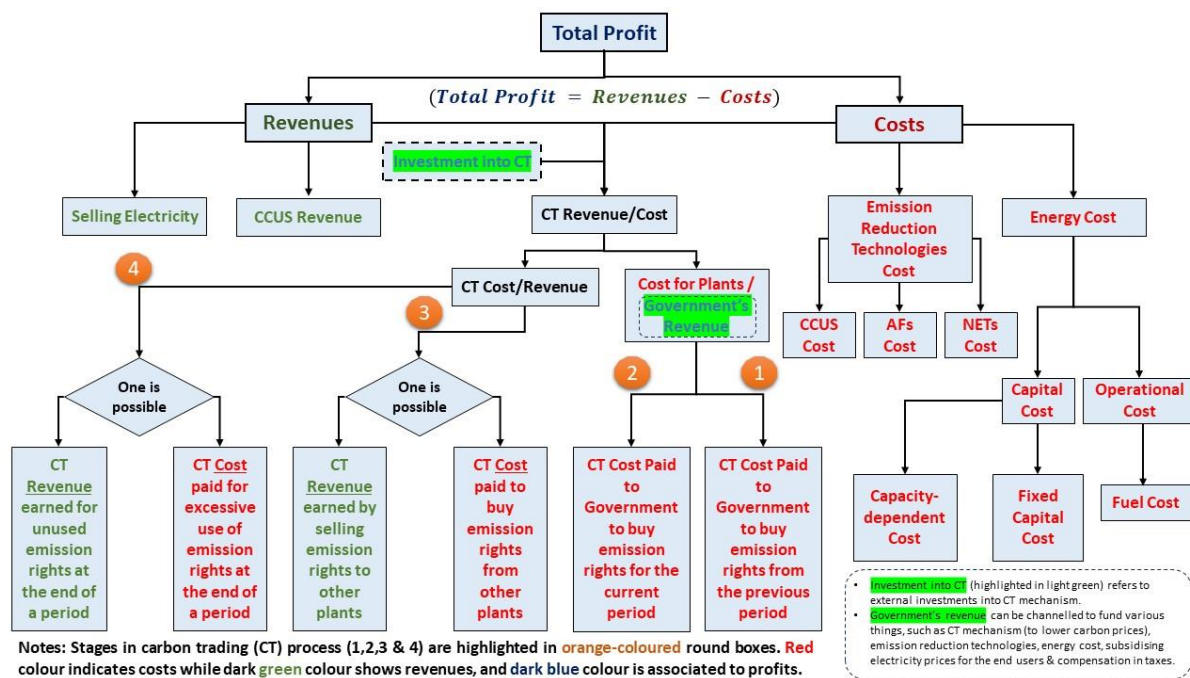


Figure 3. Financial model within our energy planning framework

The novelty of the project lies in merging technoeconomic energy planning (involving technical and financial details on energy systems design, taxes, electricity pricing, etc.), environmental aspects, a carbon trading scheme and bioeconomy in one single decision-making platform covering the ASEAN context. It is inevitable for ASEAN economies (particularly Malaysia) to implement carbon trading to meet their mid-century emission targets (Izlawanie, 2021). The Philippines has yet to set its net-zero emissions target to achieve climate goals despite being a party to the Paris Agreement (Migo-Sumagang et al., 2024). ASEAN economies (such as Malaysia and Indonesia) are a few of the largest producers of raw palm oil and have a great potential for biomass energy from crops and process residues (Loh, 2017). If ASEAN countries were to better exploit these via conversion to higher-value products (such as bioelectricity, biofuel or refined products), they could benefit significantly (Goh & Potter, 2022). In addition to integrating carbon trading, this project incorporates the bioeconomy in the decision-making energy planning software to investigate its impact on other technical, environmental and economic variables. In this project, we develop two models, one includes carbon trading, and the other does not. We have chosen Malaysia and Philippines to test and demonstrate our models because of their vital role in the overall ASEAN economy and the significant availability of biomass, leading to the potential scope of bioenergy within those economies. Recent data reports that Malaysia, Philippines, Vietnam, Indonesia and Cambodia are at the forefront of GDP growth within ASEAN region (OECD, 2023). In ASEAN, Malaysia recorded the highest GDP growth for the year 2022 and fifth highest in 2023, while the Philippines showed the second highest GDP growth for 2022 and third highest for 2023 (OECD, 2023).

2.1 Decarbonisation Policies in Malaysia

Malaysia released more than 369 Mt CO₂-e greenhouse gas (GHG) emissions in 2020, making it one of the top 25 GHG emitters in the world (Climate Watch, 2020). One of the top contributors to the high emissions in Malaysia is the continuous usage of fossil fuels in its power generation sector. To meet incremental demand from rapid industrialisation and a

growing population, close to 93% of electricity generated in Peninsular Malaysia alone was fuelled by coal and natural gas (NG) in 2020 (Mohd Salleh, 2022), while 83% of the electricity was generated by fossil fuels for the entire Malaysia in 2020 (Energy Commission Malaysia, 2020). This trend is projected to sustain at least until 2030 due to coal import agreements in place between Tenaga Nasional Berhad (TNB) and coal-supplying industries (Mohd Salleh, 2022). Although the commissioning of new coal plants has been halted following COP26 and the 12th Malaysia Plan, the impacts of coal usage in existing power plants must not be downplayed (Mohd Salleh, 2022). On the positive side, Malaysia has abundant rainforest, rainfall and solar energy (Mohd Salleh, 2022). Hence, there are plenty of opportunities for climate change mitigation in Malaysia.

In COP26, Malaysia emphasised its commitment to maintaining at least 50% of its forest and tree cover (Tan, 2021). Nevertheless, Malaysia must deal with the challenge of having the highest deforestation rates among tropical countries because of oil palm plantations (Tan, 2021). It should be noted that the natural absorption of CO₂ via trees would not fully offset Malaysia's GHG emissions despite having a large forest cover (Bhasker Nair et al., 2022). Therefore, reliance on forest coverage alone should not be the sole solution for addressing climate change and global warming. Instead, Malaysia should focus on diversifying its climate change mitigation portfolio to achieve its carbon neutrality target by year 2050. The Malaysian government had launched several initiatives in the past to address its ever-growing GHG emissions. In 2011, the National Renewable Energy Policy (NREP) was launched (Sustainable Energy Development Authority, 2011). This policy was made up of the Renewable Energy Act 2011 and the Sustainable Energy Development Authority Act 2011 (Sustainable Energy Development Authority, 2011). By initiating new renewable projects, this policy was hoped to aid in achieving a 20% renewable energy installed capacity in the power generation mix by year 2025 (Sustainable Energy Development Authority, 2011). Additionally, large-scale solar projects were launched to support sustainable energy development (Sustainable Energy Development Authority, 2011). The purpose of NREP policy was to raise awareness of the pivotal role and significance of renewable energy in the generation of sustainable energy (Sustainable Energy Development Authority, 2011). On the other hand, this policy set the benchmark in terms of driving the adoption of renewable energy among various industries in Malaysia (Sustainable Energy Development Authority, 2011). Although the targets of the NREP were commendable, they were insufficient in ensuring deep emissions cuts. Therefore, the Malaysia Renewable Energy Roadmap (MRER) was launched in 2021 (Sustainable Energy Development Authority, 2021). Under this new policy, Malaysia is targeting a 31% renewable energy installed capacity in the power generation mix by 2025, with a further increase to 40% by 2035 (Sustainable Energy Development Authority, 2021). Renewable energy share of 18% in generation capacity was recorded in 2021 (IRENA, 2023). Also, in 2022, renewable share in total installed power generation capacity was 23% consisting of 69% hydro/marine, 21% solar and 10% bioenergy capacity (IRENA, 2023). At the current pace, it is expected that Malaysia will achieve the target of 31% share of installed renewable energy capacity by 2025. This target aligns with Malaysia's goal of achieving a 45% reduction in its GHG emissions intensity per unit GDP by 2030 in comparison to its 2005 level. Note that this reduction is projected to further increase to 60% by 2035 (Sustainable Energy Development Authority, 2021).

According to National Energy Transition Roadmap (NETR), most of Malaysia's potential in renewable energy would be achieved by solar energy due to its large potential (Ministry of Economy GOVMY, 2023). Aligning with this huge potential of solar energy, Malaysia has also planned to introduce battery storage with an expected potential deployment of 500 MW by 2034 (Malaysian Investment Development Authority, 2021). Aside from the renewable energy

target, other initiatives under MRER include the Feed-In Tariff (FiT), Large-Scale Solar (LSS), Net Energy Metering (NEM) and Self-Consumption programmes. The FiT programme aims to encourage feed-in approval holders such as palm oil mills and small-scale industries to generate and sell renewable electricity to the grid at a pre-approved FiT rate (Sustainable Energy Development Authority, 2021). This programme would promote long-term investments among small-scale power producers for the generation of sustainable electricity. Meanwhile, the LSS programme aims at decreasing the development cost of large solar photovoltaic plants, thus promoting their use in the generation of clean electricity (Sustainable Energy Development Authority, 2021). The remaining two programmes i.e., NEM and Self-Consumption are concerning the installation of solar panels in domestic households (Sustainable Energy Development Authority, 2021). The former programme allows domestic users to export excess electricity generated via solar to the grid. By contrast, the latter programme prohibits the export of excess electricity. All these programmes and initiatives demonstrate Malaysia's aspirations in climate change mitigation thus cementing its leadership in the ASEAN region in climate change mitigation policy and commitment.

2.2 Decarbonisation Policies in the Philippines

The Philippines' economic growth relies heavily on its energy sector and Department of Energy (DOE) plays a vital role in developing energy policies (Morales, 2023). The Philippines' power is supplied by 152 electricity generators, and distributed using three main grids (Luzon, Mindanao and Visayas) located in three different geographical divisions of the country. These grids are responsible for the operation and maintenance of respective grids according to supply and demand of the specific geographical region (Department of Energy, 2024). Some government-owned and private companies are responsible for the electricity distribution to end users (residential, commercial, industrial and others). In 2019, 106 TWh of power was generated in the Philippines; 54.6% of the power was generated using coal and 21.1% was generated using NG (Morales, 2023). In 2022, the Luzon grid generated 72% of the total electricity produced in the Philippines (Department of Energy GOVPH, 2023). Different policies have been adopted in the past to promote low-carbon technologies within the energy sector and emissions mitigation. The Renewable Energy Act of 2008 and the Biofuels Act of 2006 promote the utilisation of renewable energy resources and local agricultural resources for biofuel production, respectively. The National Renewable Energy Program (NREP), introduced in 2011, serves as a policy framework to encourage renewable energy use and achieve market penetration targets. Similarly, the Biofuels Act aims to enhance energy security, support farmers, create rural employment, and reduce GHG emissions by leveraging local agricultural resources for biofuel production.

In 2011, the National Climate Change Action Plan by the Climate Change Commission prioritised climate change adaptation over mitigation (Migo-Sumagang et al., 2024). Recent energy targets and policy measures in the Philippines, including updates to the NREP 2020-2040 (signed in June 2022) and the Philippines Energy Plan (PEP) 2020–2040, aim to align with the government's *AmBisyon Natin 2040* plan (which is a picture of the future of Philippines as a whole) impacting UN's SDGs (Morales, 2023). The Philippines expects to achieve 35% renewable by 2030 and 50% renewable power generation by 2040 according to NREP (Department of Energy, 2022). These policies aim to reinforce a national strategy to achieve renewable energy goals and leverage positive socio-economic benefits. On the other hand, unlike other ASEAN countries such as Malaysia and Indonesia, the Philippines has no absolute net-zero emission target (Climate Action Tracker, 2023). The Philippines' updated NDC target (as of April 2021) aims to reduce GHG emissions by 75% below a business-as-usual pathway for the duration between 2020 and 2030, with most of this commitment contingent on international support (Government of Philippines, 2021). Only a small fraction

of the commitment, 2.71%, is unconditional (Government of Philippines, 2021). However, without additional measures and international support, achieving this target seems unlikely (Climate Action Tracker, 2023). In 2023, the Philippines updated its climate change agenda within the Philippine Development Plan, now incorporating mitigation efforts unlike in National Climate Change Action Plan 2011. However, mitigation in this plan is seen merely as a part of climate adaptation and still lacking political will, indicating a need for the country to prioritise a commitment to achieving net-zero carbon emissions (Migo-Sumagang et al., 2024). This outlook is demonstrated by the lack of progress of national legislation proposed in 2023 to promote a low-carbon economy (i.e., House Bill No. 7705). To achieve existing targets and to establish a net-zero target, Philippines needs to set aggressive unconditional goals, including the use of emerging technologies that are projected to contribute sustainably to the future global power mix.

2.3 Model Implementation

Our model optimises the power generation from a set of fuels or energy resources, some compensatory energy resources including biomass, the application of some emission reduction technologies within power plants such as CCS, CCUS and alternative fuels, and the deployment of independent NETs, to meet the demand and emission targets. An emissions trading and carbon pricing model facilitates the effective establishment of emission prices and caps by governments, captures the impact of future global policies around carbon trading, and provides power plants with strategic insights to simultaneously reduce emissions and costs. This unique financial concept, incorporating carbon banking, incentivises the adoption of expensive emission reduction technologies and renewable energy plants, and lowers carbon and electricity prices.

Facing escalating energy demands while prioritising economy, and energy security and its affordability, developing regions, particularly the ASEAN, stand at crossroads. They must choose between depleting domestic / international oil and gas reserves, coupled with issues like unpredictable global markets for imports, or harnessing the considerable potential of renewable energy. To facilitate policymakers in decision-making, this work offers a comprehensive analysis of the optimal utilisation of various fuel types: NG, coal, solar, hydropower, biogas, biomass, and municipal solid waste (MSW), geothermal, etc., to meet power demand.

The option for fuel substitution of coal and NG power plants in our model currently involves only co-firing, thus requiring a retrofit to be carried out on both types of power plants. In addition to co-firing, the option for CCS / CCUS employed in coal and NG plants has also been integrated into our models. Retrofitting power plants is capital-intensive but sometimes economical as compared to setting up a new plant. Biomass (available abundantly in Malaysia) (Loh, 2017) can be used to create biofuels that can be used to substitute coal and NG in current generators after some retrofitting without requiring substantial modification in the plants' infrastructure (Goh & Potter, 2022), or could be used to produce electricity directly via anaerobic digestion, biomass boilers, or gasification. Foreign investors have recently shown a significant interest in biomass-based products such as biofuels and bio-based materials. However, there is a limit to such retrofitting and co-firing, and new bioelectricity power plants with CCS (based on BECCS technology) using biofuels are inevitable to achieve deeper emissions reduction. Hence, we plan to integrate BECCS / BECCUS in our model via co-firing in existing fossil-based plants and separate bio-electricity plants incorporating CCS / CCUS technology to assess their feasibility. These technologies are recognised by the IPCC as integral to driving down emissions (Pete et al., 2019) impacting SDGs 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production) and 13 (Climate Action). Note that, Malaysia

has natural places (e.g., Demangkok, Tangga, Dulang and Jerneh) to store captured carbon in sandstone aquifers (Abd Rahman et al., 2022). The Philippines has some CCS potential, especially in the Luzon region (Asian Development Bank, 2013), but the country does not meet the IEA's criteria for the adoption of CCS technology because it lies within the Pacific Ring of Fire (a complex area of tectonism and volcanism) (Asian Development Bank, 2013; Mateo, 2012). The same limitations of storage opportunities will also limit the deployment of BECCS and direct air capture (DAC).

Our models also help policymakers in determining the potential role of low-carbon and emission mitigation / reduction technologies in the power generation sector to reach net-zero and boost the bioeconomy via local carbon market participation. The incorporation of natural climate solutions (such as afforestation) in the form of NET within our models plays a pivotal role in promoting SDGs 11 (Sustainable Cities and Communities) and 13 (Climate Action), because these solutions try to balance deforestation (resulting from palm oil plantation) and the use of fuels derived from palm oil production to generating low-carbon bioelectricity using available literature (WWF, 2024). The unchecked expansion in palm plantation capacity to yield gains driven by land and forest use should be monitored. This holistic approach could not only create job opportunities but also contribute significantly to poverty reduction as in SDGs 1 (No Poverty) and 8 (Decent Work and Economic Growth). Additionally, it will have a substantial impact on emissions rights trading, further enhancing the overall effectiveness of our strategies. Collaboration between the universities and institutions in the UK and the ASEAN region to carry out this RIDA project positively affects the SDG 17 (Partnerships for the Goals).

As we embark on economic recovery post-COVID-19, environmental conservation and climate change mitigation have surged to the forefront of agendas. While strategies vary based on economic structures and national plans, many countries commit to carbon neutrality or net-zero targets. Exploration of new technologies and alternative fuels is underway globally. However, embracing these innovations demands substantial investments, sustained partnerships, and secure fundings. Prioritising and strategising early on are imperative for effective climate action. With a well-crafted roadmap based on modelling and empirical evidence, economies can navigate this challenge. Leveraging our models, we have analysed the power sectors of Malaysia and the Philippines to contribute to this discourse, which may help in proposing a roadmap for decarbonisation of power sectors within those countries. Results (presented in the next section) for both Malaysian and the Philippines' case studies provide clear evidence of the implications of different energy policies and practical scenarios are predicted to answer our decarbonisation-related research questions (as given in the executive summary and inception report of the project).

3. Results

The developed mathematical optimisation framework is written in Python, using the Pyomo algebraic modelling package (Hart et al., 2011), and solved using SCIP (Achterberg, 2009) and DICOPT (Grossmann et al., 2002) solvers.

3.1 Case Study: Malaysia

The power sector of Peninsular Malaysia is the first case study. A total of 107 existing and planned power plants (i.e., 7 coal-based, 40 NG-based, 19 hydro-based, 36 solar-based, 4 biomass-based, and 1 biogas-based, along with compensatory biogas, biomass, hydropower, solar, and MSW plants) are made available for power generation to meet periodic demands of 142 (2024-2028), 156 (2029-2033), 166 (2034-2038), 184 (2039-2043), 203 (2044-2048) and 225 TWh / y (2049-2053), for the period 2024–2054 (Malaysian Energy Commission, 2020a). Biogas, upgraded to biomethane, and transported to NG plant's location, may be utilised as an alternative fuel in NG plant after some retrofitting (Rosa, 2018), while biomass may be utilised in coal plants as an alternative fuel for co-firing within certain limits. Both existing and planned power plants by the government and private sector are incorporated in the analysis, with data sourced from the government (Malaysian Energy Commission, 2020a). The carbon intensity of fuels, capacity expansion and service periods for power plants are also considered (Turconi et al., 2013). Upper and lower bounds are set for the electricity price variable. Taxation is not considered; however, the model can take the values of taxes for each fuel as inputs.

Note that the power demand increases from 142 TWh y^{-1} in the first period (years 2024 – 2028) to 225 TWh / y in the final energy planning period (years 2049 - 2053). These projections were made based on historical and projected demand growth obtained from a government authority (Malaysian Energy Commission, 2020b). The COVID-19 pandemic had resulted in a dip in demand growth. Therefore, it is estimated that years 2021-2030 and 2030-2039 would observe an annual power demand growth of 0.9% and 1.7% respectively (Malaysian Energy Commission, 2020b). Beyond 2039, Malaysia is projected to observe an annual power demand growth of 2% as recorded before the pandemic (Malaysian Energy Commission, 2020b).

In 2024, there are 51 renewable (solar, hydropower, biomass and biogas), 23 NG and 7 coal-based power plants contributing 22%, 52% and 26%, respectively, representing the power generation capacity of Peninsular Malaysia shown in Figure 4. Generation capacity (i.e., power generation capacity available to meet the electricity demand) is significantly higher than projected power demand to meet a sudden demand surge. Also, following its plans, Malaysia is enhancing the share of renewable electricity in its power generation mix without decommissioning fossil-based plants, leading to high installed generation capacity. Particularly, Malaysian government plans to enhance solar generation capacity over time, and then solar capacity stays the same after 2039 when other emission reduction technologies get mature. Current Malaysian plan insists that generation capacity of biomass and biogas plants remains less than 1% throughout (2024-2053), however, the optimisation results show that it should increase to meet 40% share of renewable electricity in total power generation capacity by 2035. NG capacity remains significant while rapid reduction of coal-based power generation capacity is planned over the upcoming years. Generation capacity demonstrates Malaysia's heavy current reliance on coal and NG in meeting its power demand. Consequently, the extensive use of fossil-based sources contributes to the high GHG emissions in Malaysia. The use of solar for sustainable power generation has only recently gained traction after the announcement of government initiatives (Sustainable Energy Development Authority, 2021). Seven NG and four coal-based power plants are set to be retired within the next decade (Malaysian Energy Commission, 2020a), followed by a few more in later years. The standby

installed generation capacity must be enough to replace the quota of demand met by decommissioning plants. New renewable power plants are to soon be commissioned in Peninsular Malaysia (Malaysian Energy Commission, 2020b). The current plan aligns with Malaysia’s aspiration of achieving 40% renewable electricity capacity in the power generation mix by year 2035 (Sustainable Energy Development Authority, 2021), but it is still not enough, as per our optimisation results (which are discussed later in the same section). Therefore, more renewable (solar, biomass and biogas) projects should be planned and initiated. However, note that complete dependency on these new renewable power plants would be insufficient in meeting the rising power demand in Malaysia. Therefore, NG power generators are scheduled for commissioning in the upcoming years (Malaysian Energy Commission, 2020b). The absence of new coal power plants is due to Malaysia’s climate aspirations of achieving carbon neutrality by year 2050 (Mohd Salleh, 2022).

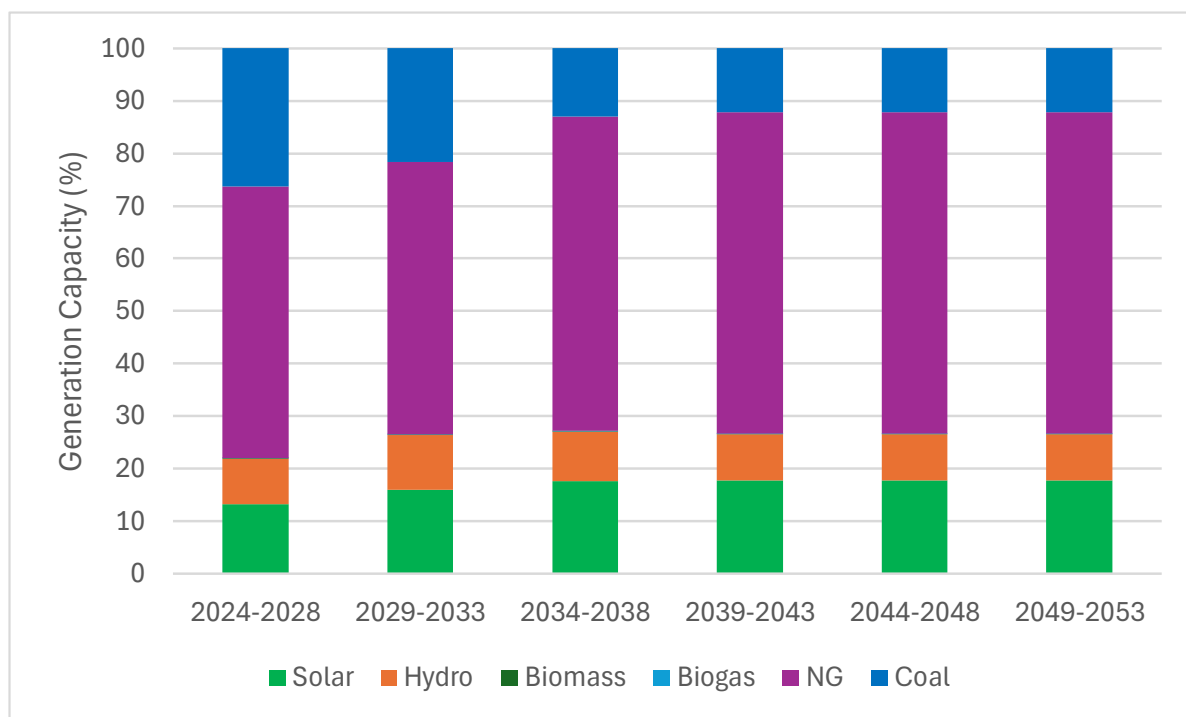


Figure 4. Power generation capacities from different fuels in Peninsular Malaysia as per Malaysian government plans

Energy-producing NETs (EP-NETs) are technologies that produce electricity during CO₂ load removal. In this work, the two EP-NETs considered are BECCS and biochar. The former involves the combustion of biomass, where the carbon content of the flue gas is captured via CCS, while the latter involves slow pyrolysis of biomass (McGlashan et al., 2012). The capital cost of a BECCS plant (Ricardo Energy & Environment, 2020) is more than a biochar plant (Homagain et al., 2016) as the installation of CCS equipment in a BECCS plant increases its capital expenditure. BECCS has a lower CO₂ intensity, thus higher Carbon Dioxide Removal (CDR) capability (Ricardo Energy & Environment, 2020), than biochar (Homagain et al., 2016). Moreover, a third EP-NET is also modelled, which can be attributed to the use of Hydrogen as an emission reduction technology in the Malaysian power sector (Yan, 2018). There can be different negative emission Hydrogen technology options, but as suggested by a Nature’s article, we have generalised it into one (Yan, 2018). The negative emission Hydrogen process combines renewable electricity, saline water electrolysis, and enhanced mineral weathering technologies. Like other power-to-gas technologies, hydrogen technology integrated into future smart multi-energy systems can enhance feasibility and capacity by providing intermittent storage or peak shaving for the electricity grid. Malaysia foresees the

implementation of Hydrogen technology to power its decarbonisation efforts in the near future (Ministry of Economy GOVMY, 2023). As per literature, due to the current technology readiness level (TRL) of H₂ technology, the associated costs with negative emission Hydrogen technology is expensive (Yan, 2018). Therefore, it will be shown later that optimisation does not select Hydrogen technology.

By contrast, Energy-consuming NETs (EC-NETs) are technologies that consume electricity during CO₂ load removal. In other words, there is a penalty in the form of power usage associated with CO₂ load removal. Three EC-NETs are considered in this work: DAC (Direct Air Capture), enhanced weathering (EW), and afforestation. DAC uses physical / chemical processes for the direct absorption of CO₂ from the atmosphere. The resin may be regenerated for further absorption (McGlashan et al., 2012). Meanwhile, EW involves the spreading of alkaline materials on land or water bodies (McLaren, 2012). These materials would react with carbonic acid (CO₂ dissolved in water) which effectively removes the carbon content from the atmosphere (McLaren, 2012). The fixed capital costs of DAC plants (Keith et al., 2018) are far more expensive than EW plants. The necessity of solvent regeneration and CO₂ pressurisation in DAC plants results in greater fixed capital costs. In EW, the absorbed CO₂ is permanently stored in a stable form at nearby water bodies (McLaren, 2012). There are no requirements for pressuring the absorbed CO₂, thus driving down the capital costs. EW plants have the highest capacity-dependent capital cost among all mitigation technologies. The main cost factors for EW are mining, crushing, grinding of rocks and transportation. EW demonstrates the greatest capacity of CDR with a CO₂ capture rate of 5.4 Mt TWh⁻¹. Note that the DAC is not self-sufficient as it requires energy (Keith et al., 2018), while both BECCS (Ricardo Energy & Environment, 2020) and biochar (Homagain et al., 2016) produce energy. The power requirement of DAC makes it a less preferable NET (Keith et al., 2018). However, a fair comparison of DAC with BECCS or biochar will need to consider an integrated system to account for differences in electricity flows. Another EC-NET considered in this work is afforestation, with slightly lower CDR potential. If a new place (e.g., an area which underwent palm plantation earlier, was used for agriculture purpose previously, etc.) is to be afforested, power / energy and some capital investments (to buy the land) are required to prepare the area for afforestation.

In this work, the alternative solid-based fuel is biomass, which could potentially substitute coal in power plants due to its lower CO₂ intensity. The two types of biomasses considered in this work are empty fruit bunches (EFB) and palm kernel shells (PKS) (Kaniapan et al., 2021) due to their availability in Malaysia. Note that both types of biomass originate from palm oil waste. PKS is 'cleaner' (lower CO₂ intensity) and thus more expensive than EFB. In other words, there is a trade-off between the CO₂ intensity and cost. Fuel substitution may also take place for NG power plants with the use of biogas. The two types of biogases in this work are derived from palm oil mill effluent (POME) (Kaniapan et al., 2021) and animal manure (Ramos-Suárez et al., 2019). Similarly, POME, which has a lower CO₂ intensity, is costlier than animal manure. The deployment of these alternative fuels would be determined by the optimisation of the superstructural models. Currently, recycling of waste is a cleaner option, but technological advancement will make other strategies (of handling waste, e.g., producing power from waste) economically competitive in the future (Chew et al., 2022). Therefore, in later periods, the waste-to-energy strategy for MSW (integration of landfill gas recovery systems and waste incinerators) is also available in the model as a low-carbon energy generation technology.

Finally, two scenarios; minimisation of budget and maximisation of profit for each planning period, are optimised with and without carbon trading to optimally meet power demand by satisfying strict emission targets of 120 (2024-2028), 110 (2029-2033), 95 (2034-2038), 75 (2039-2043), 50 (2044-2048), and 0 (2049-2053) Mt / y, aligning with Malaysia's commitment

to achieving net-zero emissions by 2050. The CO₂ emissions limits are calculated based on the CO₂ emissions intensity and GDP of Malaysia. Malaysia had pledged a 45% and 60% reduction in its CO₂ intensity per unit GDP by years 2030 and 2035 respectively, with year 2005 being the baseline level (Malaysian Energy Commission, 2020b). Malaysia recorded a CO₂ intensity per unit GDP of 0.084 kg CO₂/RM in year 2021 (Malaysian Energy Commission, 2020b). This number is projected to further decline to 0.053 and 0.038 kg CO₂/RM by years 2030 and 2035 respectively, thus aligning with Malaysia's target reduction (Malaysian Energy Commission, 2020b). On the other hand, Malaysia's GDP was recorded as USD 336 billion in year 2020 (Trading Economics, 2022). Based on the 12th Malaysia Plan, Malaysia's GDP is projected to experience a steady annual growth between 4.5% and 5.5% (Adilla, 2021). In this work, it is assumed that Malaysia's GDP will grow annually by 5%. Recognising Malaysia's aspiration to become carbon-neutral by year 2050 (zero CO₂ intensity per unit GDP), the CO₂ emissions limits are calculated to decrease from 120 Mt in Period 1 (years 2024-2028) to 0 Mt by mid-century (2049-2053). Note that the CO₂ emissions limits demonstrate a gradual decline in the earlier periods before decreasing exponentially at a later stage. Despite a reduction in the CO₂ intensity per unit GDP, the constant 5% annual growth of Malaysia's GDP meant that there was a greater allowance for emissions across the years. However, the net-zero emissions target by mid-century meant that drastic emissions reduction is required towards later periods.

The purpose of optimisation is to determine directions for policy development that mobilise all stakeholders to contribute to meeting the net-zero target. Budget minimisation underscores the imperative of cost-efficient implementation of low-carbon technologies, while profit maximisation explores the economic opportunities arising from the net-zero pathways. Policies reflecting the dynamics between these scenarios will prove to be beneficial for the government (i.e., the public) and the private entities (generation and transmission companies) involved in the Malaysian power sector. Moreover, the implemented carbon trading mechanism effectively captures the relationship between the environment and the economy, offering sustainable transitioning pathways to cleaner and economical energy resources.

The power generation mix resulting from the minimisation of budget scenario based on the available capacity is shown Figure 5. Our model does not account for pre-installed energy technology, assuming capital costs are incurred at the start of the planning period or whenever the technology is operated. Emission targets for 2024-2028 are based on current emissions (2024), with reductions planned over time between 2024 and 2053. Without carbon trading, NG is chosen due to its lower capital costs and ability to meet emission target and power demand at a minimal budget for the initial planning period 2024-2028. With carbon trading, the cost of emissions leads to a mix of NG, minimal coal, and solar to reduce carbon trading expenses during 2024-2028. The scenario without carbon trading allows NETs' deployment (a combination of afforestation and BECCS, energy produced by BECCS is greater than energy consumed by afforestation) and some CCS in coal and NG power plants, to remove or capture 139 Mt of emissions over the duration of 30 years (2024-2053), while the carbon trading scenario prefers the installation of new renewable energy plants over the operation of NETs and CCS (reducing 124 Mt of emissions over the whole planning period of 30 years), which is a more economical and environment-friendly decision as shown in Figure 7 and Figure 8. A much higher share of renewable energy in power generation is observed with carbon trading (i.e., 40% of the total electricity produced between 2024 and 2053) as compared to that without carbon trading (which is only 23%) because the carbon trading scenario chooses technologies which are economical and produce fewer emissions. Renewable energy deployment is preferred over deployment of NETs and retrofitting fossil plants with CCS due to overall lower emissions, lower costs, and sustainability (Fennell, 2019). CCS retrofitting is considered when no other economical and clean alternative is available. Renewables provide long-term

environmental and economic benefits, align with global decarbonisation trends, and enhance energy security without the limitations of finite fossil fuels. The only drawback of renewables is their intermittency (in comparison to CCS-retrofitted fossil plants), but energy storage technologies can mitigate this (The Royal Society, 2023). Hence, renewable technologies are selected because they are more sustainable as compared to NETs and CCS in cases when carbon trading is applied. Also, carbon trading has resulted in bioelectricity generation at small scale from separate biomass (producing 1.51 TWh of electricity over the duration 2024-2053) and biogas plants (generating 38.86 TWh of electricity over the planning period of 30 years). These small-scale biomass and biogas plants may possibly be meeting the electricity demands within the palm oil and other small-scale industry. Small scale industries may benefit from the FiT system by using biomass to produce electricity, and then selling it to the grid at approved rates (Sustainable Energy Development Authority, 2021). Biogas replaces NG in the last period, which depicts the high feasibility of bioelectricity generation after 2048. The high amount of bioelectricity produced using biogas results from the optimisation model predicting the installation of more biogas plants in the last period (2049-2053). Therefore, Malaysia should consider scaling up the bioelectricity share in its total power generation capacity. Notably, carbon trading has enabled the power generation contribution from all renewable energy resources (except MSW) to the grid with overall greater renewable power share when compared to the share in the base case without carbon trading. Moreover, hydro and solar plants are operated at their maximum capacities with carbon trading, which necessitates the further enhancement in their share in Malaysian power generation installed capacity. The share of coal remains low throughout, and carbon trading interestingly reduces the use of NG as well.

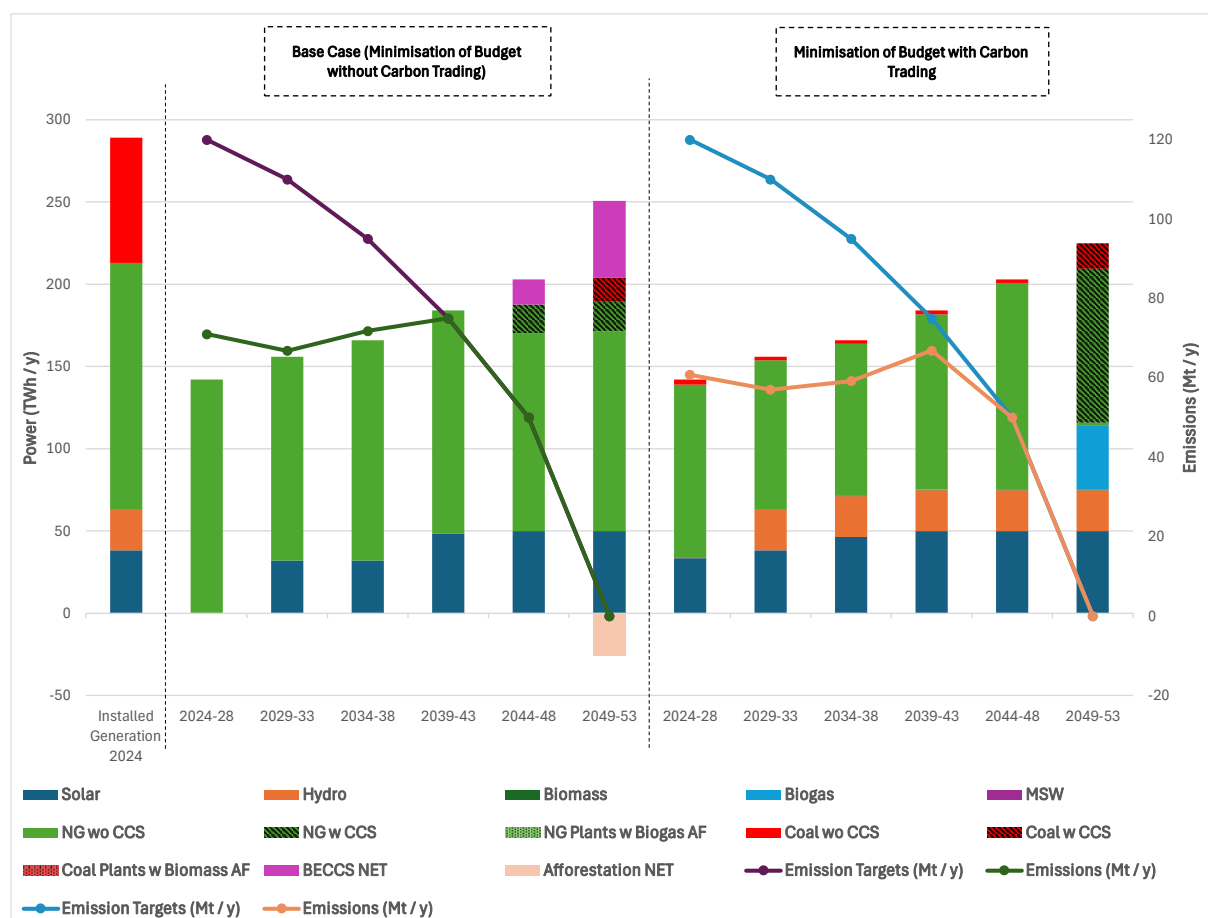


Figure 5. Power generation mix for minimisation of budget scenario

On the other hand, the optimal power generation mix for the maximisation of profits scenario is shown in Figure 6. When carbon trading is implemented, again a diverse portfolio of cleaner technologies (such as hydro, biomass and biogas) is preferred over capital-intensive emission reduction technologies to achieve emission reduction targets. Afforestation and EW EC-NETs are selected in scenario without carbon trading in addition to BECCS EP-NET. However, energy produced by BECCS NET is greater than energy consumed collectively by afforestation and EW NETs. In the first period (2024-2028), our model prefers NG to meet emission targets and power demand due to its lower fixed and capacity-dependent capital costs, maximising profits (by minimising the costs) when there is no carbon trading. When carbon trading is in place, solar and hydro are selected to mitigate carbon trading (or emission-related) costs, despite their higher capital costs but lower operating costs compared to NG. Fossil fuel plants incur greater carbon trading cost due to their higher emissions. The model assumes capital costs are incurred at the start of the planning period or when the technology is first used, favouring NG initially, resulting in its higher share in the generation mix in the beginning. In the profit-maximising scenario, a 29% higher fossil-based power contribution to the power generation mix is observed without carbon trading when compared to the case with carbon trading mechanism is in place. The critical role of carbon trading for the Malaysian power sector is evident from the results, because Malaysia has committed to stopping all new coal power stations, and policymakers must strategise to replace the capacity of retiring coal plants. Fewer NG plants are operated throughout when carbon trading is in place and biogas is preferred over NG in the last time period. Also, solar and hydro plants are operated at their full capacities after 2040, urging Malaysian government to plan the installation of more renewable energy plants.

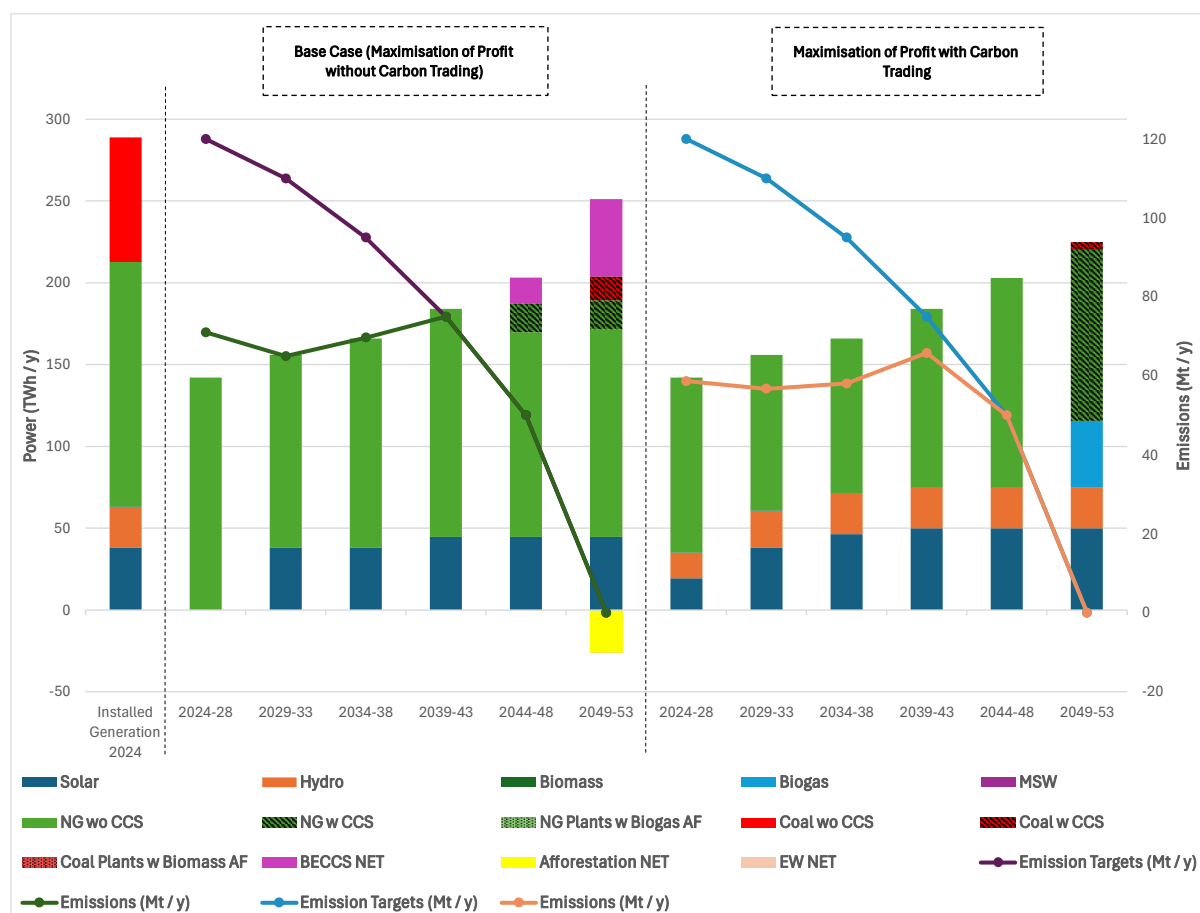


Figure 6. Power generation mix and emissions for the maximisation of profit scenario

In both scenarios (budget minimisation and profit maximisation) with and without carbon trading, projections reveal a notable shift in the electricity generation landscape of Peninsular Malaysia by 2054. If there is no carbon trading, NG is poised to dominate, generating 76% (for both maximisation of profits and minimisation of budget scenarios) of total electricity produced (for the duration 2024-2053), and with carbon trading, NG generates only 57% (maximisation of profits) - 60% (minimisation of budget) of the total electricity. The share of coal is significantly less with and without carbon trading because of the government's policy to refrain from the construction of coal-fired power plants, recognising the substantial impact of coal imports on both the environment and national expenditure. Stakeholders acknowledge the detrimental effects of coal generation, particularly its contribution to GHG emissions and climate change. Hydro generation is marginally higher in the profit maximisation scenario (i.e., 12.8% of the total generated electricity) compared to the budget minimisation scenario (i.e., 11.6%), whereas coal usage is notably less (i.e., about half) in the profit minimisation scenario as compared to that in budget minimisation scenario. Malaysia has witnessed a steady growth in installed capacities of solar PV and other renewables (offering local and cost-effective alternatives to fossil fuels), attributed to robust renewable energy policies. Results urge Malaysia to devise a clear plan for commissioning newer renewable (solar, biomass, hydro, etc.) power plants to achieve its 40% renewable electricity installed capacity target by 2035. When fossil-based plants (mostly large-scale) will be phased out, there must be enough renewable power capacity to take the place of the retiring plants. By outlining the timeline and capacities of forthcoming plants in the form of a clear roadmap, Malaysia can strategically attract more investors and integrate more renewables into its power mix, advancing its sustainability goals efficiently. To maximise the impact of renewable capacity, renewable energy targets should be extended beyond power generation to encompass end-use consumption in sectors like transportation and industry (which heavily rely on fossil fuels) via electrification and EV policies. For the profit maximisation scenario, coal is a financially more attractive option in the absence of carbon trading, as shown by the results. Without a carbon trading mechanism, there is no incentive for industries to reduce their emissions unless mandated by regulations. Conversely, the opposite trend emerges as carbon trading incentivises the adoption of low-carbon technologies, such as solar, hydro, biomass, biogas, CCS and NETs. Note that NETs either produce or consume electricity besides reducing the emissions, therefore, their optimal deployment involves factors such as cost, emissions and power generation / consumption. The final few periods of both budget minimisation and profit maximisation scenarios with and without shows greater deployment of emission reduction technologies, however, carbon trading has resulted in overall lower deployment of emission reduction technologies (alternative fuels, CCS and NETs) and preferred renewable energy technologies for emission mitigation. A diverse portfolio of emission reduction technologies to promote decarbonisation should be analysed because carbon trading is inevitable considering the future global policies around sustainability in developed and developing world. Despite Hydrogen technology not being selected by the model because of its high cost, Malaysia's plan to integrate Hydrogen (produced using renewable energy) in their power sector in the near future (probably after 2040s) is worth studying, considering the assumption that prices of renewable energy and Hydrogen technology will reduce over time. Moreover, bioeconomy (as shown by the proposed capacity enhancement for power generated using biogas) will play a significant role in decarbonisation of the Malaysian power sector.

The carbon trading scenario preferred renewable energy technologies over NETs for power generation. BECCS EP-NET was selected the most, followed by afforestation and EW EC-NETs. As shown in Figure 7 and Figure 7, the retrofitting of CCS and the utilisation of alternative fuels, such as solid biomass and biogas, alongside the deployment of NETs, become more feasible post-2040 in scenarios with and without carbon trading, and when carbon prices

range between 159 and 300 million USD per Mt of CO₂ emissions or higher for carbon trading scenarios. Scenarios with carbon trading demonstrate significantly lower emissions, showing the effectiveness of market-based mechanisms in incentivising emission reductions and fostering the transition towards a more sustainable power generation landscape in Malaysia. A notable dip in emissions between 2048 and 2054 is characterised by the intensive deployment of emission mitigation technologies to meet the net-zero target as shown in Figure 6.

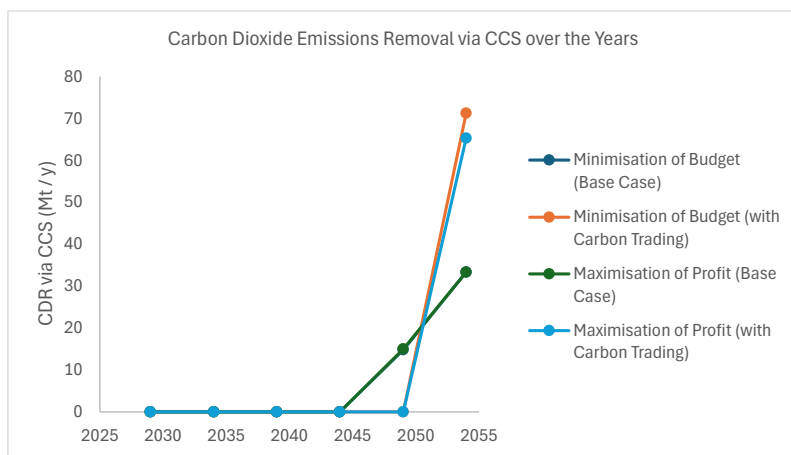


Figure 7. Carbon dioxide removal via CCS over the years

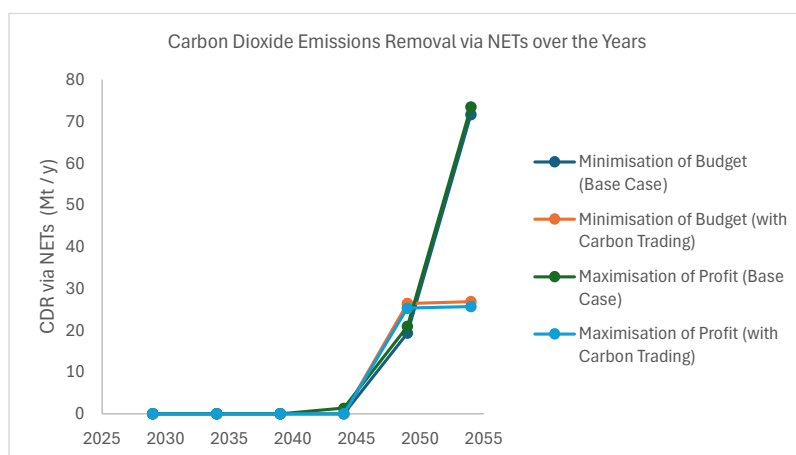


Figure 8. Carbon dioxide removal via NETs over the years

Carbon prices are shown to increase gradually for both budget minimisation and profit maximisation scenarios. Higher carbon prices have resulted in cleaner electricity (as we proceed to later periods) for the Malaysian power sector. Electricity prices are predicted to be high (i.e., hitting the upper bound) in the case of profit maximisation. This is an obvious result, as the optimiser will seek to generate maximum revenue. Prices increase by 57% from 75 mil USD / TWh in first period (2024-2028) to 118 mil USD / TWh in the last period (2049-2053). The Malaysian government may propose new plans to enhance the renewable energy share in total power generation capacity, and then new optimal carbon prices may also be found, through use of the modified DECO2 tool developed as a part of this RIDA project.

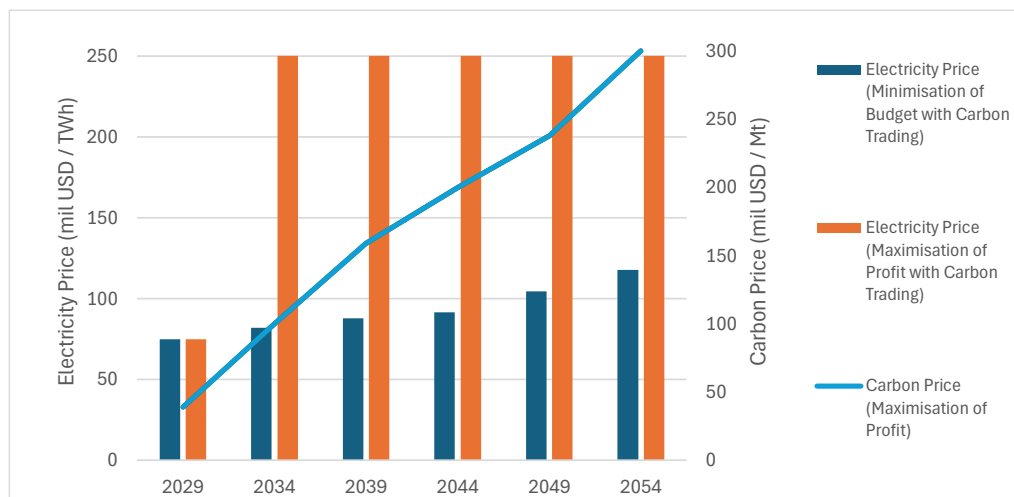


Figure 9. Electricity and carbon prices over the years

In case of carbon trading scenarios, plants earn revenue in two ways; by participating in carbon trading mechanism (i.e., buy selling / buying emission rights) and by selling electricity as a part of their core energy business. The ratio is calculated as the income from carbon trading divided by the income from selling electricity in a specific period for each fuel (as shown in Figure 10 and Figure 11), and is a key indicator of economic competitiveness with carbon trading taking place via local carbon markets over time. Higher earnings from carbon trading mechanism leads to higher ratios, showing that the fuel prefers carbon trading business over the core energy business. Lower ratio depicts that the carbon trading is not generating enough profits when compared to revenue from selling power. As carbon prices rise, plants will aim to balance these businesses (carbon trading and selling electricity) to avoid additional costs, highlighting the importance of this indicator. This ratio is influenced by carbon price, emissions intensity, traded emissions, generated power (i.e., available power generation capacity for a specific fuel), and electricity prices. If the competition is among the renewable energy technologies, lower CO₂ emissions intensity (i.e., technology producing lesser emissions) leads to higher ratios, highlighting greater profits from carbon trading mechanism when compared to revenue generated by selling electricity. Generally, for all renewable and fossil fuels, higher ratios signify greater economic competitiveness only when carbon trading mechanism is in place. Over time, renewable energy technologies become increasingly competitive, eventually surpassing fossil fuels in the later periods. As we move to later periods, emission reduction technologies are deployed and the renewable share increases, fossil-based plants are no longer encouraged to reduce emissions using alternative fuels or by employing technologies like CCS. As a result, their participation in the carbon trading mechanism is lessened, leading to reduced carbon trading revenues. This reduction in carbon trading income eventually makes fossil fuels economically less competitive and carbon trading income to electricity selling revenue ratio decreases for them. As carbon trading mechanisms make emission reduction technologies economically more viable, we observe a notable decline in the ratio for NG. In the last period, NG plants are decommissioned, and biogas plants are proposed to be commissioned, leading to a decrease in economic competitiveness of NG plants. With rising carbon prices, renewable and low-carbon technologies emerge as more competitive options. To produce a same amount of power, fossil fuel plants buy more emission rights, while renewable plants buy fewer rights or they may even sell rights to fossil plants, hence, renewable plants become more profitable with higher carbon prices. This ratio highlights the profitability shift to renewables as carbon

prices increase. The competitiveness of solar and hydro technologies often aligns due to their assumed similar emissions intensities. Because of higher predicted electricity prices, higher carbon trading to electricity selling income ratios are observed for minimisation of budget scenario as compared to that of the minimisation of budget scenario. Higher ratios depict the dominance of carbon trading business over electricity selling business. Electricity prices between those predicted by the budget minimisation and profit maximisation scenarios may lead to proper balancing of carbon trading and core energy business.

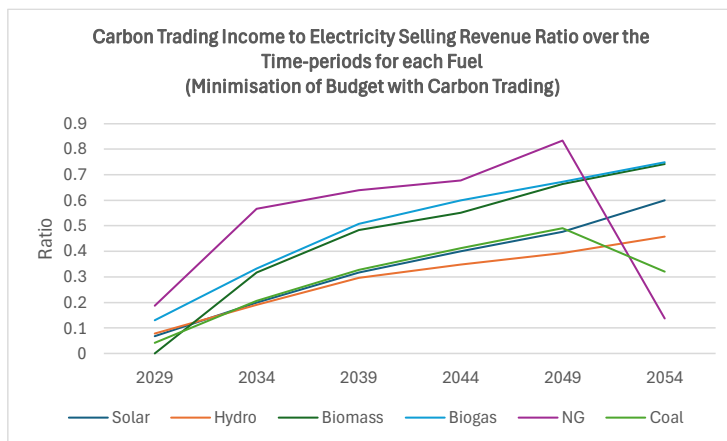


Figure 10. Carbon trading income to power generation income ratio over the years for minimisation of budget scenario

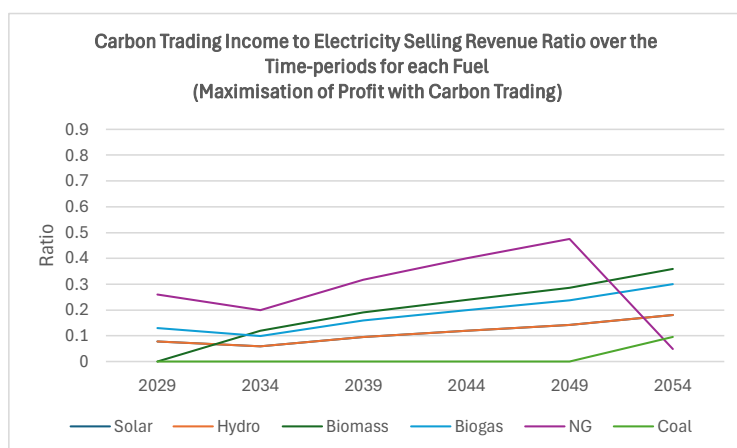


Figure 11. Carbon trading income to power generation income ratio over the years for maximisation of profits scenario

Government generates a substantial revenue from carbon trading as it earns as a result of selling and buying back the emission rights. Initially, government sells emission rights to the plants. Then, some of the earnings are used to pay back the plants who have utilised fewer emission rights than bought, and some plants end up paying more to the government as they have exceeded the purchased emission rights. Government revenue from carbon trading increased from 2.28 billion USD in 2024-2028 to 26.87 billion USD in 2049-2053 under profit maximisation, while fluctuating between 1.76 billion USD and 15.7 billion USD for budget minimisation. Plants' revenue from carbon trading rose from 2.36 billion USD in 2024-2028 to 29.04 billion USD in 2049-2053 under budget minimisation, fluctuating between 2.28 billion USD and 17.91 billion USD for profit maximisation.

In both budget minimisation and profit maximisation scenarios, net costs (as shown in Figure 12) increase until 2048, after which they decline once low-carbon technologies economically outcompete fossil-based ones. Consequently, higher carbon prices enhance the feasibility of

low-carbon technologies, reducing overall costs and boosting profits. However, continuous cost increases until 2048 lead to a persistent decline in profits. Notably, the sharp profit increase in the profit maximisation scenario in the initial period is attributed to the rise in electricity prices from the lower bound (75 million USD / TWh) to the upper bound (250 million USD / TWh), which stabilises thereafter. Post-2048, profit growth is driven by carbon trading mechanisms and the improved economic competitiveness of emission reduction technologies and renewable energy sources. Low profit for the budget minimisation scenario with carbon trading suggests that it will be interesting to see the impact of subsidies on the overall generation mix and economics of power sector in the future studies. Also, note that Malaysian government subsidises its energy (especially fossil fuel) sector, and it can possibly increase the profits (even with lower electricity prices for the consumers). IEA estimated that Malaysian government spent 4,450 million USD on fossil fuel subsidies in 2009 (Bridel & Vis-Dunbar, 2013), while these subsidies amounted to 3,000 million USD in 2021 (UNESCAP, 2023). These fossil subsidies threaten Malaysia’s plan of expanding renewable energy share in power generation installed capacity.

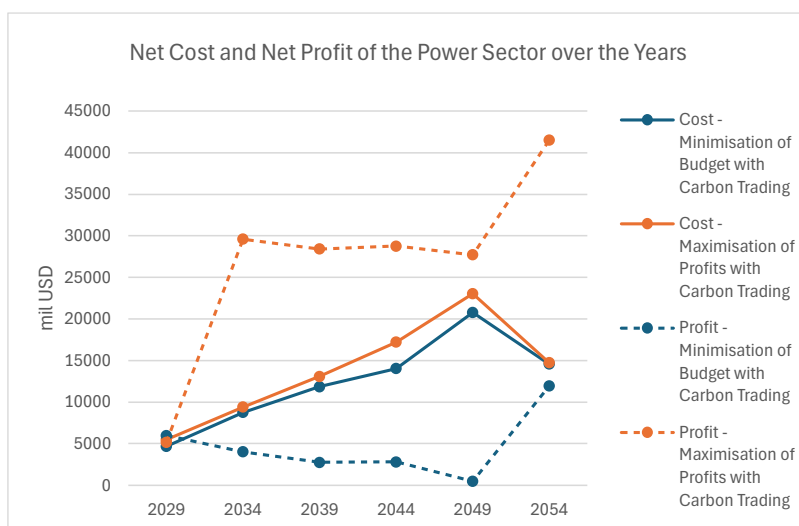


Figure 12. Net profit and net cost over the passage of time

Over time, CO₂ emissions intensity decreases (but not monotonically) in both minimisation of budget and maximisation of profits scenarios, with and without carbon trading as shown in Figure 13. However, carbon trading leads to overall lower CO₂ intensities due to the preference for low-carbon technologies (especially renewable energy technologies) and overall lower emissions, highlighting the efficacy of carbon trading in decarbonising the Malaysian power sector. The results indicate the feasibility of achieving net-zero emission targets by mid-century, but substantial emissions reductions are imperative in later periods especially after 2039. This underscores the pressing need for continued efforts to transition towards cleaner energy sources and implement effective emission reduction strategies in Malaysian power sector.

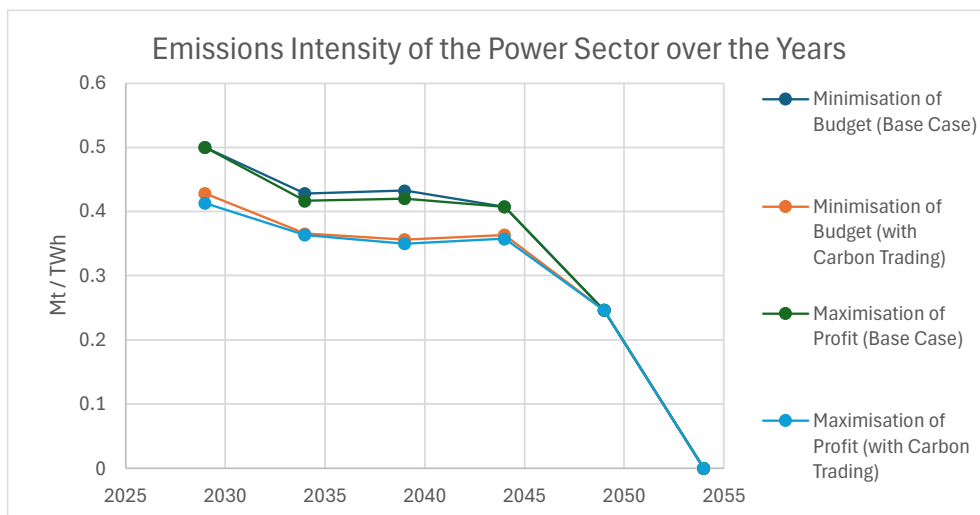


Figure 13. CO₂ emissions intensity from Malaysian power sector over the years

Another instance was case-tested on Malaysian power sector, where electricity prices were forced to increase gradually over time for maximisation of profit scenario between initial 75 million USD / TWh and maximum 250 million USD / TWh price (as shown in Figure A1 in Appendix A of this report). Overall, similar trends were observed, but the deployment of emission reduction technologies (NETs and CCS) were increased. Obtained power generation mixes for this scenario are shown in Figure 14. The maximisation of profit without carbon trading (base case) and with carbon trading are again compared. In the base case without carbon trading, the power generation initially relies heavily on NG and coal, driven by the existing infrastructure and lower short-term costs. However, this results in emissions consistently meeting targets until 2039, the introduction of CCS and NETs then becomes inevitable to meet further emission targets. The power generation mix also gradually shifts towards renewable sources such as solar and hydro, motivated by declining costs and improved efficiencies in these technologies for the case without carbon trading. In the scenario with carbon trading, the economic incentives for reducing carbon output encourage a more aggressive reduction in emissions. Carbon trading creates a financial motive to invest in cleaner technologies and reduce emissions, as companies can trade emissions allowances. This scenario also sees the introduction of CCS in the last period, but with a more substantial reliance on renewable sources. EC-NET (afforestation) and EP-NET (BECCS) technologies actively remove CO₂ from the atmosphere in the last two periods, complementing CCS and further driving down emissions. The combination of renewable energy technologies, carbon trading, CCS, and NET leads to a drastic reduction in emissions by the final period (2049-53), aligning more closely with the emission targets. The transition from fossil fuels to renewable energy sources in the Malaysian power sector is driven by both technological advancements and economic policies. The optimisation results emphasise that introducing renewable energy technologies, integrating CCS, deploying NETs and participating in carbon trading are essential strategies for balancing profitability with sustainability and environmental responsibility.

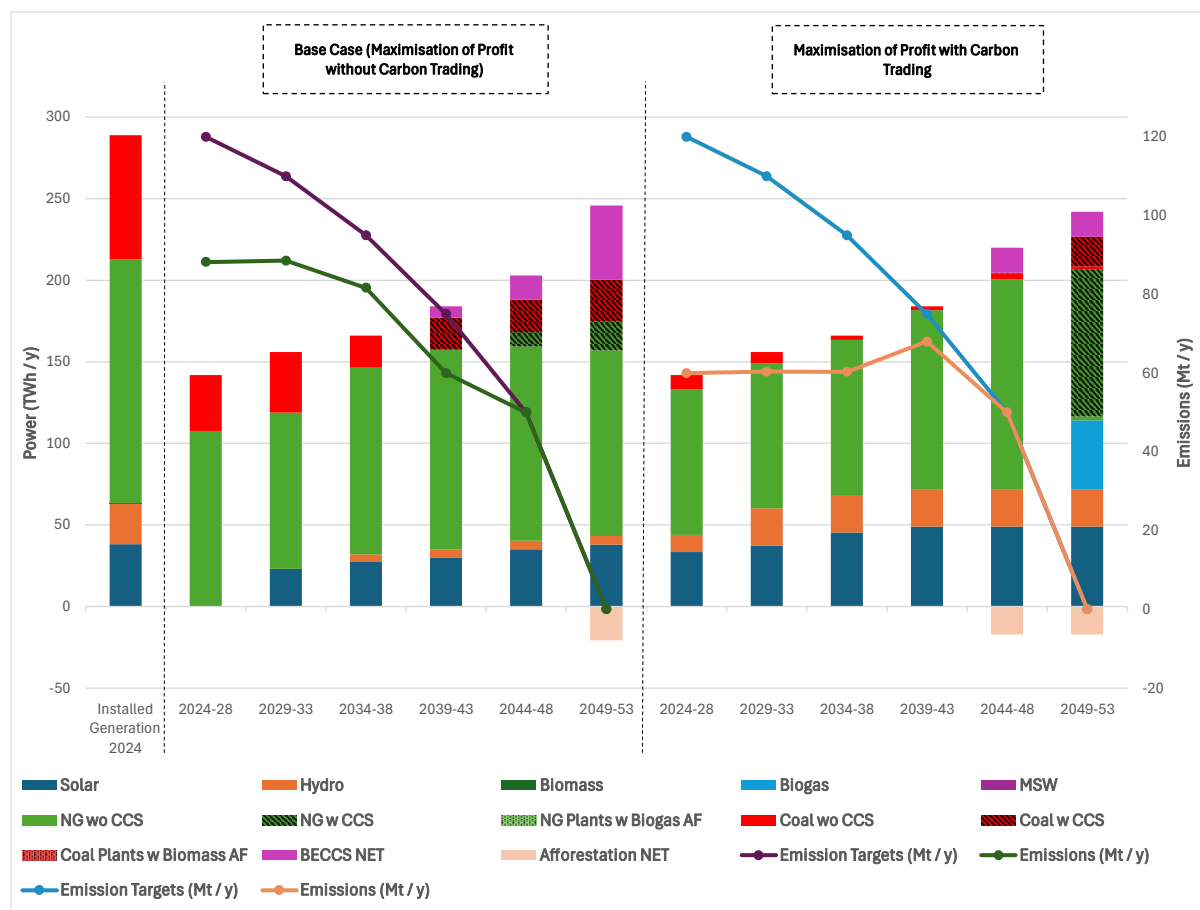


Figure 14. Power generation mix and emissions over the years for maximisation of profit scenario with gradual increase in electricity prices

As indicated by the gradual increase in electricity prices case, the gradual reduction in emissions was observed for the maximisation of profit scenario without carbon trading, while all previous results (with and without carbon trading) predicted a slight increase in emissions between 2034 and 2038, leading to a notion that previous emission targets were not ambitious enough, therefore, emission targets were re-adjusted (based upon the previously-mentioned results for the Malaysian case study) and the problem was re-solved. The solution could not be obtained even after an hour of simulation (i.e., emission targets are not met), and DICOPT printed the relaxed MIP solution (which is not the optimal solution for the whole power system).

3.1.1 Policy Recommendations for Malaysia

The results indicate that with appropriate carbon pricing and trading policies, power plants are incentivised to adopt cleaner technologies and improve operational efficiencies, leading to overall greater emissions reductions. Carbon trading favours renewable energy deployment over CCS and NETs, generating additional revenue. Higher carbon prices shift the trend towards utilisation of renewable energy generation to meet power demand and emission targets, while lower prices prefer fossil plants. The decline in emissions intensity also correlates with the increased deployment of renewable energy sources and the integration of bioenergy solutions. This trend underscores the importance of a diversified electricity mix in achieving lower carbon intensity. Despite renewable expansion, Malaysia needs CCS and CCUS to meet its emission targets because NG will remain an important contributor to generation mix, and

optimisation results predict that the NETR's aim of establishing 3-6 CCUS clusters by 2050 is practical (Ministry of Economy GOVMY, 2023). Fossil subsidies (UNESCAP, 2023) could threaten Malaysia's renewable expansion plan of achieving 40% share of renewables in installed generation capacity (Sustainable Energy Development Authority, 2021). To avoid huge capacity payments resulting from the expansion of installed power generation capacity, Malaysia should decommission old fossil-based plants while installing renewable energy capacity. This decommissioning (phasing-out of fossil plants) will lead to greater contribution of renewables in meeting the power demand, which stands at 19% (17% hydro, 1.5% solar and wind, 0.5% others) in 2022. Results indicate that carbon trading and fossil phase-out are inevitable for the Malaysian power sector to achieve its target of generating 29% of the power using renewable energy resources by 2030 (EMBER, 2024a). NETR sets out reduction of coal share in installed generation capacity to 19% by 2040 and 0% by 2050, while enhancing renewable share in installed capacity to 41% by 2040 and 70% by 2050 (Ministry of Economy GOVMY, 2023). Complete coal phase-out is possible if renewable energy capacity is enhanced and CCS / CCUS are implemented, however, Malaysia does not have clear post-2035 plan (with details of future power plants and emission reduction technologies) to achieve these targets set out by NETR. Solar growth is envisioned by both NETR and our optimisation results (Ministry of Economy GOVMY, 2023), indicating the consideration of potential expansion of solar share in generation capacity by policymakers while carving out detailed post-2035 plan for achieving net-zero by 2035 in a responsible and sustainable manner. Afforestation is limited as per optimisation results, maintaining the significance of Malaysia's goal of keeping 50% forest and tree cover (Tan, 2021). Optimisation results suggest that NETR goal of achieving 1400 MW installed capacity of bioenergy is achievable (Ministry of Economy GOVMY, 2023). Optimisation results suggest afforestation as we move near to mid-century, hence, necessitating the forest cover policy and regulation of palm and rubber plantation. The forest cover policy should lead to development of strict regulations around palm plantation expansion (Tan, 2021). This comprehensive approach underscores the potential of Malaysia's power sector to achieve greater sustainability through balanced policy and market strategies.

3.2 Case Study: Philippines

In 2023, fossil fuels generated 78% of the Philippines' electricity, while low-carbon sources accounted for over a fifth, primarily from hydropower and geothermal (EMBER, 2024b). Solar and wind made up only 2.5%, far below the global average of 13% and the ASEAN average of 4.4% (EMBER, 2024b). Over the last decade, the country witnessed a nearly twofold increase in power sector emissions, driven by a more than doubling of coal power generation to meet rising demand (EMBER, 2024b).

In 2024, installed generation capacity of Luzon Grid stands at 173 TWh/y as shown in Figure 15, which is far more than the expected demand of 81 TWh / y (Department of Energy GOVPH, 2023). Fossil fuels make up about 75%, while renewables make up 25% of the total installed capacity (Department of Energy GOVPH, 2023). A total 133 power plants (consisting of 15 coal-based, 11 oil-based, 7 NG-based, 16 biomass-based, 4 geothermal-based, 34 solar-based, 42 hydro-based and 4 wind-based electricity plants) are connected to this grid (Department of Energy GOVPH, 2023). Among fossil fuels, coal (followed by NG) has the highest installed capacity of about 77 TWh / y, which is 44% of the total capacity connected to the Luzon grid. Among renewables, hydro (followed by solar and then geothermal) has the highest share in

power generation capacity (Department of Energy GOVPH, 2023). Despite a greater share of solar, geothermal plants are actively utilised more to meet the power demand.

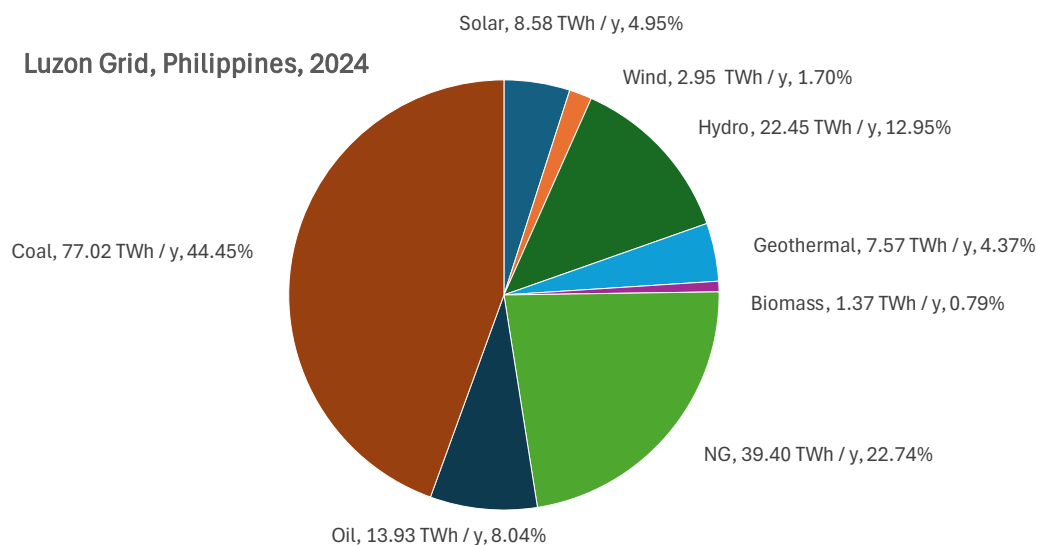


Figure 15. Installed Power Generation Capacity of Luzon Grid, 2024

To achieve the government’s long-term vision ‘the AmBisyon Natin 2040’ for the Philippines, Department of Energy formulated the Philippine Energy Plan (PEP) 2020-2040 that outlined a clear set of objectives for the country’s power sector (Department of Energy GOVPH, 2019). The Philippines aims to achieve 35% renewable electricity by 2030, while the IEA's global target of 60% renewable electricity by the same year. By 2040, the country targets a 50% share of renewable energy in its power generation mix (Department of Energy GOVPH, 2019). To support the transition from coal to NG, the Philippines has commenced LNG imports and is promoting the utilisation of NG over coal for power generation due to the available installed NG generation capacity (Department of Energy GOVPH, 2019). Between 2020 and 2040, there is a planned 1.5% increase in aggregated NG consumption from the transport and industry sectors (Department of Energy GOVPH, 2019). Additionally, the Philippines plans for a 10% penetration rate of electric vehicles for road transport by 2040, alongside transitioning to cleaner electricity (Department of Energy GOVPH, 2019). The Philippines, through its Nationally Determined Contribution communicated in April 2021, has committed to reducing and avoiding GHG emissions by 75% by 2030 (UNDP, 2021). This reduction is divided into 2.71% unconditional and 72.29% conditional commitments, reflecting the country's ambition for GHG mitigation across agriculture, waste, industry, transport, and power sectors from 2020 to 2030. These committed targets include at least a 12% reduction in GHG emissions from the energy sector.

To see what directions Philippines may follow to achieve its emission reduction targets of 77 (2024-2028), 70 (2029-2033), 60 (2034-2038), 45 (2039-2043), 25 (2044-2048), and 0 (2049-2053) Mt/y, two scenarios; budget minimisation and profit maximisation for each planning time period, are optimised with and without carbon trading to meet power demand. Similar emission reduction technologies (NETs, alternative fuels, and CCS / CCUS) are utilised as in the Malaysian case study. Emission targets are set based upon the current emissions and the emissions reduction capability (i.e., minimisation of emissions performed using the same developed models) of the Philippines’ power sector.

The generation mix for the minimisation of budget scenario is shown in Figure 16. In the budget minimisation scenario without carbon trading, coal accounts for 54% of total electricity generated from 2024 to 2053, while NG satisfies only 7% of the demand. The low cost and existing infrastructure for coal make it a preferred choice for minimising budget. However, with the integration of carbon trading, coal share decreases to 46%, and NG share increases to 24%. A reason for the high utilisation of NG and relatively lower reduction in coal share is the full utilisation of available solar, wind, and hydroelectricity potential. Without carbon trading, only 29%, 18%, and 63% of installed solar, wind, and hydro capacities are utilised, respectively, whereas with carbon trading, these figures rise to 91%, 100%, and 96%. If there were more installed capacity for these renewable energy technologies, they could have potentially replaced the coal and NG share more effectively and CCS deployment would have been reduced even further, particularly with the carbon trading mechanism. Carbon trading increases the cost of emissions, making coal economically less attractive and encouraging the use of low-emitting NG and renewables. The substantial improvement in renewable utilisation suggests that economic incentives from carbon trading can drive a shift towards cleaner energy sources. Although carbon trading results in less utilisation of geothermal energy, enhancing its installed capacity is still suggested for the utilisation in late 2040s. Conversely, scenarios without carbon trading propose overall greater enhancement of geothermal installed capacity. Additionally, separate biomass plants and biogas as an alternative fuel within NG plants contribute more to meeting power demand in the presence of carbon trading compared to scenarios without it. The deployment of energy-consuming NET (afforestation in this case) and CCS between 2039 and 2054 in the presence of the carbon trading mechanism is because of the increased usage of fossil fuels (especially coal). These technologies together aim to meet emission targets and power demand. Results suggest that greater installed renewable electricity capacity could have been more economical and sustainable because it could have replaced the deployment of afforestation EC-NET, fossil-based generation and CCS-retrofitted power from coal and NG plants, to meet the same power demand and emission targets. Note that the Philippines' power mix is reliant on fossil fuels and that EC-NETs are powered by fossil plants with and without CCS. Installed generation capacity is almost two times the power demand, therefore, the Philippines can develop strategies which involve the decommissioning of emissions-intensive and uneconomical power plants.

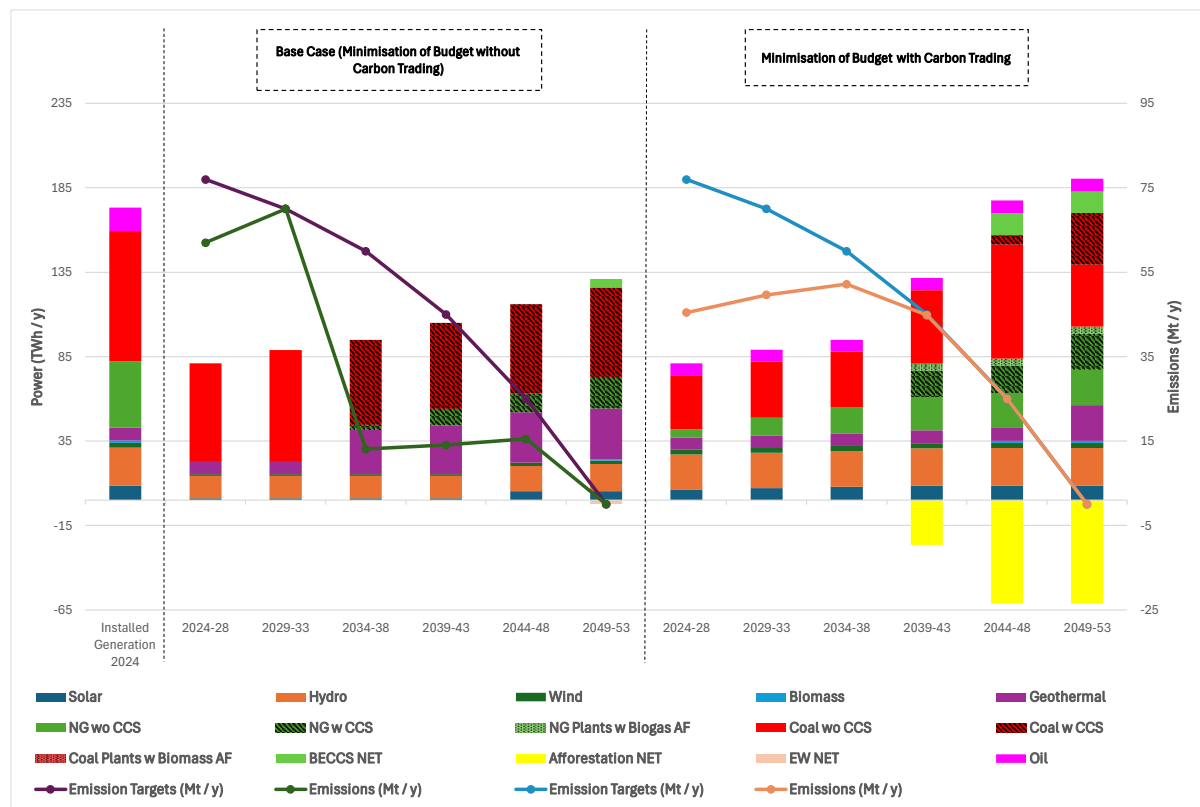


Figure 16. Power generation / consumption and emissions for minimisation of budget scenario over the years

In the profit maximisation scenario, with or without carbon trading, a similar trend in the power generation mix is observed (Figure 17) as compared to that of the budget minimisation scenario (Figure 16). Profit maximisation without carbon trading focuses on cost-effective energy sources, maintaining a high reliance on fossil fuels due to their lower operational costs. With the carbon trading mechanism, wind, hydro, and solar power installed capacities are fully utilised (i.e., 99-100% of their installed capacities, which is even greater than those predicted by the budget minimisation scenario showing the economic competitiveness of these technologies), alongside 25% utilisation of biomass generation capacity (slightly less than that predicted by the minimisation of budget scenario). This slight reduction in biomass utilisation could be due to higher operational costs compared to other renewables. Again, the deployment of EC-NETs (i.e., afforestation) after the 2040s to meet stringent decarbonisation targets is accompanied by the increased share of coal and NG fuels for electricity generation. Also, CCS is deployed on fossil plants to reduce some of the emissions. Here, the afforestation EC-NET was deployed to offset the emissions power sector. There would have been less requirement of CCS and EC-NET deployment, if greater renewable energy capacity would have been installed to meet power demand and emission targets. It can also be noted that carbon trading has greatly preferred afforestation (EC-NET) over CCS deployment when compared to the scenario without carbon trading. There is an urgent need for the planning / installation of additional renewable energy capacity because deploying afforestation (i.e., EC-NET) and fossil plants (with CCS) balance emissions but at a much greater cost. Additionally, results recommend that geothermal capacity should be enhanced (to be utilised in later periods) to support the transition towards cleaner electricity generation mix. Higher carbon prices were tested, but similar trends were observed for the deployment of EC-NETs for the Philippines' case study.

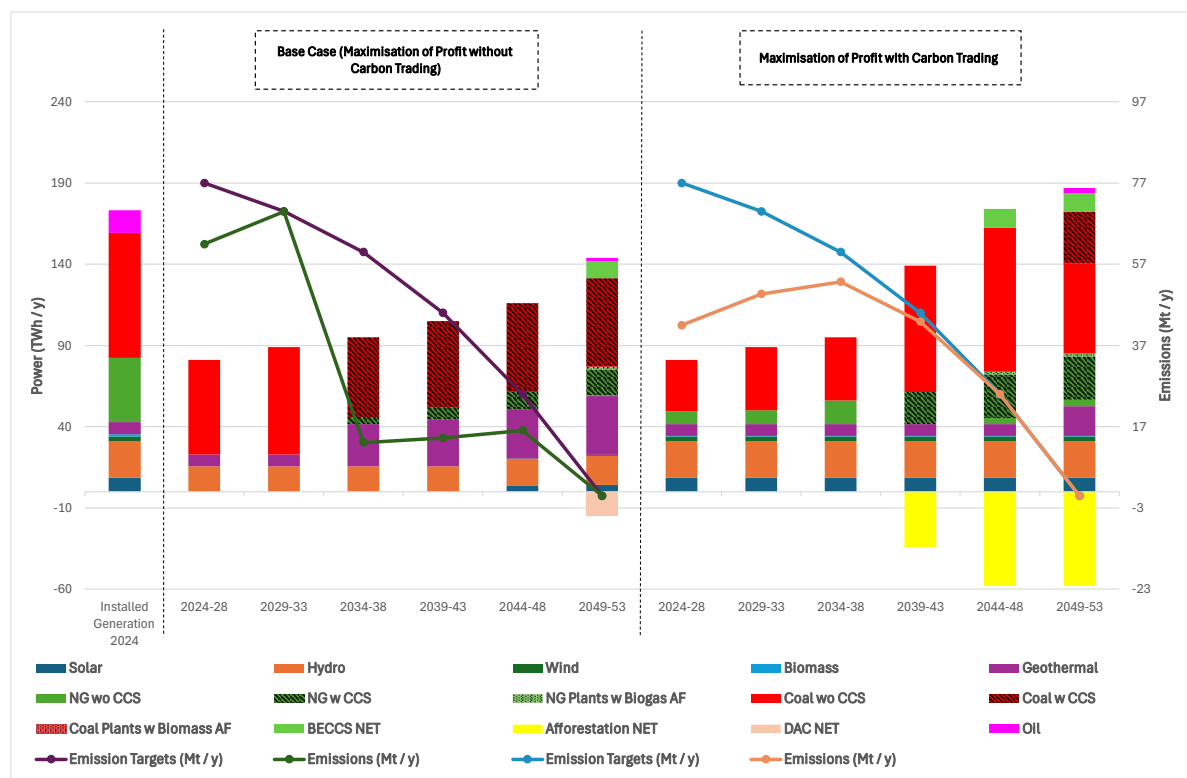


Figure 17. Power generation / consumption and emissions for the maximisation of profit scenario over the years

Results prove that Philippines can achieve net-zero (not pledged yet) by 2053 if it employs some strict regulations. As the legalities around pledging for net-zero target takes time, therefore, Philippines should consider pledging for net-zero by 2060 target, and the DECO2 decision-making tool may be crucial in determining a viable plan to reach this target. All scenarios successfully meet emission targets as shown in Figure 16 and Figure 17, but emissions are lower without carbon trading due to extensive implementation of CCS technology within NG and coal plants. With carbon trading, CCS technology is reduced, and renewable plants operate at full capacity to reduce the carbon trading cost borne by plants to the government, leading to the deployment of independent NETs. The system economically deploys EC-NETs, which are powered by fossil-based power plants as renewable power installed capacity is already fully operated to meet the power demand. In scenarios without carbon trading, CCS and DAC NET removes more than 284-285 Mt of emissions over 30 years, compared to 80-85 Mt with carbon trading implemented. Also, NETs (including DAC) remove 16-20 Mt of emissions without carbon trading, but afforestation NET remove 87-90 Mt with carbon trading over the same period. Overall, the demand for CDR via CCS and NETs is reduced by 44% with carbon trading, requiring 130-133 Mt of CDR with carbon trading and 300-305 Mt without carbon trading. Note that extensive CCS and DAC deployment is not feasible because of the geography of Philippines (as the country is located within the Pacific Ring of Fire), and IEA advises against the implementation of CCS in Philippines (Mateo, 2012; Asian Development Bank, 2013). Therefore, scenarios showing the least deployment of CCS are economically and technically more feasible. CCS can be implemented at small-scale (as shown in carbon trading scenarios predicted by our model for the Philippines) because of the availability of some suitable CCS sites near Manila in Luzon region. Some of captured emissions may also be used to meet the CO₂ gas requirement of industry in the form of CCUS. As shown in Figure 16 and Figure 17, carbon trading scenarios show the least implement of

CCS technology, even that could have been avoided if more renewable energy capacity is installed and available to meet the power demand between 2039 and 2053. Policymakers should look to develop energy policies which limit CCS deployment.

The CO₂ capture potential for the Philippines has been analysed (Asian Development Bank, 2013). The analysis focused on the Calabarzon region, comprising Cavite, Laguna, Batangas, Rizal, and Quezon, significant contributors to national emissions. Despite identifying potential storage locations near capture sites, the Philippines was shown to lack immediate opportunities for CCS in NG processing (Asian Development Bank, 2013). Only three fields met the criteria, with a promising site holding 251 Mt CO₂ storage capacity, unavailable until around 2030. Note that the CCS deployment of around 284-285 Mt / y (between 2034 and 253) in scenarios without carbon trading (as shown in Figure 18) exceeds the potential storage capacity of 251 Mt CO₂ emissions, while 87-90 Mt removal of CO₂ emissions with carbon trading in place (as shown in Figure 18) seems feasible as per the mentioned CO₂ storage capacity. High seismic activity complicates site selection, resulting in the unavailability (unsuitability) of most of the Philippines’ candidate sites for CCS, but the Central Luzon Basin (grid studied in our work) emerge as the best candidate for saline aquifers despite seismic risks (Asian Development Bank, 2013). Alternative options like geothermal, ophiolites, and coal seams offer nearer-term storage potential, requiring significant research / testing. Ophiolite complexes, particularly in Zambales, provide promising CO₂ storage by mineralising CO₂, mitigating seismic release risks. The limited oil and gas field CO₂ storage opportunities in Philippines over the next 20 years necessitate exploring energy options depending less on the CCS deployment.

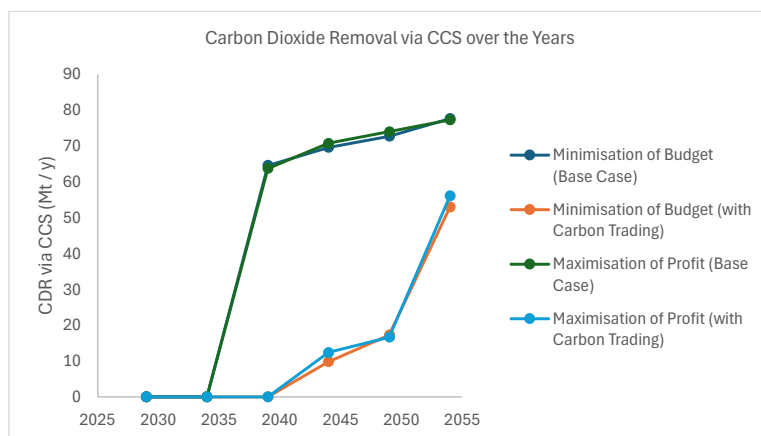


Figure 18. Carbon dioxide removal via CCS over the years

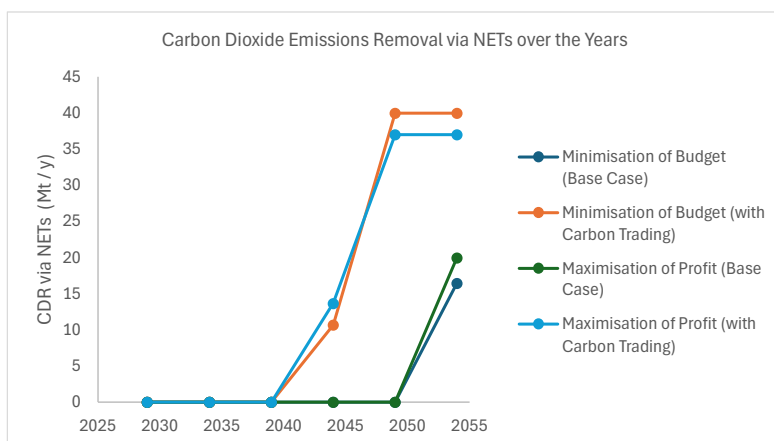


Figure 19. Carbon dioxide removal via the deployment of NETs over the years

Carbon prices are projected to rise steadily in both scenarios (with carbon trading only) as shown in Figure 20. Higher carbon prices increase overall revenues for both the government and power plants, but the revenues generated by the government is a cost incurred by the power plants. In the profit maximisation scenario, electricity prices are forecasted to be high, reaching the upper bound, so that maximum profits from selling electricity are achieved. Increasing carbon prices may also impact the electricity prices highlighting the economic pressure enforced by carbon trading on power plants to balance costs and emissions. Rising carbon prices reflect the increasing cost of emissions, driving up electricity prices as fossil fuel-based power generation incur higher costs. For the budget minimisation scenario, electricity prices are expected to increase by 93% from 75 million USD per TWh in the first period to 150 million USD per TWh in the last period. The increase is majorly because of the deployment of expensive EC-NETs to meet emission targets.

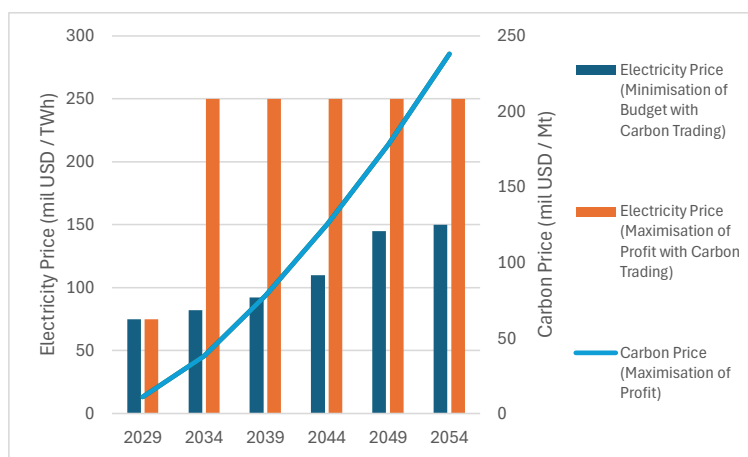


Figure 20. Electricity and carbon prices over the years

The ratio of carbon trading income to electricity selling revenue for each scenario is shown in Figure 21 and Figure 22. The power generated by each fuel significantly influences the ratio of carbon trading income to electricity income, with renewable energy resources having a lower share in total installed generation capacity. Despite increases in carbon prices (which was tested), this ratio remains low for renewables. Renewables generate lower carbon trading income due to their low emissions, but the income from selling electricity produced using renewable energy resources also remains low because of lesser installed generation capacities, leading to lower carbon trading income to electricity revenue ratios. This indicator (as shown in Figure 21 and Figure 22) highlights the need for greater capacity to enhance economic competitiveness (i.e., the ratio of carbon trading income to electricity revenue) under carbon trading policies for renewable energy technologies. Higher ratios for budget minimisation scenario as compared to profit maximisation scenario (because of comparatively lower electricity prices predicted for budget minimisation) indicate the dominance of carbon trading over the electricity selling business. If the model is constrained to predict electricity prices between those predicted by the budget minimisation and profit maximisation scenarios, the Philippines may possibly achieve a proper balance between carbon trading and the core energy business.

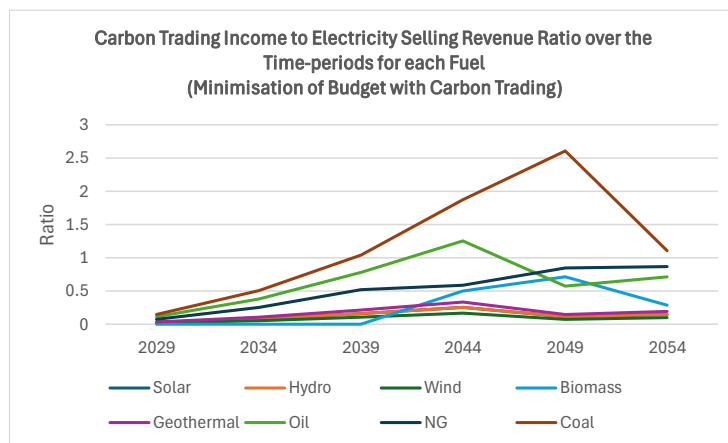


Figure 21. Carbon trading income to power generation income ratio over the years for minimisation of budget scenario

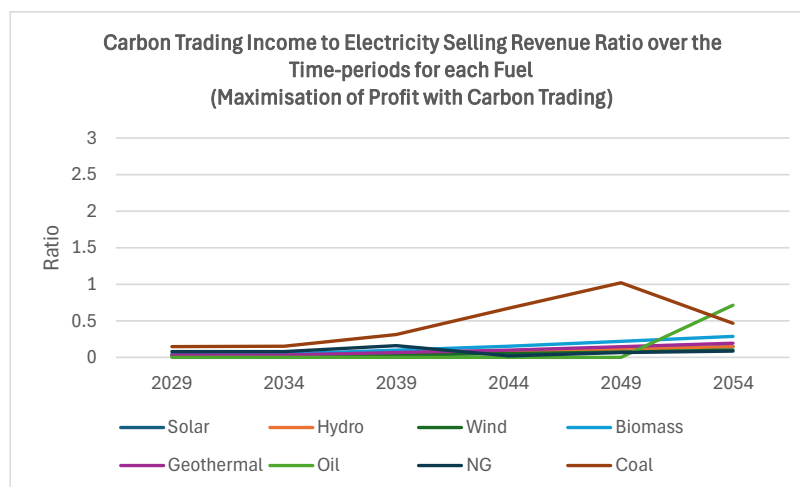


Figure 22. Carbon trading income to power generation income ratio over the years for maximisation of profit scenario

The government generates substantial revenue from carbon trading, profiting from the sale and repurchase of emission rights. Initially, the government sells emission rights to power plants. A portion of the earnings is then used to reimburse plants that have utilised fewer emission rights than purchased, while others end up paying more to the government for exceeding their allocated emission rights. This mechanism created financial incentives for both government and plants. The government and plants generated revenues between 0.46 billion USD to 11.55 billion USD in different time-periods between 2024 and 2053.

It can be seen (from Figure 23) that the power sector is incurring costs because of carbon trading and that profits are lower. Higher profit in the profit maximisation scenario is because of the increased electricity prices, while in the last period, carbon trading results in profit (leading to lower costs) in both budget minimisation and profit maximisation scenarios. This highlights the long-term economic benefits of transitioning to lower-emission technologies (renewables, NETs, CCS, etc.). The Philippines subsidises its energy sector (especially coal and oil) and it possibly increases the profits of the energy companies. The Philippines subsidises oil by 2,560 million USD in 2010 and 2011 (Mendoza, 2014). No data is available, but some estimates suggested that Philippines spend 10,000 million USD on energy subsidies in 2015 (Climate Transparency, 2020).

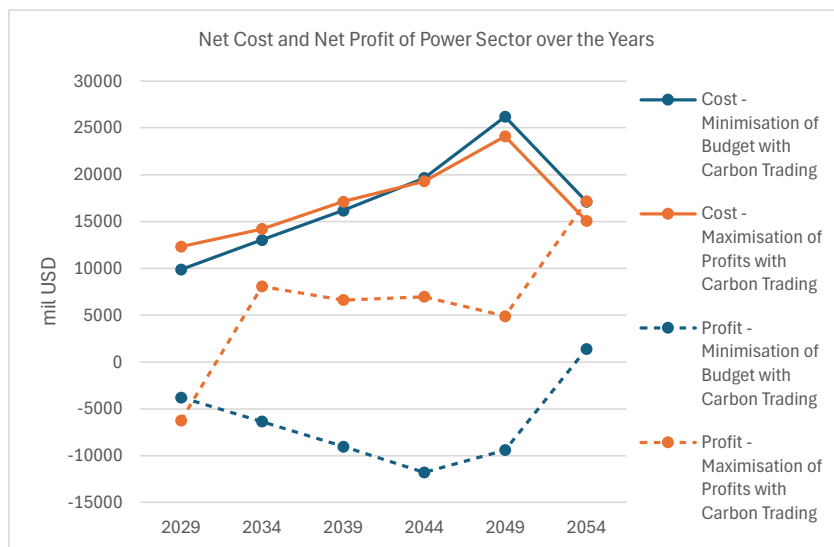


Figure 23. Costs and profits over the years

The CO₂ emissions intensity (as shown in Figure 24) demonstrates the impact of different policy scenarios on the environmental performance of the power sector. The sharper decline in emissions intensity with carbon trading underscores the effectiveness of this mechanism in driving the transition towards cleaner energy sources. By imposing costs on emissions, carbon trading makes fossil fuels less economically attractive, accelerating the shift towards renewables and low-carbon technologies. Because of the excessive implementation of CCS in third period (2034-2038), lower emissions intensities are observed post-2039 for the scenarios without carbon trading. But note that CCS implementation at large-scale (as explained previously) is not feasible for the Philippines due to the lack of storage capacity / sites and complex seismic activity. Realistic and gradual decrease in emissions intensity for the scenarios with carbon trading is observed.

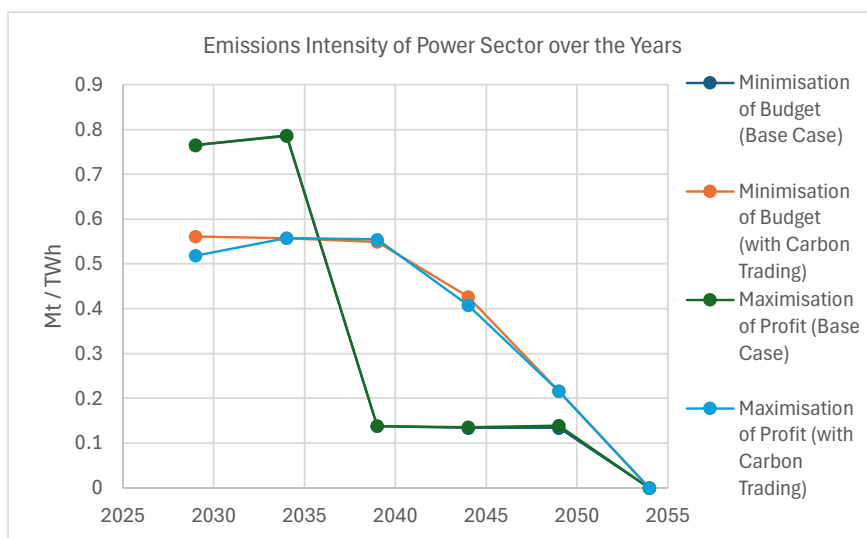


Figure 24. CO₂ emissions intensity of power generated over the years

Without CCS or CCUS, the Philippines case study was re-solved for scenarios with carbon trading, it led to results with very high deployment of EC-NETs, excessive utilisation of alternative fuels (almost fully replacing the coal and NG fuels in coal and NG plants), higher costs, lower profits and more emissions. Unrealistically high alternative fuel usage and NETs’

deployment is observed, therefore, these optimisation results without CCS / CCUS are not desirable.

3.2.1 Policy Recommendations for Philippines

Results suggest that a diverse portfolio of emission reduction technologies, CCS / CCUS (or a technology which fully replaces CCS / CCUS in coal and natural gas plants economically and removes emissions as well, such as the use of low-carbon alternative fuels instead of coal and NG in respective plants with minor retrofits) is inevitable for the Philippines' power sector to meet net-zero target. Note that the deployment of CCS / CCUS is limited to capture capacity of 251 Mt of emissions (Asian Development Bank, 2013), and it is possible to achieve net-zero even with this limit on CCS by implementing carbon trading, expanding renewable energy capacity, decommissioning fossil plants, and deploying emission reduction technologies (particularly afforestation). According to its NREP, the Philippines expects to achieve renewable power generation of 35% by 2030 and 50% by 2035 (Department of Energy, 2022). Our optimisation results fail to achieve this plan (35% by 2030 is achieved with carbon trading but 50% by 2035 is not achieved) because of the unavailability of the detailed expansion plans (power plants installation, deployment of emission reduction technologies, etc.) for the Philippines. Policymakers are recommended to devise clear achievable aims for the Philippines' power sector to realise plans envisioned by NREP. The Philippines' updated NDC aims to reduce GHG emissions by 75% from 2020 to 2030, with 2.71% unconditional and the rest contingent on international support (Government of Philippines, 2021). Achieving this target without additional measures seems unlikely, but carbon trading could generate some important revenue and reduce the Philippines' dependence on foreign investments for its decarbonisation efforts. Unlike the 2011 plan, the Philippines updated its climate change agenda within the Philippine Development Plan to include mitigation efforts in 2023 (Migo-Sumagang et al., 2024). This climate mitigation strategy (which seems to be a part of the old climate adaptation strategy) and the slow progress on low-carbon economy legislation (House Bill No. 7705, 2023) reflects a lack of political will to pledge for net-zero target. Optimisation results suggest that the Philippines can achieve its NREP targets and commit to net-zero by 2060 through aggressive unconditional goals, strict regulations, promotion of emerging innovative technologies, and implementation of carbon trading mechanism.

4. Discussion evolving from the Workshops and Optimisation

Results

The optimisation results of the study have significant implications for the power (and energy) sectors of Malaysia and the Philippines, providing critical insights for policymakers and stakeholders, so that the policies and objectives are refined. Both nations face escalating energy demands and an urgent need to reduce carbon emissions. The developed optimisation frameworks offer a systematic methodology to balance these dual objectives, highlighting pathways to be included in the energy policies to minimise emissions while maximising economic benefits. Our project team visited Malaysia and Philippines in March 2024, and organised energy and climate in ASEAN workshops and discussion sessions in Kuala Lumpur, Kuching and Manila. Local stakeholders (academics, industrialists and stakeholders working in governments' energy / climate departments) were invited to provide feedback on our work (such as methodology used, data, etc.) and engage in critical discussions (capturing the local context) around decarbonisation in ASEAN countries. The feedback and evolving discussions were used to tailor our case studies on the decarbonisation of the power sectors of Peninsular Malaysia and Luzon grid (of Philippines). The local context in methodology and discussions on case studies highlights the significance of this stakeholder-informed research work (i.e., approach) for ASEAN decarbonisation.

For Malaysia, which has committed to achieving carbon neutrality by 2050, the results affirm the viability of integrating bioenergy, and carbon capture technologies into the national electricity generation mix. The projected increase in renewable electricity capacity, particularly solar, and the incorporation of battery storage systems align well with Malaysia's Renewable Energy Roadmap targets (Sustainable Energy Development Authority, 2021). Moreover, subsidies on fossil fuels should be lessened because they can threaten the expansion of renewable share in generation capacity (UNESCAP, 2023). Malaysia should decommission fossil plants and install / commission renewable plants simultaneously, else, the country will be dealing with huge capacity payments. Establishing a carbon trading system will encourage power plants to reduce their emissions by operating renewable plants, contributing to a more sustainable energy and power sector. This aligns with discussions from the Kuala Lumpur workshop on Energy and Climate in ASEAN, where stakeholders identified the potential for biomass utilisation, CCS, and Hydrogen adoption as critical for reducing emissions in hard-to-abate sectors like power, cement, and steel. The workshop also raised a point that the palm oil industry is gradually ramping down (i.e., no more new forests will be made available for palm oil plantations, industries will maintain current plantation land, and palm industries will improve the oil yield to increase the production), and the industrialists claimed that they are not responsible for considerable deforestation, comparing their industry to the rubber industry. Other industries are also responsible for deforestation (such as rubber and wood industries), but it cannot be denied that 2.7 million hectares land of tropical forest was used for palm plantation between 1990 and 2005 in Malaysia and the Philippines (Dunning, 2018). Palm plantations increased by 2.5 times between 2001 and 2016 in Malaysia (Murphy et al., 2021). Various studies have been conducted to develop methods and provide evidence to limit further palm plantation into carbon-rich forests in Malaysia (Xu et al., 2022), and these techniques can be integrated into decision-making tools (Andiappan et al., 2022). Palm oil industrialists also mentioned that it is not currently economical to use biomass from the palm oil industry (i.e., palm kernel shell or PKS) to produce electricity, and the optimisation results support their opinion because the utilisation of PKS to generate bioelectricity is relatively low. Our model also selects the utilisation of PKS biomass but only after 2038. Malaysia currently exports PKS, Japan being the major buyer. In 2020, out of 1 million metric tons of PKS exported by Malaysia

to the world, 981,624 metric tons (99.6% of the total exported PKS) was exported to Japan (Kharibi & Mariati, 2020). This exported PKS is wholly used within Japan's medium and large feed-in-tariff-eligible biomass power plants (Kharibi & Mariati, 2020). This feed-in-tariff system was introduced by Japanese Ministry of Energy for renewable energy generation to cut dependence on oil, LNG and nuclear energy after Fukushima incident in 2012. The Japanese government aims to increase its renewable energy share to 24% by 2030 from the current 18%, boosting demand for palm products like stearin and PKS, particularly for biomass plants (Kharibi & Mariati, 2020). Renewable energy expansion (in Japan and other parts of the world) offers significant opportunities for Malaysian PKS exporters to increase their exports to these important markets. A question arises whether Malaysia can start using biomass (PKS) in its large-scale coal power plants (instead of coal) or not. To use PKS as an alternative fuel, Malaysia will need to perform capital-intensive technical adjustments in its power plants. Currently, Malaysia lacks the technological know-how, and it is expensive to import bioelectricity technologies and expertise. Therefore, palm industries find it more economical to export PKS to Japan rather than using it within Malaysia to produce bioelectricity. If Malaysia invests in improving these emission reduction technologies now, they will become economically feasible and play their part post-2040 when drastic emission reductions are required to achieve net-zero target as suggested by the optimisation results. Palm oil industrialists mentioned that if the Malaysian government implements financial incentives (around taxation and improved FiT system) and carbon trading mechanisms with carbon prices high enough (because low carbon prices benefit the fossil sector), they may improve the technology and utilise the biomass from the palm oil industry (i.e., PKS) for power generation within Malaysia as an opportunity. Switzerland and Sweden proved that carbon prices as high as 131 million USD and 126 million USD per Mt of emissions in 2023, respectively, did not cause much economic damage, and achieved significant emission reductions (Mengden, 2023).

The Kuala Lumpur workshop emphasised the economic potential for developing countries to invest in advanced decarbonisation technologies (such as CCS, bioelectricity generation using gas and solid biomass, and Hydrogen), which are currently being exported from developed nations. The workshop highlighted opportunities supporting net-zero in ASEAN like the £30 million UK-ASEAN Green Transition Fund (<https://www.gov.uk/government/publications/uk-southeast-asia-regional-development-partnership-summary/uk-southeast-asia-regional-development-partnership-summary-july-2023>), which could provide necessary financial and technical support for scaling up these innovations for the green and sustainable transition in ASEAN. Additionally, discussions on the Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2023), i.e., carbon tariff on (scope 3 emissions of) emissions-intensive products imported into the European Union, stressed the need for ASEAN countries to prioritise decarbonisation to avoid financial penalties and leverage opportunities in the global CO₂ removal market, projected to exceed USD 1 trillion by 2050. CBAM legislation will take its effect in 2026 in European Union, followed by its implementation within the UK in 2027 (Department for Energy Security & Net Zero, 2023). Moreover, Malaysia subsidises fossil-related activities (UNESCAP, 2023), and the optimisation results suggest that Malaysia should shift these energy subsidies towards carbon trading mechanisms (to compensate low-carbon technologies if they are incurring losses because of carbon trading) and directly into low-carbon technologies to achieve its net-zero target. Optimisation results also predicted some financial losses, and the subsidies for the low-carbon technologies can make up for those losses. Also, the revenue generated by the government from carbon trading could be used in the following ways:

- To financially compensate low-carbon technologies if they are incurring losses due to emissions trading mechanism,

- Investments into capital-intensive emission reduction and low-carbon technologies (CCS, NETs, EVs, etc.),
- Compensating the general public by lowering taxes using the generated revenue, or
- Lowering the electricity prices for the electricity consumers.

Malaysia's commitment to reduce energy intensity by 32% by 2025, as part of the ASEAN Plan of Action for Energy Cooperation (APAEC) Phase II, underscores its proactive stance on sustainable energy practices (ACCEPT, 2020). The country's support for developing an ASEAN regional energy policy and power grid to promote energy resilience, along with its commitment to preserving natural forests and planting 100 million trees by 2025, highlights its leadership role in regional climate action (ACCEPT, 2020).



Figure 25. Highlights from the workshop in Kuala Lumpur, Malaysia

Although the Philippines has not pledged net-zero target yet, the significant gradual reduction in CO₂ emissions over time in scenarios incorporating carbon trading underscores the potential of market-based mechanisms to enhance renewable energy adoption and improve overall carbon footprints. Results depict that optimisation studies and policy research can help Philippines in setting up its net-zero by 2060 target. The results indicate a critical need for decommissioning old, emissions-intensive plants and installing new renewable electricity generation facilities before implementing carbon trading policies and EV policy adoption. Manila's workshop underscored the urgency of decarbonising the electricity, whose carbon footprint becomes part of the carbon footprint of practically all the other products and services produced in the economy. The discussions also pointed out that increased electricity demand from EVs in the future must be met with clean energy sources in order to maximise the benefits of EV policy. This strategy ensures that the carbon trading (promoting low-carbon technologies and renewable energy) becomes advantageous for both public and the other stakeholders, and the increased electricity demand from EVs does not exacerbate emissions but supports a cleaner energy transition. An energy / sustainability expert (Professor Raymond, De La Salle University) from Philippines mentioned afforestation as an important NET for the Philippines, and our optimisation results showed large-scale deployment of afforestation NET after 2038 critical to achieving net-zero in Philippines. Optimisation results and workshop discussions emphasised the need for the Philippines to pledge to a net-zero target so that the foreign and

local investors are encouraged to invest in low-carbon technologies within the country, and the stakeholders develop / adopt effective policies / strategies to achieve the carbon-neutrality target.

The Philippines' government envisions CCS deployment, but geographical limitations make widespread implementation unlikely as suggested by IEA and the point was discussed in the workshop (Mateo, 2012). However, there is potential for CCS near central Luzon (Asian Development Bank, 2013) and the utilisation of carbon captured from the power sector. The Philippines' other low-carbon energy resources, such as solar, wind, geothermal, and biogas, offer more feasible and economical pathways. The need for nuclear energy remains questionable, given the other abundant renewable resources. Short-term policies are not efficient in tackling the existing environmental concerns, rather, long-term policies should be adopted to take on the challenge of decarbonising the country's power sector. The introduction of Renewable Energy Certificates (RECs) in the Philippine Renewable Energy Market and the Electric Vehicle Act indicates the government's active steps towards reducing emissions, but renewable power capacity enhancement is inevitable to make these policies effective. A clear net-zero target, and substantial foreign aid / investments are essential for achieving significant emission reductions.



Figure 26. Highlights from the workshop in Manila, Philippines

Both Malaysia and the Philippines rely on fossil fuels to produce power. If they do not find and install alternative ways (such as renewable energy and emission reduction technologies), they will be forced to import a significant amount of fossil fuels in the near future. This dependency, coupled with uncertain fuel prices due to global geopolitics, complicates the energy security and economic growth within ASEAN region, highlighting the urgency for policymakers in ASEAN region to revise / formulate long-term policies to enhance power supply and economic security within the region. Moreover, workshop participants also raised a point that there is the need of variable electricity pricing (depending upon the time of the day, weather, etc.).

The implications of this study can extend beyond Malaysia and the Philippines, offering valuable insights for the broader Southeast Asian region. Countries like Indonesia, Thailand, etc., which share similar energy and economic profiles, can benefit from the demonstrated

efficacy of carbon trading mechanisms. Integrating carbon trading with existing energy policies can lead to substantial CO₂ emission reductions while boosting economic performance. This dual benefit can catalyse regional collaboration on climate action, driving innovation in low-carbon technologies (renewable and other emission reduction technologies) and fostering economic growth through green investments. The significance of the performed case studies lies in highlighting the impact of the share of renewable power in installed generation capacity (which depends significantly on the policy directions of a country). As shown in Figure 27, the renewable share in total installed power capacities is 4th (26%) and 5th highest (23%) for Philippines and Malaysia, respectively, among nine ASEAN countries, making these case studies on Philippines and Malaysia significant for the ASEAN countries with lesser share (such as Singapore, Indonesia and Thailand) (IRENA, 2022). Note that the renewable share in Luzon Grid was 25%, while it was 22% in Peninsular Malaysia as shown in Figure 15 and Figure 4. The results clearly indicate that the effectiveness of carbon trading in meeting zero emissions is influenced by the share of renewable electricity in a country's installed power generation capacity, indicating that more renewable capacity towards later periods could have been more beneficial for both budget and the emissions reduction. The successful implementation of carbon trading and electricity generation planning optimisation in Malaysia and the Philippines can catalyse similar initiatives across the region.

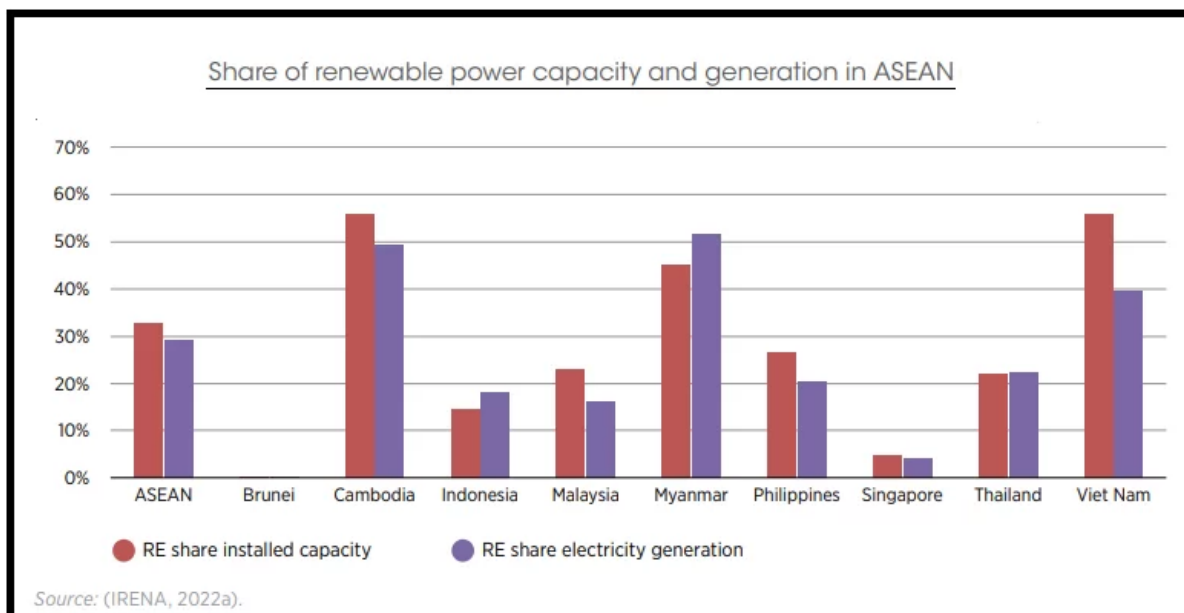


Figure 27. Renewable share in installed capacity and power generation across ASEAN region

The pace at which ASEAN Member States have adopted national power development plans and policies has significantly transformed the energy system, with renewables increasingly penetrating the electrical grid. Notably, the rapid increase in the share of solar power in Cambodia and Vietnam has been a remarkable development for ASEAN (Phoumin et al., 2021). However, a major challenge across ASEAN is the high cost of upgrading and integrating variable renewable energy sources like wind and solar. This requires substantial investments in grid infrastructure, IoT technology, and energy infrastructure improvements (Nepal et al., 2021). During a virtual conference on CCUS organized by Economic Research Institute for ASEAN and East Asia in February 2021, experts emphasised the need for ASEAN to transition from a fossil-based energy system to a cleaner one (Phoumin et al., 2021). This transition should incorporate clean coal technologies and CCUS, which can capture CO₂ from flue gas and the atmosphere, recycle it for utilisation, and secure permanent storage options. CCUS can significantly reduce CO₂ and GHG emissions. Urgent steps are required to decarbonise the

energy sector, including the rapid deployment of clean fossil fuel technologies, renewable energy development, and doubling energy efficiency, as the energy sector accounts for two-thirds of global GHG emissions.

The scalability of the modified DECO2 framework at the ASEAN level and other developing regions in the world is highly promising. Given the shared economic, environmental, and energy challenges across ASEAN countries, adopting comprehensive energy planning tools can drive regional collaboration and policy harmonisation. The framework's flexibility in accommodating various energy sources, emission reduction technologies, and market mechanisms and economic instruments makes it adaptable to the diverse electricity landscapes within ASEAN. Establishing a regional integrated energy market in Southeast Asia is key to achieving the ASEAN Economic Community (AEC), ensuring a steady power supply to meet rising electricity demand and support anticipated economic growth in the region (Indeo, 2019). The ASEAN Power Grid initiative, aimed at enhancing energy security and sustainability through regional energy cooperation, can benefit from insights provided by the developed framework. By facilitating optimal energy resource allocation and carbon trading across borders, the region can achieve more significant emissions reductions and economic benefits. Moreover, ASEAN has collectively pledged to decarbonise the region's power sector through the AEC (Nguyen, 2023), and our optimisation models can validate the feasibility of those plans and provide tailored recommendations to achieve them. This plan sets a goal of achieving a 23% share of renewable energy in the total primary energy supply and aims for renewable energy to constitute 35% of ASEAN region's installed power capacity by 2025 (Nguyen, 2023). Each ASEAN country is taking steps to achieve its clean energy targets (Nguyen, 2023). Indonesia aims to generate 23% of its primary energy supply from renewable sources by 2025, focusing on solar power generation and subsidies for EVs. Malaysia targets 20% renewable energy in its power capacity by 2025, with plans for large-scale solar projects and expanding battery energy storage systems. The Philippines has set a goal of 20 gigawatts of renewable energy capacity by 2040, primarily through solar and wind power generation. Thailand aims for a 30% clean energy share in total final energy consumption by 2036, utilising a mix of hydropower and solar power. Vietnam plans for a renewable energy share of 32.3% by 2030 and 44% by 2050 in its total primary energy consumption, supported by a Just Energy Transition Partnership with the International Partners Group, which will mobilise 15.5 billion USD in finance over the next five years. Singapore, considered a mature market, has set a solar target of at least 2 gigawatt-peak by 2030 and is collaborating with the US to identify clean energy partnership opportunities for ASEAN. Despite ASEAN's commitment to green energy, experts believe the region requires numerous projects and substantial additional investments to meet climate goals (Nguyen, 2023). Vietnam needs between \$8 billion and \$14 billion annually until 2030 to develop new power plants, while Malaysia must invest at least \$375 billion to achieve a net-zero target by 2050. Indonesia will need to nearly triple its energy investment by 2030 from current levels to reach net-zero by 2060. The Philippines requires at least \$121 billion in renewable energy investments between 2020 and 2040 to meet its clean energy goals. Government interventions alone will not suffice; a combination of public and private funding is essential for Southeast Asia to accelerate its transition to greener energy generation.

Furthermore, the framework's emphasis on bioeconomy and natural climate solutions aligns well with ASEAN's rich biodiversity and agricultural base. The optimisation results predict that the power sector will greatly benefit from solid biomass and biogas after 2040 to meet emission targets. Therefore, it is recommended to construct biomass power plants and add their share into installed generation capacity for later use when deeper emission cuts will be required. These initiatives will attract the investors to invest in bioenergy-related research and projects. Countries like Malaysia, Indonesia and Myanmar, with substantial biomass resources, can

leverage these insights to develop their bioenergy sectors, contributing to regional decarbonisation efforts. ASEAN countries should seek collaborations and knowledge sharing with countries experienced in decarbonisation technologies and carbon trading, such as the UK and EU countries. Prioritising research and development efforts will expedite the commercial deployment of negative emission technologies and emissions trading schemes, making them integral to the energy and power sector.

A dedicated interconnected platform in the ASEAN region is needed to meet global emission targets. Building on the carbon trading model presented in this study, various platforms with central emission banks at global, continental, national, and regional levels should be created to monitor and control emissions. These interconnected platforms will connect global emission banks to continents, continental banks to nations, and national banks to regions within a country. Emission banks will allocate emission rights among different entities via carbon trading schemes, similar to how governments allocate emission rights to power plants. This interconnected regional emissions trading scheme can play a vital role in effectively reducing regional emissions and ensuring the achievement of economic and global warming targets (Hameed et al., 2023).

The results of this study and the insights from the workshops underscore the critical role of carbon trading in achieving emissions reduction and economic growth in the power sector. The study provides a robust framework for policymakers and industry leaders in the Malaysia, Philippines and across Southeast Asia to adopt and scale up innovative climate solutions. By leveraging regional cooperation and international support, ASEAN countries can significantly enhance their climate resilience and sustainable development trajectories.

5. Comparison of Case Studies and their Implications

The results indicate that both Malaysia and the Philippines need to install more renewable energy capacity to meet their emission reduction targets. Subsidies and investments should also be channelled to renewable energy sector. ASEAN regulators should develop an effective transmission and distribution network to ensure a steady flow of capital into renewables, emphasising the critical need for a robust infrastructure to support this transition from fossil fuels to renewables. Decommissioning old, emissions-intensive plants is crucial to increasing the generation share of renewable energy and avoiding capacity payments linked to standby fossil plants. Stakeholder workshops endorsed some of our findings. For instance, in Malaysia, it is currently economically infeasible to convert biomass from the palm oil industry into power, leading to its export to Japan. The model predicted no utilisation of this biomass until at least 2038, validating workshop discussions. Additionally, fossil subsidies were identified as a hindrance to renewable expansion. Improved FiT systems in Malaysia the Philippines could attract more investments in the renewable power sector, aligning with model predictions.

From a technical standpoint, both regions face the challenge of balancing fossil dependence with renewable energy adoption. For Malaysian case study, optimisation results indicate the importance of carbon pricing and trading in promoting cleaner technologies. Carbon trading significantly favours renewable energy over CCS and NETs, generating additional revenue and encouraging cleaner power generation. Malaysia aims to increase the renewable share in installed capacity to 70% by 2050. People from palm industry argued that Malaysia lacks the technology that convert biomass (PKS) to bioelectricity, and it is expensive to import this technology. Therefore, it is an open research and innovation project within Malaysia. Different discussions mentioned hydrogen as important future technology for Malaysia (Sustainable Energy Development Authority, 2021). On the contrary, the Philippines must limit CCS / CCUS implementation due to geographical constraints but can expand solar and wind energy. High deployment of afforestation is sometimes not possible (currently Philippines has 21 Mt CO₂/y capacity of carbon sinks, which adds up to 630 Mt for next 30 years in case the capacity remains constant, which is unlikely) (Climate Action Tracker, 2023). Therefore, the Philippines should also look to implement NETs other than afforestation and CCS / CCUS (such as using bamboo, etc.). Considering the geography of Philippines, the country should look to floating wind turbines (many projects are planned but none of them is currently operating) as well (as suggested in the workshop) (Buljan, 2023). Detailed and clear expansion plans are essential for both Malaysia and the Philippines to achieve their renewable energy and decarbonisation goals.

From policy perspective, results highlight that Malaysia needs to reduce fossil subsidies and enhance carbon trading mechanisms, encouraging the investors to invest in low-carbon technologies. Malaysia plans to achieve 41% renewable share in installed generation capacity by 2040 and 70% by 2050, and this target should be translated to share in power generation. Decommissioning fossil-based plants and increasing renewable energy capacity are pivotal to sustainably achieve lower emissions and higher profits. Malaysian NETR and workshop discussions emphasise biomass utilisation and CCS, given that enough financial incentives are in place, aligning with optimisation results. The Philippines, however, struggles with slower progress in low-carbon legislation and requires substantial foreign aid and investments. The Philippines aims to achieve 50% renewable share in power generation, and this policy should be reflected by putting forward a clear plan with implementation deadlines. Setting clear net-

zero targets and implementing improved FiT and market-based mechanisms like carbon trading are crucial for generating revenue and reducing reliance on international support. Manila's workshop highlighted the urgency of decarbonising electricity sector and promoting afforestation as a critical NET (requiring policy legislations to tackle deforestation), reflecting the model results. However, the reliance on afforestation is not enough and renewable expansion is inevitable.

Engagement with stakeholders via workshops helped a lot in developing a sound discussion around results. The model analysis and stakeholder workshops have been instrumental in showcasing and understanding the differences and similarities between the two regions. In Malaysia, workshops highlighted the economic potential of advanced decarbonisation technologies and the need to re-allocate fossil fuel subsidies towards carbon trading and low-carbon technologies. Feedback from stakeholders pointed out practical challenges (linked to implementation of policies), such as the economic infeasibility of using PKS biomass for electricity generation (validated by the model results). For the Philippines, workshops stressed the development of aggressive climate mitigation (rather than climate adoption) policies and international cooperation to achieve decarbonisation goals, with discussions highlighting the need for detailed expansion plans and the significant role of afforestation post-2038. For example, models failed to achieve 50% renewable power generation by 2040 (for Philippines) with the available data. Some views on CCS in the Philippines' workshops were validated by our optimisation results showing the feasibility of minimal CCS deployment. Both workshops emphasised the role of carbon trading in promoting renewable energy and reducing emissions, providing a clear pathway for policy refinement and implementation in both countries.

In conclusion, while Peninsular Malaysia and the Luzon grid in the Philippines share common challenges in transitioning to a low-carbon energy sector, their technical and policy approaches differ significantly. Malaysian strategy of enhancing renewable energy capacity share and still relying on fossil subsidies contradict each other, while the Philippines need clearer policy direction and substantial foreign support. Other ASEAN countries who have pledged their net-zero targets should facilitate the Philippines in setting up its net-zero target. The model analyses, complemented by stakeholder workshops, have been crucial in helping us understand the dynamics of the power sectors of Malaysia and the Philippines, and offer tailored recommendations to enhance each country's decarbonisation efforts.

6. Project Limitations

Because of time constraints and limited resources, various potential ideas and improvements could not be realised. This led to some limitations in our work. However, work may be continued on integrating these ideas and removing these limitations should we be successful in obtaining additional funding in the future. The limitations are listed as follows:

- Project limitations mainly revolve around the data as it changes with the time depending upon the varying local conditions and the international affairs.
- Uncertainties have not been incorporated in our work. Detailed sensitivity analyses and optimisation under uncertainty should be performed to see the impact of different parameter values.
- Pre-installed energy technologies (power plants) are not considered in this work, and the plants always pay capital costs in the initial time-period.
- ASEAN countries are enhancing their power generation installed capacities rapidly and capacity payments will be playing their significant part in the future, but the model does not consider these payments.
- The MINLP formulation introduces various optimisation-related complexities such as infeasibilities and accurate initialisation, which may be challenging for non-specialist users and may result in some solutions not being globally optimal.
- The developed approach and the model are quite adaptable to the developing nature of emerging economies (such as ASEAN and ODA-eligible nations), but to extend their utilisation to other ASEAN countries, local data is required.
- More technical insights could be added into the model, but it may make optimisation computationally more expensive (more constraints and variables). It may also lead to changing the proposed approach.
- The model has very high degrees of freedom; more constraints and technical insights are required to make the model computationally less demanding.
- This study does not cover all the aspects of power sector management such as varying demand (depending upon the consumers' response, time of the day and the season), energy efficiency, energy conversion, energy storage, transmission costs, transportation and storage of fuels, etc.
- Consumers' behaviour is an important factor for emission reduction. They can opt to consume energy when renewable energy is injecting power into the grid. This aspect is also lacking in the model.
- A time-period in the developed model does not account for seasonal variations in power demand. The model can be discretised into more time domains (time of the day i.e., peak and off-peak time, seasons, etc.) to capture consumers' response (i.e., demand profile) effectively. This can lead to integration of dynamic electricity pricing within our models. Currently, our MINLP model can only predict average electricity prices (over a considered time-period within planning horizon).
- The role of energy subsidies is not considered in this work. We may work on it in the future to see the impact of subsidies on decarbonisation efforts.
- Reliance of the Philippines' future decarbonisation strategy on foreign support make the country's emissions reduction pledges highly conditional. The outputs of our case study may possibly be different than the Philippines' future aspirations and policies because we will not be directly considering the support from developed countries to decarbonise the electricity sector of the Philippines.

- The Philippines' government envisions CCS, while the IEA and ADB report say that CCS is not feasible for the country because of its geography, therefore, we have shown the cases which include both high CCS and low CCS use.

After securing further funding, we will try to improve our models and remove the mentioned drawbacks. Another research direction includes a bi-level extension of developed decision-making frameworks. Such a formulation will allow the game theoretic interplay between government and industry to be modelled with more nuance. The challenge will then be how to solve the model (even bi-level LPs are NP-hard).

7. Potential Next Steps

We will continue to improve the basic limitations linked to power generation planning within developing countries (such as the inclusion of capacity payments and considering pre-installed power plants, etc.) to make our decision-making tool adaptable to the emerging nature of ASEAN economies without additional funding. We will develop and propose a detailed plan for Philippines net-zero by 2060 target. Another critical next step after the conclusion of this RIDA project is establishing sustainability of the project, through seeking future funding schemes to build long-term collaborations and extend the impact of the project. Our team has contacted the PR (public relations) and research advertisement team of the University of Surrey, and we plan to post our activities on social media and other news platforms (such as the university’s website). Through the publication of papers and dissemination activities, we are hopeful that we can secure future funding and interest from other universities and governments in ASEAN. Moreover, we are developing an electronic-brochure (e-brochure or mini-website) for the developed software / models, and we will advertise it via various social media platforms. Also, we are organising the final hybrid workshop at the University of Surrey under this RIDA project and in collaboration with Institute of Advanced Studies where we will try to engage some funders and UK government in addition to relevant stakeholders (industrialists, academics and policymakers from the governments and research institutions of ASEAN countries).

This project has laid foundations for long-term collaboration and the partners’ belief in the quality of the research. Potential for future funding schemes is a key driver behind this RIDA project (this project is already an extension for DECO2 project related to ASEAN countries, which shows its potentially sustainable nature). Through the project, we were able to secure additional Research England ODA funds to support our activities and research. With this additional funding, we delivered a seminar / workshop at Swinburne Institute of Technology Sarawak Campus, Malaysia. We were also able to hire an additional research assistant to help us with Philippines’ case study for the RIDA project. This additional fund also helped us to invite some speakers from universities other than partner institutes in Kuala Lumpur workshop, and we offered travel bursaries to people travelling to Kuala Lumpur to attend one of the workshops held in ASEAN region.



Figure 28. Highlights from the Workshop in Kuching, Sarawak

Beyond additional technical outputs, the software has impact innovation potential as a policymaking toolkit for decarbonisation strategy for industries, individual companies,

regional cooperations or local and national governments. The partnership-strengthening collaboration opportunities ensures the long-term collaboration between partners, and all partners are already discussing to move this collaboration (on RIDA and other potential projects) forward. Several funding schemes could be sought due to the multi-national research collaboration. In the UK several schemes are available. International Science Partnerships Fund (ISPF) may be sought to spread our activities in ASEAN countries other than Malaysia and Philippines. The research falls clearly within the Global Challenge Research Fund (GCRF), by addressing challenges in ASEAN countries and UN SDGs. Additionally, UKRI EPSRC funding will be available, as a core remit of theirs is energy and computation. The UK–ASEAN Catalytic Green Finance Facility (ACGF) Trust Fund from UK and Asian Development Bank (ADB) may also be leveraged to enhance the impact of our on-going RIDA project. Bill & Melinda Gates Foundation may also potentially be used to transfer the impact of our work to the local people in an effective way. Moreover, PhD funding may also be applied for studying the complexities within carbon trading model using black box modelling and optimisation techniques. Master’s students may also be educated on developed software, and their ideas should also be integrated. A few MSc students (from University of Surrey and Swinburne University of Technology Sarawak Campus) are currently working on improving the software formulation and expanding its case-testing on other developing countries (such as Thailand and Mauritius).

In addition, our extensive consortium has additional collaborators in the USA, South Africa, China, Philippines, India, and Pakistan where additional funding opportunities may be sought to further engage the global research community with this project. There may be opportunities for nations with more developed decarbonisation strategies and lower carbon intensities (e.g., UK and USA) willing to fund research and development activities carried out in ODA-eligible nations such as Philippines, Malaysia, Pakistan, India, Thailand, etc., to improve development, quality of life, and decarbonise imported products, while contributing to UN SDGs.

Team

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Appendix A

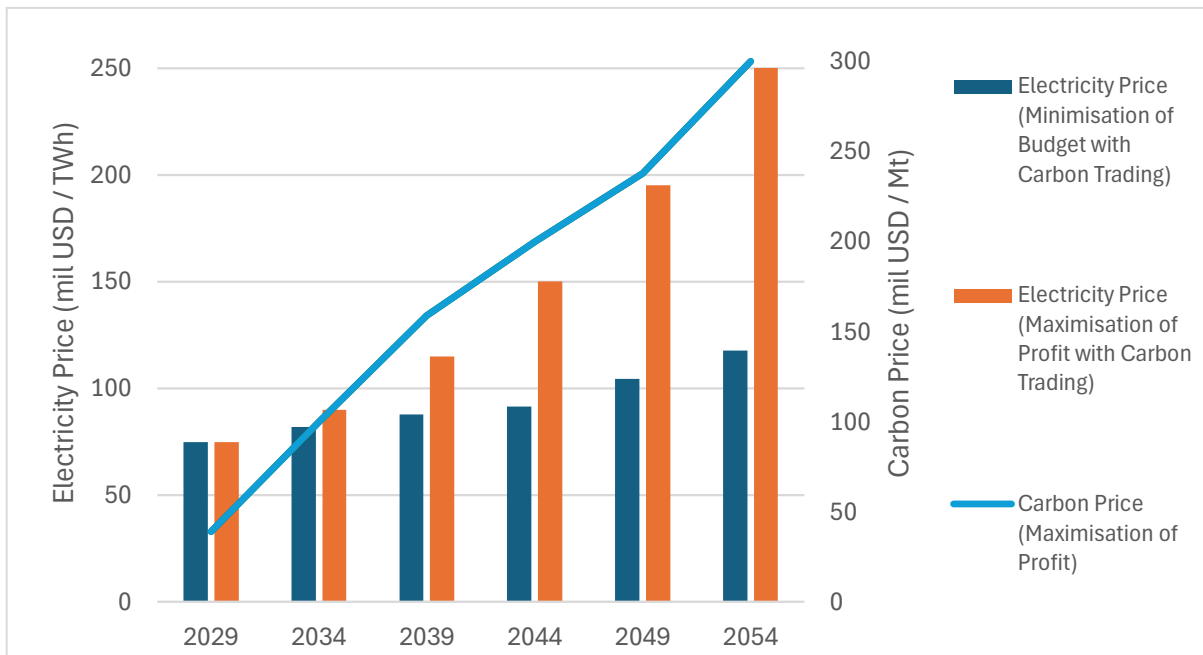


Figure A1: Electricity and carbon prices over the years for Malaysian case study