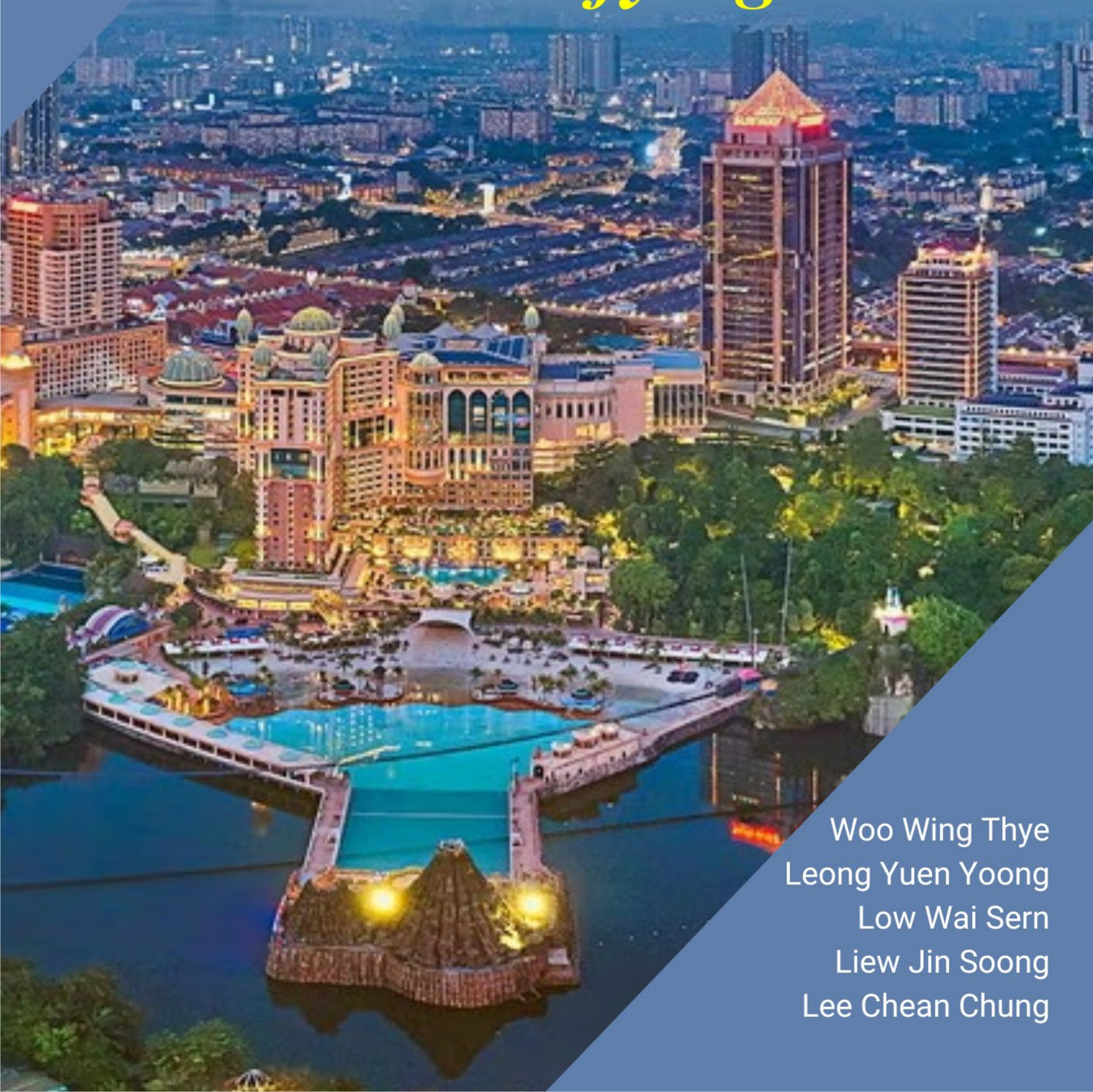
ASEAN Green Future Project Phase 2.2 Report

December 2024

Optimising Malaysia's *Electrifying* Future



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About ASEAN Green Future

ASEAN Green Future is a multi-year regional research project that involves the UN Sustainable Development Solutions Network (SDSN), Climateworks Centre and nine country teams from leading universities and think tanks across Southeast Asia (Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam). The researchers undertake quantitative and qualitative climate policy analysis and develop net zero pathways to inform policy recommendations and support the strategic foresight of policy makers.

The Phase 1 country reports present priorities and actions to date, and key technology and policy opportunities to further advance domestic climate action. The Phase 1 regional report positions Southeast Asia's low carbon transition pathways within a global context using the country reports and other studies. This series of reports, produced through a synthesis of existing research and knowledge, builds the case for advancing the region's climate agenda. Phase 2 of the ASEAN Green Future project uses modelling to quantitatively assess the different decarbonisation pathways for Southeast Asia.

Acknowledgements

The authors deeply appreciate the contributions of Dimas Fauzi, Uttam Ghimire, Charlie Heaps, Pimolporn Jintarith, Kuntum Melati and Silvia Ulloa, from the Stockholm Environment Institute (SEI). Since March 2023, SEI's dedicated training and mentorship have equipped ASEAN Green Future (AGF) researchers with the expertise to leverage the Low Emission Analysis Platform[1] (LEAP) and the Next Energy Modelling system for Optimisation (NEMO) for crucial tasks in greenhouse gas emissions mitigation assessment, power generation planning and scenario optimisation. Through this collaboration, AGF researchers have gained a common language, standardised tools, and a transparent platform that fosters seamless communication and collaboration across Southeast Asia. SEI's initial regional model served as a springboard, allowing AGF researchers to build upon this solid foundation and conduct independent analyses, fostering long-term sustainability in regional energy planning. This empowering shift reduces dependence on external expertise and empowers stakeholders to actively participate in the energy transition and contribute to informed decision-making.

The authors express their gratitude for the invaluable contributions of Wang Xiaofei (Global Energy Interconnection Development and Cooperation Organization), Sam Friggens (independent consultant and technical specialist in energy transition, infrastructure, and climate change), and Dr. Goh Chun Meng (UN Sustainable Development Solutions Network, Asia Headquarters, Sunway University).

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Disclaimer

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Cover Description

万里盛世叹朝暮，遥想当年开垦苦。
辛培人杰百年树，年年岁岁杏坛处。
~ 吴俊霖

[1] Heaps, C.G., 2022. LEAP: The Low Emissions Analysis Platform. [Software version: 2020.1.107] Stockholm Environment Institute. Somerville, MA, USA. https://leap.sei.org

CONTENTS

List of Figures

List of Tables

EXECUTIVE SUMMARY

The ASEAN Green Future (AGF) initiative, a multi-year regional research project led by the UN Sustainable Development Solutions Network (SDSN) and Climateworks Centre, is charting pathways for Southeast Asia to achieve net-zero emissions aligning with the Paris Agreement's goal of limiting global warming to well below 2°C. This collaborative effort unites nine country teams from universities and think tanks across the region.

PHASE 2: DEEPENING DECARBONISATION ANALYSIS (2022-2024)

Following the successful completion of Phase 1 in 2021, AGF's Phase 2 research focuses on three key areas:

1. **Comparative policy scenarios:** This segment explores the impact of existing policies and more ambitious policies through simulations.

2. **Near-zero power policy optimisation:** Utilising optimisation models, AGF researchers develop pathways for achieving a near-zero emissions power generation sector.

3. **Regional power interconnection analysis:** This research investigates the role of regional transmission line interconnection in facilitating decarbonisation across Southeast Asia.

Building on the strong foundation laid in the AGF-Malaysia 2.1 report (Woo, et al. 2023), this report focuses on Area 2.

Purpose of modelling

This report builds upon the Malaysian government's recent decarbonisation policies and roadmaps, including the National Energy Transition Roadmap (NETR) (2023), National Biomass Action Plan 2023-2030 (2023) and the Hydrogen Economy and Technology Roadmap (2023). It leverages energy sector modelling to assess the effectiveness of these existing policies in achieving a near zero emissions power generation sector for Malaysia. In essence, the modelling serves as a tool to:

- Evaluate policy sufficiency: Determine whether current policies are sufficient to drive the necessary decarbonisation within the power generation sector.
- Identify potential gaps: Identify any potential gaps or areas where existing policies might not be enough to achieve the desired emissions reduction goals.
- Inform policy decisions: Provide insights and data to inform future policy decisions and ensure a successful transition to a near-zero emissions power generation sector.

Scope of modelling

This study leverages two leading energy modelling and optimisation tools from the Stockholm Environment Institute (SEI): The Low Emission Analysis Platform (LEAP) and the Next Energy Modelling System for Optimisation (NEMO). These tools are combined to construct a comprehensive model of the Malaysian power sector, encompassing:

- Supply: power generation sector
- Demand: transportation, industry, residential, and commercial sectors

This integrated approach allows the power sector model to inform and support the decarbonisation of the broader energy system and economy. The model incorporates assumptions regarding growth rates, electrification (such as electric vehicle uptake), and energy efficiency improvements within the demand sectors. It is important to note that the cost optimisation scope is confined to the power generation sector itself and does not encompass potential trade-offs with other abatement options in the wider economy.

Scenarios modelled

The model explores least-cost pathways for power generation under three scenarios:

- **Existing Policy (EP):** Simulates power generation and demand based on current policies.
- **Optimised EP:** Identifies power generation mix with the lowest financial cost path within existing policy.
- **Optimised More Ambitious Policy (OMAP):** Examines the least-cost path under more ambitious emissions reduction targets for both demand and generation:
  - **Demand-side efficiency:** This strategy prioritises reducing overall electricity consumption through efficiency measures in the demand sectors.
  - **Decarbonised generation:** This approach focuses on transitioning the power sector towards clean energy sources with low carbon emissions, i.e. 100% renewables. Two key assumptions are incorporated into the model:
    - **No new fossil fuel capacity additions after 2030:** This policy restricts the construction of new power plants reliant on fossil fuels.
    - **Phased retirement of fossil fuels:** Assumes a complete coal phase-out by 2030, followed by natural gas and diesel by 2050.

Rationale for scenario selection

The scenarios presented in this report were carefully chosen to achieve three key objectives:

- **Evaluate current policies:** The scenarios assess the effectiveness of existing policies in achieving energy and environmental goals.
- **Optimise power generation:** One scenario focuses on optimising the power generation sector within existing policy frameworks, aiming for the most cost-effective approach.
- **Optimise more ambitious power generation pathway:** An additional scenario explores a more ambitious policy approach, showcasing potential outcomes for Malaysia.

Relation of these scenarios to the National Energy Transition Roadmap (2023)

The following elements were incorporated into the model:

- **Projected capacity mix:** The model utilised the projected power system installed capacity mix outlined in the NETR for the period 2025-2050 under the Existing Policy scenario.
- **Key targets:** Key targets established in the NETR for energy efficiency, renewable energy, hydrogen, bioenergy, and green mobility were integrated into the model as assumptions under the Existing Policy scenario.

Interpreting model results for policy recommendations (2019-2050)

The analysis examines model results across several key dimensions to inform policy recommendations for achieving a near-zero emissions power sector in Malaysia. These dimensions include:

- **Future power generation mix:** This analysis explores the potential evolution of the power generation sources over the modelling timeframe.
- **Greenhouse gas emissions:** The model quantifies the impact of different scenarios on greenhouse gas emissions, allowing for a comparison of their effectiveness in achieving decarbonisation goals.
- **Investment needs:** The model assesses the investment requirements associated with various power generation capacity configurations, informing cost-effective pathways for the transition.
- **Electricity production costs:** The economic implications of different generation pathways were evaluated through electricity production cost analysis, highlighting potential cost fluctuations across scenarios.
- **Social costs:** The model considered potential social costs associated with various power generation options, ensuring a well-rounded assessment of different pathways.

Additionally, external factors were examined to explore key decarbonisation pathways. This included assessing the potential for accelerated deployment of renewable energy such as solar and supporting technologies, which could potentially reduce reliance on natural gas as a bridging fuel.

Based on these comprehensive analyses, specific policy recommendations are presented to guide Malaysia's transition towards a near-zero emissions power sector.

Limitations and considerations: sensitivity and resilience analysis

Energy sector modelling results are inherently dependent on input assumptions, such as future technology costs, resource availability, and fossil fuel prices, all of which are subject to considerable uncertainty. While this study provides valuable insights into potential decarbonisation pathways for Malaysia's power sector, it did not conduct sensitivity analyses to assess the impact of these uncertainties. Such analyses could explore, for example, cost variations across scenarios, fluctuations in the technology mix, or the interplay of solar and hydro availability—as shown by their respective availability curves— with electricity demand patterns throughout the year, especially considering Malaysia's two monsoon seasons.

Sensitivity analysis is crucial for informing resilience analysis, which provides a more robust and insightful assessment of long-term energy strategies. Due to the inherent uncertainties surrounding future developments, interpreting the modelling results for least-cost pathways and optimal technology or resource mixes requires caution. It is essential to consider the resilience of different pathways in the face of potential disruptions. For instance, pathways heavily reliant on hydropower or biomass could be more vulnerable to climate change impacts, such as droughts, potentially leading to poorer energy services or unexpected cost increases. Similarly, pathways that appear cost-effective under baseline assumptions might not be as economical under different circumstances, such as significant fossil fuel price spikes.

This study did not include this type of in-depth resilience analysis. However, such considerations are essential when framing and presenting the results, as well as when developing policy recommendations. Future research should incorporate both sensitivity and resilience analyses to provide a more comprehensive and robust understanding of how key results might vary under a wider range of future possibilities and inform more resilient policy decisions.

RESULTS: EXISTING POLICY AND ITS OPTIMISED SCENARIO

- **Future power generation mix:**
  - **Solar PV:** The optimised scenario strategically reduces projected solar capacity from 72.3 GW to 56.3 GW (NETR target) in 2050 while maintaining the generation factor (1.3 TWh/GW).
  - **Dispatchable low-carbon generation:** Optimisation prioritises efficient use of existing renewable capacity.
    - **Large hydro[2]:** Significant capacity reduction (-28%; from 13.1 to 9.5 GW) but a surprising increase in generation (+11%; 76.0 to 84.1 TWh) due to improved utilisation (generation factor jumps from 5.8 to 8.9 TWh/GW).
    - **Small hydro[3]:** Similar to large hydro, a capacity decrease (-67%; from 2.0 to 1.2 GW) is offset by a slight decline in generation (-7.7%; from 11.7 to 10.8 TWh) and a significant rise in generation factor (5.9 to 9.0 TWh/GW).
    - **Biomass:** This sector faces the most significant decrease in both capacity (-45%; from 1.8 to 1.0 GW) and generation (-77%; from 9.6 to 2.2 TWh). Generation factor decreases from 5.3 to 2.2 TWh/GW. Further investigation is needed to understand the cause and potential mitigation strategies.

[2] >30 MW (https://www.energy.gov/eere/water/types-hydropower-plants)
[3] 100 kW – 30 MW (https://www.energy.gov/eere/water/types-hydropower-plants)

    - **Biogas:** Shows promise with a slight decrease in capacity (-28%; from 0.8 to 0.6 GW) but an increase in generation (+9.8%; from 4.4 to 4.8 TWh) and a substantial jump in generation factor (5.5 to 8.3 TWh/GW).

  - **Natural gas:** The optimised scenario proposes a significant increase in natural gas capacity, exceeding NETR targets by almost two times. While generation increases, a decline in the generation factor (from 5.5 to 5.0 TWh/GW) suggests potential overcapacity. Thus, a cost-benefit analysis of the proposed natural gas capacity increase should be conducted.

  - **Firm power - high carbon:** Optimised policy aligns with NETR targets, phasing out coal and diesel by 2050.

- **GHG emissions:**

  - The Optimised Existing Policy offers a more promising path towards decarbonisation. It achieves a **11% reduction in power generation emissions in 2050 compared to Existing Policy,** and at a **lower cost** (15% lower cumulative investment by 2050).

  - However, neither scenario reaches the goal of near-zero emissions, highlighting the need for more ambitious policy measures.

- **Regional considerations:** Malaysia's Existing Policy and Optimised Existing Policy scenarios fall short (25%) of the ASEAN Plan of Action for Energy Cooperation (APAEC) target of 35% renewable energy capacity share by 2025.

- Overall, the optimised scenario prioritises cost-effective and efficient use of existing renewable resources. Further investigation is needed for biomass and careful consideration is required for the proposed natural gas expansion.

RESULTS: MORE AMBITIOUS POLICY AND ITS OPTIMISED SCENARIO

- More Ambitious Policy brings about a 6% reduction in electricity consumption in the demand sectors in 2050 compared to Existing Policy.

- **Future power generation mix:**

  - **Solar PV**: Dramatic increase projected (81.0 GW by 2050), exceeding NETR target (56.3 GW) by 44%. This translates to a projected solar PV generation of 105 TWh, exceeding the 74 TWh projected under Optimised Existing Policy by approximately 42%.

    Within a least-cost optimisation framework, storage costs may become a hurdle for further solar expansion. This implies that future cost reductions in battery storage could lead the optimised solution to favour even greater solar adoption.

    Recent work by Weber et al. (2024) shows that Malaysia can achieve a 100% renewable energy grid through solar and pumped hydro. Pumped hydro storage is the lowest cost long term storage method and is available off-the-shelf on a large scale.

  - **Dispatchable low-carbon sources:**
    - **Large hydro:** Increased capacity from 9.5 GW (Optimised Existing Policy) to 13.6 GW (+44%), with generation rising correspondingly from 84.1 TWh to 120.7 TWh (+44%). This significant increase in large hydro development warrants further environmental impact assessments.

    - **Small hydro:** Increased small hydro development, with capacity increasing from 1.2 GW (Optimised Existing Policy) to 4.2 GW (3.5x), and generation rising proportionately from 10.8 TWh to 37.5 TWh (3.5x). This suggests that greater consideration should be given to small hydro power development.

    - **Biomass:** Biomass power generation is poised for a dramatic expansion, from 1.0 GW (Optimised Existing Policy) to 23.9 GW (a 24-fold increase) by 2050. This translates to a 57-fold rise in annual generation, from 2.2 TWh to 125.2 TWh. To ensure this growth is sustainable, a comprehensive land-use study is essential.

      Developing dedicated, sustainable tree plantations for multiple uses, including bioenergy, offers a strategic solution. Scaling up biomass supply must be incremental and evidence-based, integrated within a broader land-use strategy. This approach should consider factors like carbon storage, avoided emissions, biodiversity, soil health, water resources, and land rights. Ultimately, a sustainable biomass industry fosters social and political acceptance, leading to long-term viability.

    - **Biogas:** Modest increase in biogas capacity from 0.6 GW (Optimised Existing Policy) to 0.7 GW (+17%). Generation decreases slightly from 4.8 TWh to 4.2 TWh (-13%). While biogas may not significantly increase renewable power generation capacity, its primary benefit lies in its ability to close the natural carbon loop. This offers a range of advantages, including avoided emissions, boosting bio-energy production, improving soil fertility, enhancing agricultural productivity, and strengthening farmers' economic resilience.

- **Costs:**
  - Higher generation costs in 2050 (10.6 US cents/kWh) compared to the Existing Policy scenario (8.8 US cents/kWh).
  - Long-term benefits: Improved health, energy security, and potential cost savings with carbon pricing.
  - Accounting for the social cost of carbon strengthens the case for the Optimised More Ambitious Policy. As the social cost increases, this policy becomes significantly more cost-effective compared to Existing Policy and Optimised Existing Policy, primarily due to its substantially lower emissions.
- **GHG emissions:**
  - Dramatic reduction by 2050 (2 $MtCO_2$-eq) compared to Existing Policy (108 $MtCO_2$-eq) and Optimised Existing Policy (96 $MtCO_2$-eq) scenarios.
  - 98% of Malaysia's overall energy sector GHG emissions remain outside the power generation sector in the Optimised More Ambitious Policy scenario in 2050. Decarbonisation across all sectors requires additional strategies beyond greening the power grid. Industries and transportation, in particular, pose a challenge due to the difficulty of electrifying certain processes and vehicles. This underscores the critical need to develop and increase the share of green hydrogen, biomethane, and bio-LNG used in these sectors to achieve comprehensive decarbonisation.
- **Ambition vs. reality:** The projected 2025 renewable capacity share (30%) falls short of the aspirational ASEAN target (35%). Further policy refinements may be needed for faster renewable development.
- **Storage needs of 100% renewable electricity:** Analysis suggests Malaysia needs 1.96 GWh of storage per million people for 100% renewable electricity, significantly lower than advanced economies (20 GWh/million) due to differing energy landscapes (Blakers, Lu, et al. 2022). However, as variable renewables increase, storage needs will rise. Studies suggest a minimum of 8 hours of discharge time (Silverstein 2024), with some projections reaching 120 hours of discharge time in the US (Carrie 2022). Malaysia's relatively stable climate means that the energy storage needs are likely to be less extensive than in regions with more pronounced seasonal variations.

POLICY RECOMMENDATIONS FOR THE POWER GENERATION SECTOR: INSIGHTS FROM MODELLING

Power generation

- The current strategy of relying on natural gas as a "bridge fuel" for reliable baseload power generation necessitates a comprehensive re-evaluation. To expedite a more cost-effective and environmentally sustainable energy transition, a strategic shift from planned natural gas power plants towards expanded solar power generation and energy storage solutions merits serious consideration. This approach leverages the ongoing advancements and cost reductions within the renewable energy sector, particularly solar.
- Given its vast potential, affordability, and key role across all conceivable energy transition pathways, unlocking solar power's full potential is paramount. This necessitates coordinated action on multiple fronts, including storage technologies, grid upgrades, and

targeted investments. Beyond cost considerations, the choice between solar and natural gas has significant implications for Malaysia's energy independence, energy security (as measured by import dependency), and overall balance of trade.

- The backbone of the global energy transition is electrification, energy efficiency, solar, wind, storage and grid. Policymakers should explore incentives and funding mechanisms to accelerate the development of grid infrastructure capable of integrating a growing share of variable renewable energy sources.
- Biomass power holds promise as a significant contributor to achieving a 100% renewable energy grid in Malaysia. However, to fully understand its long-term viability, a comprehensive assessment of its future sustainable potential is necessary. This includes sustainable biomass supply assessment and a comprehensive land-use study and supply chain analysis. This will be crucial to ensure the long-term environmental and financial viability of biomass power in Malaysia. By integrating these studies with a broader land-use strategy, Malaysia can ensure that biomass expansion is grounded in sustainability principles. This strategy should consider carbon stocks, avoided emissions, biodiversity, soil health, water requirements, and land rights. A comprehensive approach that incorporates these considerations will enable Malaysia to harness the potential of biomass power while mitigating potential environmental and social risks.
- Malaysia possesses significant, under-utilised potential for animal waste-based biogas production. It is a multi-faceted solution that enables circular waste management, methane emission reduction, water purity protection and poverty alleviation. Further investment and policy support for biogas development should be considered.

Storage

- **Pumped storage hydro (PSH) offers a significant advantage:** It is a well-established, cost-effective long-term storage solution readily available for large-scale implementation.
- **Hybrid PSH-battery systems:** Leverage the strengths of PSH (long-term storage) and batteries (short-term flexibility) for a robust grid.
- **Implement best practices for PSH development:** Utilise international recommendations for efficient and cost-effective PSH projects.

Transmission lines and interconnections

- The cheapest way of decarbonising the power sector in Malaysia requires a coordinated Southeast Asian regional approach, which enhances resource sharing, cost savings, efficiency, smart material use and reliability of supply.
- **Strategic transmission line expansion:** Prioritise connecting renewable energy zones to load centres and modernise existing grid infrastructure for integrating variable renewable sources.
- **Moving beyond simply increasing capacity:** Identify interconnections that offer the greatest long-term benefits in terms of cost effectiveness, environmental impact and grid stability.
- **Consider two planning horizons** for a comprehensive and adaptable strategy for regional power interconnection:
    - **Long-term vision:** Ultra-high voltage (UHV) direct current (DC) backbone grid with significantly higher capacity (e.g., 1000 kV) compared to the existing 230 kV or 500

kV AC lines. This could transform the region by enabling efficient transmission of large-scale renewable energy across vast distances.

- **Near-term optimisation:** Optimise the current ASEAN Power Grid plan while laying the groundwork for future integration with a potential UHV DC grid.

BROADER ENERGY TRANSITION RECOMMENDATIONS: BEYOND THE POWER GENERATION SECTOR

Transport

- **Shift freight to rail:** Increase rail's modal share through targeted incentives and improved regional connectivity.
- **Biofuel production:** Mandate biofuel blending and support small biogas producers for biomethane and bio-LNG production.

Industry

- **Electrify industrial processes:** Ensure affordable renewable energy to incentivise adoption of electric heating.
- **Reduce demand for carbon-intensive materials:** Promote circular economy measures like material substitution and product reuse/recycling.
- **Implement energy efficiency measures:** Execute NETR's energy efficiency plans and consider carbon pricing as a potential tool.
- **Accelerate digital transformation and sustainable data centre development:** To drive efficiency, sustainability, and innovation across various industries, Malaysia should continue to prioritise digital transformation and the development of sustainable data centres. By leveraging data centres, the country can: (Adriana 2024)
    - Enhance operational efficiency: Optimise supply chains, enable remote work, and streamline business processes
    - Drive innovation: Foster the adoption of artificial intelligence, machine learning, and other advanced technologies
    - Reduce carbon footprint: Promote energy-efficient data centre design and operations, and encourage the use of renewable energy sources.
- **Prioritise advanced nuclear technologies:** Advanced nuclear reactors can provide high-temperature heat, enabling the decarbonisation of energy-intensive industries like chemicals and refining.

Commercial and residential sectors

- **Increase energy efficiency targets:** Expand building energy codes, green building standards, and appliance efficiency programs.
- **Encourage behavioural changes:** Promote actions like raising air conditioner temperatures and adopting energy-efficient appliances.

1. MALAYSIA'S DECARBONISATION RELATED POLICIES AND ROADMAPS: 2023 AND BEYOND

In 2023, the Malaysian government unveiled a wave of decarbonisation policies, including the National Energy Transition Roadmap, Hydrogen Economy and Technology Roadmap, and the National Biomass Action Plan. This review dissects these key documents through the lens of their support for maximising renewable energy generation in Malaysia.

National Energy Transition Roadmap (NETR)

NETR sets two ambitious targets: a 70% renewable energy share by 2050 and a moratorium on new coal power plants.

- NETR seeks to curb emissions through six key levers: energy efficiency, renewable energy, hydrogen, bioenergy, green mobility, and carbon capture, utilisation, and storage (CCUS).

- Leveraging the natural retirement of existing facilities and a ban on new construction, coal-fired generation is projected to nearly disappear by 2045 (Figure 1).

- Natural gas has been positioned as a "bridge fuel" for baseload power generation in the NETR. However, its ongoing greenhouse gas emissions, estimated at 490 gCO_2-eq per kWh, necessitate a critical re-evaluation of this strategy. While fuel cost and energy security remain important considerations, the long-term sustainability of relying on a fossil fuel, particularly given Malaysia's growing import dependence (approximately 25% of gas needs in 2023) (Malay Mail 2024), necessitates a more expeditious transition towards cleaner energy sources.

- Although Figure 1 depicts a relative decrease in natural gas capacity by 2050, closer examination reveals an absolute capacity increase from 26 GW (2035) to 30 GW (2045), highlighting the need for a more ambitious decarbonisation pathway.

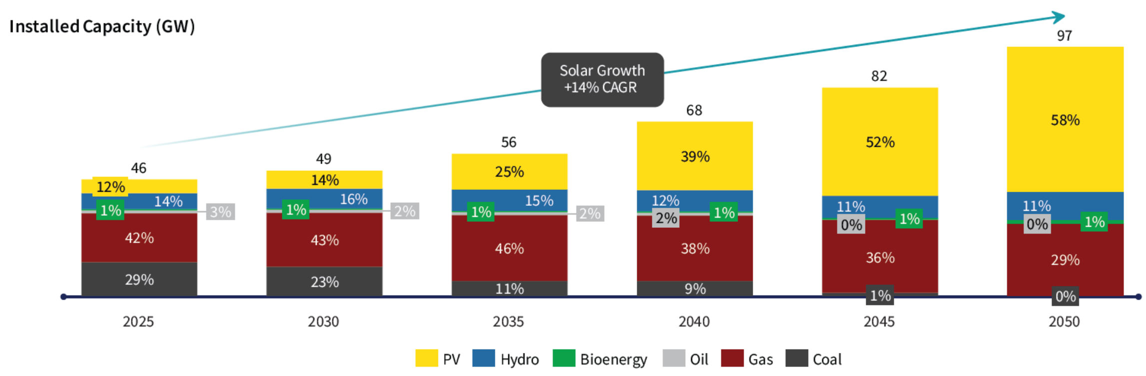

Figure 1: Projected power system installed capacity mix 2050 (National Energy Transition Roadmap 2023)

- Malaysia shares Southeast Asia's focus on natural gas as a crucial element of regional energy security. As outlined in the 2018 Gas Advocacy White Paper, ASEAN member states are collaborating to create a common gas market and foster regional communication, building infrastructure preparedness for the evolving energy landscape (ASEAN Centre for Energy 2020). This pursuit, however, presents a significant challenge: navigating a unique path towards a cleaner future while maintaining regional coherence.

- To integrate Malaysia's abundant variable solar power into the grid, increased storage and interconnectedness are crucial.

  - Three pillars support successful cross-border power systems: political will, technical standards, and robust institutions. While harmonised grid codes and regional operators are crucial, early progress hinges on political leadership and commitment, often formalised through memorandums of understanding (MoUs). (Hevia-Koch, et al. 2023)

  - The ASEAN Power Grid, for example, began with a 1997 MoU endorsing the project and setting its direction. More granular sub-regional agreements like the Greater Mekong Subregion's MoU and the Lao PDR-Thailand-Malaysia-Singapore Joint Statement followed, detailing implementation steps, objectives, timelines, and institutional frameworks.

- Additionally, focused development of dispatchable renewables like wood pellets could effectively replace coal for baseload power (Leong, Woo and Platts 2023).

  - Malaysia's Malakoff launched a biomass co-firing project in 2022, starting with a 0.5% trial burn. They plan to scale up gradually through pilot phases: 2% co-firing in 2024 and 3-5% in 2025, utilising primarily empty fruit bunch pellets and exploring other sustainable biomass alternatives. (The Edge 2024)

- According to 2019 data from the Energy Commission, Malaysia achieved a total installed biomass power generation capacity of 440.5 MW. This includes 70.65 MW from grid-connected power plants, contributing approximately 1.2% of the nation's total electricity generation. (Ministry of Plantation and Commodities 2023)

- To secure a cleaner energy future, Malaysia should prioritise a roadmap for transitioning uncontracted gas power plants and existing coal power plants to renewable energy. This phased approach, informed by case studies on replacing a gas power plant with renewables and converting a coal power plant to biomass, will unlock valuable insights and best practices for a smooth, cost-effective clean energy transition.

Green mobility ambitiously aims for an 80% share of electrified vehicles (4-wheelers and 2-wheelers) within the national fleet by 2050.

- This widespread electrification opens doors for cost-effective energy storage using EV batteries.

- By implementing Vehicle-to-Grid (V2G) technology, Malaysia can leverage these batteries to store surplus solar energy and inject it back into the grid during peak demand, simultaneously empowering EV owners to generate revenue. This has been successfully implemented in the United Kingdom.

Aspiring to generate 2.5 million tonne per annum (Mtpa) of green hydrogen by 2050, NETR prioritises hydroelectric and solar power sources.

- Global access to electrolysers is still limited, making them a significant cost barrier, as it represents a third of overall production expenses.

- To address this challenge, the Ministry of Science, Technology and Innovation (MOSTI) spearheads the development of domestic green electrolyser manufacturing capability. This initiative aims to both reduce electrolyser cost and improve their efficiency.

NETR's energy efficiency targets seem to fall short of the ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025.

- ASEAN aims for a 32% energy intensity reduction by 2025 based on 2005 levels (1.6% annual reduction) through market-driven efficiency improvements in buildings, transport, and industry.

- Malaysia's NETR target of 23% industrial/commercial energy savings by 2050 compared to the business-as-usual scenario translates to a 0.85% implied annual energy intensity reduction, falling short of the ASEAN target.

Hydrogen Economy and Technology Roadmap (HETR)

HETR identifies one fossil fuel source, i.e. natural gas, for producing blue hydrogen; and three renewable energy sources for producing green hydrogen – solar PV, hydropower, and bioenergy.

HETR recommends making blue hydrogen Malaysia's prime target in the short to long-term so that the country's sizeable oil and gas sector can be pivoted into the hydrogen economy.

- While leveraging existing expertise in the oil and gas sector has its advantages, prioritising blue hydrogen in the short to long term raises the concern about prolonging dependence on fossil fuels, which creates inconsistencies with the ambitious goals of the energy transition.

Promising potential lies in leveraging Malaysia's rich solar resources for green hydrogen production.

- However, a cautious approach is warranted to scrutinise essential elements like weather patterns, infrastructure for transporting and storing hydrogen, and market demand.

- A thorough investigation is necessary to ensure the presence of optimal conditions, including high solar irradiation, long term availability of water, mature and cost-effective solar PV technology, advanced and efficient electrolysers, and policy frameworks.

HETR points to the hydropower potential for green hydrogen in Sarawak. Whilst that is undeniable, pre-allocated electricity and ambitious industry plans necessitate exploring options for capacity expansion and responsible resource allocation.

- International industry heavy weights that are conducting feasibility studies in Sarawak to produce green hydrogen, green ammonia[4] and green methanol at a commercial scale are exploring production capacities that would require an electricity amount exceeding the expected electricity generation from the upcoming 1.285 GW Baleh dam by 3.2 GW[5]. (Liew and Leong 2022)

- Unlike hydropower, which can disrupt ecosystems, displace indigenous communities, and require lengthy planning and construction, solar power offers swift deployment and flexible placement on unused land. This minimises disruptions to existing communities and habitats, making it a more environmentally and socially responsible choice.

- Beyond traditional metrics like cost, allocating electricity in Sarawak also considers job creation potential and bidders' willingness to pay. Feeding electricity directly into industries creates 200 times more jobs per MW capacity compared to converting it to green hydrogen (based on industry input). (Leong 2022)

- Job creation tends to increase along the green hydrogen production chain, from upstream activities like hydrogen generation to downstream applications such as industrial use. This

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[4] The production of nitric oxides (NOx) during green ammonia synthesis poses a significant environmental challenge and necessitates the implementation of effective mitigation strategies.

[5] The Baleh hydro dam's (expected commission in 2026) capacity is 1285MW. Assuming Baleh's capacity factor is 71.41%:

- 71.41% of 1285 MW = 917.62 MW
- 917.62MW x 24h x 365 days / 1000 = 8038 GWh per year

Assuming electrolysers use 50kWh to produce 1kg of hydrogen, Baleh can produce up to 161k tonnes of hydrogen per year. Sarawak's hydrogen production plans add up to 560k tonnes per year. The gap of 399k tonnes per year would require another 3.2 GW of hydropower capacity to produce.

highlights a potential trade-off: prioritising industrial electrification for immediate job creation might limit the pursuit of longer-term sustainability goals achievable through green hydrogen development.

HETR's focus is on palm biomass combustion (2.3 GW) and biogas (550 MW) from palm oil mill effluent (POME) (Ministry of Science, Technology and Innovation 2023).

- The problem with the biomass thought track is that palm biomass needs to be returned to the land to feed the soil, and not combusted to produce electricity for water electrolysis. Doing otherwise will severely impact soil fertility and agricultural productivity (Platts and Leong 2020).

- While currently limited in scale, biogas production from palm oil mill effluent holds potential as a source of green hydrogen in Malaysia, especially for decarbonising hard-to-electrify sectors.

- While Malaysia boasts 451 operational palm oil mills (129 in Sabah and 84 in Sarawak) (MPOB), only 90 (primarily in Peninsular Malaysia) contribute biogas-based power generation to the electricity grid. This limited adoption stems from an unfavorable economic proposition. The feed-in tariff (FiT) for biogas remains low at RM0.28-0.32 per kWh, falling short of the base tariff in Peninsular Malaysia (RM0.3945 per kWh) and Sabah (RM0.3452 per kWh). For Sarawak, with a base tariff of RM0.315 per kWh, FiT does not even apply. Compounding this issue are the additional costs associated with grid connection, and the unfamiliar task of grid maintenance, which palm oil mills need to bear. The need for new infrastructure and expertise creates a significant financial hurdle, especially for mills further than 5km from existing grids, rendering electricity grid-based biogas utilisation financially unviable. (Leong 2022)

- Gas Malaysia is driving biomethane development within the country. The company's gas purchase agreements with palm oil mills and planned commissioning of additional biomethane projects mark an important step towards decarbonising the gas system. (Edge Invest 2023, The Malysian Reserve 2023)

  - Gas Malaysia has established gas purchase agreements with Sedenak Palm Oil Mill and Coronation Palm Oil Mill in Johor in 2023.
  - Processed biogas produced by these mills is being injected into the Natural Gas Distribution System (NGDS) network.
  - The Sedenak biomethane plant commenced commercial operations in June 2023.
  - Gas Malaysia plans to commission two more biomethane projects by the first half of 2024 to further contribute to the NGDS network.

- The optimal utilisation of this biogas at each facility necessitates a strategic evaluation of key factors. Established technology, rapid implementation, and existing infrastructure favour electricity generation, while processing biogas into bio-methane, bio-LNG and bio-hydrogen fuel offers higher revenue potential, broader market reach, and deeper decarbonisation impact on hard to electrify sectors.

- By carefully considering their unique circumstances and strategic goals, palm oil mills can choose the pathway that maximises their revenue and contribution to a sustainable future.

National Biomass Action Plan 2023-2030 (NBAP)

Returning plantation biomass and agriculture biomass to the land is crucial for maintaining soil fertility.

- The National Biomass Action Plan (NBAP) explores the potential of various biomass sources like plantation biomass, woody biomass, agricultural biomass, livestock waste, and fisheries waste. This diverse resource base collectively generates 183 million tonnes per year, with palm biomass being the dominant contributor (85%). The country has an estimated total of 5.67 million hectares of oil palm plantations, producing more than 90 million tonnes of dried palm biomass.

- According to NBAP, Malaysia produced 4.4 million tonnes of palm kernel shell (PKS) annually (p. 18), of which 1.25 million tonnes were exported in 2022 (p. 25) to key markets like Japan. The balance is likely to be used as boiler fuel by palm oil mills.

- According to NBAP, Malaysia generates a significant 7.3 million tonnes of empty fruit bunch (EFB) annually (p. 18). Current practices, as outlined by Sustainable Energy Development Authority (SEDA) Malaysia (2021), often involve allocating roughly half of this EFB for mulching purposes, while the remaining half is either disposed of or incinerated as boiler fuel. However, a concerning common practice in Southeast Asia is pile abandonment, where unused EFB are discarded around palm oil mills. This practice leads to unpleasant odours and methane generation due to anaerobic decomposition, posing environmental concerns.

- To promote sustainable EFB management, the Ministry of Plantation and Commodities could implement incentive programs that encourage palm oil companies to convert EFB into organic fertiliser. This initiative would not only address environmental concerns from pile abandonment but also potentially increase crop yields for palm oil companies by improving soil fertility. Furthermore, fertiliser production from EFB can help maintain the natural soil carbon cycle, even with a growing focus on biomass for renewable energy.

- NBAP (p. 18) indicates that Malaysia produces 7.3 million tonnes of empty fruit bunches (EFB) annually. Palm oil millers typically send half for mulching and dispose or incinerate the other half (SEDA Malaysia 2021). Pile abandonment of EFB around palm oil mills is a common practice in Southeast Asia, leading to environmental concerns like odour and methane emissions. To encourage the utilisation of EFB, the Ministry of Plantation and Commodities should consider incentive programmes to support palm oil companies in converting EFB into organic fertiliser. This will help to balance the drive to use utilise plantation and agricultural biomass for renewable energy production and reduce disruption of the natural soil carbon cycle.

- Most fisheries waste have found other value-added applications and is not seen as a potential source of bioenergy.

Tree plantations emerge as a promising source of biomass for producing wood pellets.

- **Solar vs. biomass footprint:** Biomass energy crops can require significantly more land (29-154 times) to produce the same amount of electricity compared to solar PV (Geyer, Stoms and Kallaos 2013). This highlights the importance of careful planning to minimise land-use impact when considering biomass energy.

- **Rehabilitation and renewal:** Replanting degraded or deforested land with biomass crops offers a dual benefit. It provides renewable energy while simultaneously contributing to ecosystem healing.

- **Sustainable biofuel option:** Pellets derived from sustainably sourced and harvested trees offer a renewable biofuel option for industrial applications, promoting energy security and potentially reducing reliance on fossil fuels.

- To encourage this approach, the Ministry of Plantations and Commodities provides soft loans for tree plantations. Despite receiving RM914 million in soft loans, Malaysian tree planters are plagued by labour and profitability issues, and most do not achieve financial sustainability (Law 2022).

- Malaysia's tree plantation companies struggle with outdated regulations and governance systems initially designed for natural forest logging.

- In most cases, the rate of tree clearing far outpaces that of tree planting, which is falling behind schedule by years (Law 2022). Replanting faces human and technical challenges, potentially stemming from a lack of clear economic incentives for companies responsible for deforestation. By bridging these gaps and fostering a holistic approach to replanting and tree plantation development, both environmental and economic goals can be achieved (Leong, Woo and Platts 2023).

Malaysia produces significant amounts of poultry (4 million tonnes per year) and ruminant/swine manure (nearly 6 million tonnes per year), currently used for organic fertiliser and biogas production.

- The market currently faces an oversupply of chicken manure-based bio-fertiliser.

- Notably, the NBAP provides state-specific details on manure production. Two states, Johor and Pahang, stand out with poultry and cattle manure exceeding 1 million tonnes each, while Perak and Malacca each produces over 800,000 tonnes annually. The geographical proximity of Johor, Pahang, and Malacca allows them to potentially form a cluster for biogas and biomethane production.

Beyond the three key roadmaps explored above, Table 1 offers an overview of other relevant Malaysian government policies and roadmaps, highlighting their potential influence on demand trends and market evolution.

Table 1: Summary of Malaysian government policies and roadmaps related to decarbonisation, 2023 and beyond

Title	Author	Year released	Period covered	Highlights
Carbon Pricing Instrument	Ministry of Finance	Expected in 2024		
National Biomass Action Plan	Ministry of Plantation and Commodities	2023	2023 – 2030	Estimates Malaysia's biomass potential at 182.6 million tonnes per annum, with 86% from oil palm.[6] • Quotes 440.5MW of biomass power capacity reducing emissions by 395 $GgCO_2eq$ (2019) but does not specify future targets.[7]
Energy Efficiency and Conservation Act (EECA)		Oct 2023		• EECA will be enforced 12 months after it is gazetted, and consumers will then have 5 years to comply or face penalties ranging from RM20,000 to RM100,000. • Companies with an energy consumption exceeding 21,600 gigajoules are required to implement energy-saving measures and are subject to periodic energy audits. • Office buildings exceeding 8,000sqm must ensure energy intensity performance conform to prescribed energy efficiency ratings. • Energy-using products must adhere to energy performance standards to obtain the requisite energy efficiency certificates and labels before they can be manufactured or distributed. Energy Commission is granted wide investigative and enforcement powers to ensure compliance with EECA provisions.
Hydrogen Economy and Technology Roadmap (HETR)	Ministry of Science, Technology and Innovation	Oct 2023		• Provides an overview of the hydrogen industry development across Southeast Asia and benchmarks against more advanced countries like Australia, Japan, South Korea, UK, US and China.

[6] Plantation biomass 164m tonnes (89.8%), agricultural biomass 4.2m tonnes (2.3%), woody biomass 3.5m tonnes (2.0%), livestock industry waste 10m tonnes (5.6%), fisheries industry waste 0.7m tonnes (0.4%) (Pg. 17).

[7] Key breakthroughs envisioned in the plan include the implementation of a biofertiliser blending initiative, conversion of palm biomass into fuel pellets for export or co-firing with coal-fired power plants, development of bio-based carbonised products such as biochar, activated carbon and graphite as well as interventions to reduce imported animal feed for improved food security.

				• Models two scenarios: Business As Usual (BAU) which will produce 7 million tonnes of hydrogen per annum by 2050[8]; and Emissions Driven Scenario (EDS), which will produce 16 million tonnes of hydrogen per annum by 2050.[9&10]
National Industry ESG Framework *(the how)*	Ministry of Investment, Trade and Industry	Oct 2023	Phase 1, just transition: 2024-2026	• Three missions – support manufacturing firms to learn, be agile and adopt ESG practices; transform challenges into opportunities; foster symbiotic public-private partnership for value creation • Four supporting pillars - standards, financing, capacity building, and market mechanisms – for accelerating the transition towards sustainable practices among manufacturing companies. • Six enablers – stakeholder engagement, human capital and capabilities, digitalisation, technology, financing and incentives, policy and regulation
New Industrial Master Plan 2030 *(the what)*	Ministry of Investment, Trade and Industry	Sept 2023	2023-2030	Mission-based approach, instead of a sectorial approach. Four common missions across sectors: advance economic complexity, tech up, net zero, and economic security and inclusivity. Mission 3: Push for Net Zero (pages 95-114) is related to AGF and decarbonisation: 3.1.1 Develop sectoral decarbonisation pathways to guide transition 3.1.2 Decarbonise "hard-to-abate" sectors 3.1.3 Introduce carbon policy, accounting and tax 3.2.1 Enhance adoption scheme for energy efficiency or renewable energy 3.2.2 Accelerate availability and accessibility of renewable energy source for industry 3.3.1 Catalyse EV as a key growth driver 3.3.2 Grow CCUS as a new sector 3.3.3 Develop circular economy framework for the industry 3.4.1 Accelerate transformation of industrial estates into eco-industrial parks Unfortunately, the NIMP lacks quantitative details on these initiatives.
National Energy Transition Roadmap (NETR)	Ministry of Economy	July & Aug 2023	2023 – 2050	• Reduce emissions through 6 key levers – energy efficiency, renewable energy, hydrogen, bioenergy, green mobility, and carbon capture, utilisation and storage (CCUS) • Targets 70% renewable share and 0% coal share of installed capacity by 2050 • Targets RM15b in investments for smart devices installation

[8] BAU: 1.6% reduction of GHG emission intensity, RM201 billion cumulative investment needed, RM663 billion contribution to GDP, and 168,000 jobs created by 2050 (pg. 104).

[9] EDS: 6.9% reduction of GHG emission intensity, RM577 billion cumulative investment needed, RM1.6 trillion contribution to GDP, and 211,680 jobs created by 2050 (pg. 104).

[10] BAU models zero hydrogen demand for electricity generation, while EDS includes 20% blending of hydrogen with natural gas and co-firing of coal with green ammonia from 2030.

				• Energy efficiency targets of 23% for industry and commercial sectors, and 20% for residential by 2050. compared to business-as-usual
Strategic Development & Cross-Border Trade Policy for Renewable Energy	Ministry of Natural Resources, Environment & Climate Change (NRECC)	May 2023	2023-2050	• Increase the generation capacity for RE to 70% by 2050 • Encourage self-contained systems, i.e. localised RE as opposed to large scale solar • Direct allocation to government departments to acquire solar for government buildings • Allow cross border RE trading
Malaysia Energy Transition Outlook	International Renewable Energy Agency (IRENA); Ministry of Natural Resources, Environment & Climate Change (NRECC)	2023	2023 – 2050	Explores two possible highly decarbonised routes of 100% renewables by 2050, and 90% renewables with carbon capture and storage by 2050. In both cases, most of the capacity is solar and hydro.[11]
Sabah Energy Roadmap and Master Plan 2040 (RAMP 2040)	Energy Commission of Sabah (ECoS)	2023	2023 – 2040	Key targets include 30% renewable energy share by 2035, 100% rural electrification, and achieving a sustainable electricity tariff.

[11] RE100: 81% solar, 15% hydro, 3% biomass
RE90: 68% solar, 19% hydro

2. MODELLING AND SCENARIOS

2.1 Methodology

a) Software

This study leverages two powerful tools developed by the Stockholm Environment Institute (SEI) for building a comprehensive Malaysian power sector model: the Low Emission Analysis Platform (LEAP), widely adopted for energy policy and climate assessment, and the high-performance, open-source Next Energy Modelling System for Optimisation (NEMO).

b) Optimisation setup

To minimise financial costs while meeting energy demand in each projected year, NEMO optimises the generation mix by considering generation costs alongside inequality constraints on maximum generation capacity and minimum ultilisation of each energy options. This optimisation process translates these cost and constraints functions into a system of equations, which are then solved iteratively until an optimal solution is reached. This study employs partial optimisation, focusing on optimal electricity generation. NEMO uses HIGHS, an open-source solver for linear, mixed-integer and quadratic programming systems, for this purpose.

c) Scope

This report's power sector model adopts a comprehensive approach, considering both the supply side – encompassing diverse electricity generation sources – and the demand side, represented by key sectors like industry, transportation, residential and commercial. The model is utilised to explore three carbon reduction scenarios for power generation:

i. **Existing Policy (EP):** Simulate the path for power generation and projected demand based on current policies.

ii. **Optimised EP:** Explore the least-cost path for power generation within Existing Policy.

iii. **Optimised More Ambitious Policy (OMAP):** Explore the least-cost path for power generation based on more ambitious emission reduction targets for both power generation and demand sectors.

d) Time

- **Current time period**[12] (also known as base year or first scenario year) is 2019. The latest data is available from Malaysia's Fourth Biennial Update Report (2022).

- **Historical time period**[13] is 2001-2018. 2001 represents the beginning of:

– Malaysia's Kyoto Protocol commitment (2002) and benefits like the Clean Development Mechanism (CDM) access.
– Significant economic changes: Ninth Malaysia Plan, Multimedia Super Corridor growth, National Automotive Policy.

- **End year** of the study is 2050.

e) Discount rate

This analysis employs a 7% discount rate, in accordance with the standardised assumptions for levelised cost of energy (LCOE) calculations published by the International Renewable Energy Agency (IRENA 2023).

f) Inflation rate

International Monetary Fund (IMF): Forecasts an ASEAN inflation rate of 2.7% from 2025 to 2029, with individual countries ranging from 1% (Brunei) to 7.8% (Myanmar) in 2028[14].

Asian Development Bank (ADB): Forecasts an ASEAN inflation of 3.2% in 2024 and 3.0% in 2025, aligning with their projections for Developing Asia[15] as a whole.

Considering the longer projection period offered by the IMF (2025-2029), an inflation rate of 2.7% is adopted for the AGF model.

g) Source of data

The LEAP model leverages reliable data carefully curated from publicly accessible, published reports.

h) Assumptions and constraints

GDP, population, electrification rates, appliance ownership, energy intensity, and sectoral economic activity serve as key drivers for electricity demand projection, incorporating current government projections, targets, and studies. These drivers are elaborated upon in the Appendix.

Table 2 details the assumptions and constraints underpinning the LEAP model.

[12] The year for which one has the most complete and reliable data. This serves as the starting point for one's modelling and projections.
[13] The years preceding the current time period/base year. It is useful for calibrating the model against observed trends, informs future assumptions and projections, and enabling benchmarking to assess changes in efficiency, technology, and policy.
[14] https://www.statista.com/statistics/804325/inflation-rate-in-the-asean-countries/
[15] https://www.adb.org/outlook/editions/april-2024

Table 2: Key assumptions in the Existing Policy and key constraints in the Optimised Scenario

Sectors	Key assumptions in Existing Policy scenario	Key assumptions in More Ambitious Policy scenario
Power generation	▪ Malaysia targets 31% RE in installed power generation capacity in 2025, 40% in 2035 and 70% in 2050. ▪ The Malaysia Renewable Energy Roadmap (MyRER) (SEDA Malaysia 2021) and National Energy Transition Roadmap (NETR) (Ministry of Economy 2023) have designed the RE capacity mix shown below to achieve the targets. ▪ MyRER sets forth ambitious bioenergy targets, exceeding those outlined in NETR by a factor of 2.5. For this analysis, the bioenergy targets established in the MyRER are chosen for modelling. These more ambitious goals represent a potential pathway for Malaysia's energy transition and warrant further exploration. ▪ The capacity targets outlined in the Sabah Energy Roadmap and Masterplan 2040 (Energy Commission of Sabah 2023), which was published in September 2023, one month after NETR, are not specifically modelled because it likely references and complements the national goals outlined in the NETR, elaborating how Sabah will achieve its energy transition within the larger Malaysian framework.	**Current MAP scenario: 100% renewable energy future** ▪ No new addition of fossil fuel new capacities from 2030. ▪ Phaseout coal by 2030 and natural gas by 2050. ▪ LEAP adds RE capacity (e.g. solar and BESS hybrid, solar PV, hydro, biomass, wind, biogas, municipal solid waste, geothermal), batteries and pumped hydro storage to the system as needed to meet the total and peak electricity demands. Exploring the optimal integration of pumped hydro storage alongside battery storage solutions will shed light on the most effective storage mix to ensure grid stability and reliability with a fully renewable energy system. ▪ Dispatch merit order: 1 – solar and BESS hybrid, biomass, biogas, municipal solid waste steam turbine, wind onshore and offshore 2 – hydropower[18], geothermal 3 – coal, natural gas, diesel power plant **Future MAP scenarios:** ▪ **Investigating carbon capture and storage (CCS) technology:** Another future scenario to be explored

[18] Hydropower's current merit order dispatch of 2 is strategically maintained due to its significant capacity. Assigning it a dispatch order of 1 could significantly curtail the utilisation of other renewable sources like solar.

	2025 (MW)	2035 (MW)	2050 (MW)
Solar	4,706	7,280	59,000
Large hydro	5,862	8,062	9,470
Small hydro	1,153	1,219	1,219
Biomass	862	998	970
Biogas	333	406	406
Geothermal	-	30	30
Total RE capacity	12,916	17,995	71,095
Total non-RE capacity*	28,749	26,993	25,905

*Calculated

- Data on new generation capacity additions and retirements for Peninsular Malaysia and Sabah were incorporated from the official reports of Peninsular Malaysia Generation Development Plan 2020 (2021-2039), Sabah Electricity Supply Industry Outlook 2019 by the Energy Commission (2021, 2019) into the LEAP model.[16]
- Dispatch merit order[17]:

  1 – solar and battery energy storage system (BESS) hybrid, wind onshore and offshore

  2 – coal, natural gas, hydropower, geothermal, municipal solid waste steam turbine, biomass, biogas

involves the continued use of natural gas and biomass power generation, coupled with CCS technology. Assessing the feasibility and economic viability of CCS can provide valuable insights into potential pathways for mitigating greenhouse gas emissions from these power sources.

- **Exploring hydrogen's role in decarbonisation:** Future iterations of the MAP will explore the complex trade-offs involved in using hydrogen as a decarbonisation strategy. This analysis will move beyond just production and transportation methods for hydrogen gas and delve into potential changes in energy demand across different sectors. Many decarbonisation strategies involve replacing existing fuels in sectors like transportation and industry. This shift could lead to a significant increase in hydrogen demand beyond its use in power generation and storage. By modelling these multifaceted considerations, policymakers can gain a comprehensive understanding of the potential role hydrogen can play in Malaysia's clean energy future.

[16] Sabah Energy Roadmap and Master Plan 2040 by the Energy Commission of Sabah (2023) have yet to be incorporated into the model.
[17] The dispatch merit order is arranged this way so that the generation profile produced by the LEAP mode matches the historical generation data from government sources more closely.

3 – diesel power plant

	Framing of Optimised Existing Policy scenario	Framing of Optimised More Ambitious Policy scenario
Power generation	This scenario assumes no emission restrictions and retains the Existing Policy's capacity addition targets and renewable energy goals. However, LEAP's optimisation engine prioritises cost-effectiveness when determining additional capacity beyond the pre-defined numerical targets set by NETR. This means that any further expansion is driven by cost considerations, not necessarily by RE preferences. **Maximum capacity addition:** Limits new generation added in a planning period, reflecting real-world constraints like construction timelines and resource availability. ▪ Coal: zero ▪ Natural gas: unlimited ▪ Solar PV: unlimited ▪ Large hydro: unlimited ▪ Small hydro: 100 MW per year ▪ Mini hydro: 10 MW per year ▪ Biogas: 10 MW per year (average plant sizes are small; limited by fuel availability) ▪ MSW: 50 MW per year (average plant sizes are small; limited by fuel availability) **Minimum utilisation:** Setting a fixed minimum constraint by directly imposing a lower bound on the decision variable representing the generation capacity of each unit in the power system. This ensures that the unit generates at least a certain minimum amount of power, expressed as a percentage of its maximum capacity.	Same as Optimised Existing Policy scenario.

	Key assumptions in Existing Policy scenario	Key assumptions in More Ambitious Policy scenario
	▪ 50% for all technologies, except for hydro, which is set at 25%[19].	
Residential	▪ Electrification rate of households is 100% (World Bank Group 2024) ▪ The residential sector is disaggregated into urban and rural categories to account for potential differences in appliance ownership and energy efficiency levels. Urban households are generally modelled with a higher penetration rate of appliances and a greater focus on energy-efficient technologies compared to rural households.[20] ▪ The National Energy Efficiency Action Plan 2016-2025 (NEEAP) sets ambitious targets for appliance penetration rates and energy efficiency improvements. For example, the efficient lighting rate is projected to increase from 10% in 2018 to 55% by 2025. [21]	▪ Electrification rate of households is 100% (World Bank Group 2024) ▪ This scenario expands upon the NEEAP by establishing energy efficiency targets beyond its 2025 timeframe. The model projects a gradual increase in the penetration rate of energy-efficient appliances, reaching 100% by 2060. While this target may appear ambitious, the extended timeframe acknowledges Malaysia's projected transition to a highly developed economy by 2060, potentially enabling greater investment in energy-efficient technologies.
Services / Commercial	▪ Three factors drive commercial sector electricity demand: value added[22], fuel share of electricity, and final energy intensity[23]. Historically, value added and fuel share of electricity have risen, while energy efficiency has improved. The model projects these trends to continue.	▪ The current Energy Efficiency and Conservation Act (EECA) is projected to cover 500 out of 1.7 million commercial consumers, representing 21% of the commercial segment's energy consumption. This highlights the potential for significantly expanding the scope of energy efficiency policies.

[19] Hydropower's high capacity necessitates a strategically lower minimum utilisation rate within the model. Assigning it a minimum utilisation rate on par with other technologies would effectively curtail (or significantly reduce the output of) many other generation sources in the LEAP model.

[20] While the National Energy Technology Roadmap (NETR) establishes a 20% energy efficiency improvement target for the residential sector, this modeling exercise employed LEAP's bottom-up approach (where energy consumption is built up from individual applications) for a more granular analysis of potential efficiency gains.

[21] Detailed penetration rates of each appliance and its energy efficiency can be found in the Appendix.

[22] The measure of how much an industry contributes to the economy by transforming raw materials into valuable goods and services.

[23] Measures how much energy an industry uses to produce a unit of output (like a car, a tonne of steel, or a kilowatt hour of electricity). It's a way to gauge how efficiently the industry utilises its energy resources.

	▪ The Existing Policy scenario models a 23% improvement in final energy intensity by 2050 based on Malaysia's NETR targets achieved through various initiatives [24]. Adoption will be driven through the Energy Efficiency and Conservation Act bill.	▪ Recognising this gap, the More Ambitious Policy scenario doubles the energy intensity improvement target to 46%. This ambitious target reflects the potential for broader coverage under strengthened policy measures.
Industry	▪ The modelling approach for the industry sector mirrors that of the commercial sector, and both sectors utilise targets established in NETR. Industrial electricity demand is primarily driven by three factors: value added (economic output), fuel share of electricity (reliance on electricity vs. other fuels), and final energy intensity (energy consumption per unit of output). Historically, these trends have shown an increase in value added and fuel share, alongside improvements in energy efficiency. The model projects these trends to continue. ▪ To assess potential energy savings under existing policies, the Existing Policy scenario assumes a 23% improvement in final energy intensity by 2050. This target aligns with the NETR and is expected to be achieved through various initiatives [25] driven by the Energy Efficiency and Conservation Act.	▪ The More Ambitious Policy scenario builds upon the Existing Policy scenario's projected 23% improvement in final energy intensity. This more ambitious approach adds an additional 4% demand reduction from circular economy measures in the steel sector.[26] ▪ Furthermore, the fuel share for electricity jumps from 34% in 2019 to 46% in 2050. This aligns with the International Energy Agency's (IEA) projection for industry electrification needed to achieve net zero by 2050 (International Energy Agency 2020). For comparison, in the Existing Policy scenario, electricity share modestly increases to 39% by 2050, following historical trends.
Transport	▪ National Energy Transition Roadmap (2023) outlines the adoption of green mobility practices and technologies to reduce the emissions in the transport sector. The update to the model largely contains the policies and targets related to land-based transport while aviation and marine	No More Ambitious Policy is developed for the transport sector.

[24] Including but not limited to public awareness programmes, green building codes, and retrofit of government buildings. Refer to Appendix for details.
[25] Including but not limited to public awareness programmes, improving Minimum Energy Performance Standards, and mandatory audits. Refer to Appendix for details.
[26] These measures include material substitution, efficient design, and recycling. Details of the calculation behind the 4% figure can be found in the Appendix.

transport sectors remain under review. The following targets for 2050 have been implemented:

- Light vehicles:
  - Increase the penetration of xEV (4W) share of the vehicle fleet to 80%
  - Increase the penetration of two-wheelers (E2W) share of the vehicle fleet to 80%
- Heavy vehicles:
  - 5% of heavy vehicles to utilise hydrogen by 2050
  - National Energy Policy targets B30 biodiesel blending by 2030
- Public transport:
  - Increase the public transport modal share to 60% by 2050

- The following target is under review as to how they can be modelled effectively:
  - Increase rail freight modal utilisation to 5% by 2030

3. ANALYSIS AND EXTERNAL FACTORS

This report is informed by the LEAP model sdsn_agf_main_v3.3.5 MY-ALPHAv3. Three policy scenarios are analysed across five key dimensions of the power sector:

a) Demand and energy efficiency
b) Variable renewables
c) Dispatchable low-carbon generation
d) Firm power high-carbon generation
e) System flexibility

Additionally, the report considers the influence of external factors, including geopolitics, technological advancements, and economic considerations, on future development and policy direction.

3.1 Existing policy

a) Demand and energy efficiency

The electricity demand for the residential, agriculture and fishing, services / commercial, industry and transport sectors is projected to be 393 TWh in 2050, which is an 152% increase compared to 156 TWh in 2019. Figure 2 shows how each sector contributes to the increase in demand out to 2050. The majority (79%) of the increase in electricity demand is a result of changes in demand from services and industry. This is due to the increasing value-add of services to the Malaysian GDP, and the modest target of energy efficiency in the sector which covers just 21% of commercial consumption and less than 1% of total users (The Edge 2023).

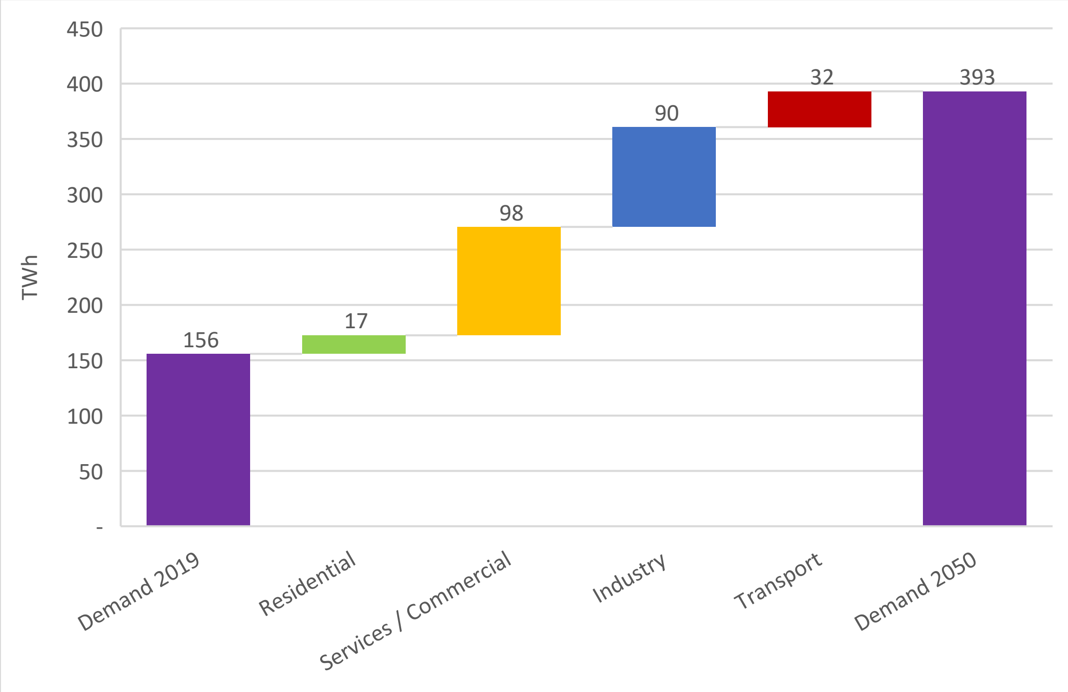

Figure 2: Contribution by sectors to increased electricity demand in the Existing Policy scenario (2019 and 2050)

These demand scenarios explore efficiency measures that mitigate the projected increase in electricity demand:

- **Residential.** Regulatory and labelling efforts focus on promoting energy-efficient appliances in the residential sector. Urbanisation and electrification of household tasks will likely drive demand growth despite efficiency measures. Government programmes have successfully encouraged energy-efficient appliance adoption.

  - **Regulations:** 1994 Electricity Regulations (amended 2013) enforce Minimum Energy Performance Standards (MEPS) and efficiency ratings, promoting appliance efficiency.

  - **Labelling system:** Introduced in 2006, the system initially covered key appliances, expanding to encompass a wider range over time. MEPS provides the foundation for the system.

  - **National strategy:** The five-star rating system aligns with the National Energy Efficiency Action Plan (2015) estimates and targets.

  - **Urbanisation:** Urbanisation and electrification of household tasks, particularly cooking, are projected to drive electricity demand growth (Figure 3). While efficiency gains from regulations and labelling will moderate demand increases for cooling[27] and lighting, cooking is expected

[27] For example, while the adoption of more efficient refrigerators (which use up to 50% less energy) coincided with a 25% population growth rate in Malaysia, energy demand for refrigeration remained relatively stable. This suggests that efficiency gains largely offset the increased demand from population growth.

to show a substantial rise in electricity consumption as it is the last major household activity to be electrified.

- **Government programmes:** SAVE[28] programmes (launched in 2011, 2021, 2022, and 2023 with increasing incentives) have successfully promoted energy-efficient appliance adoption, leading to significant energy and cost savings, and emission reductions.

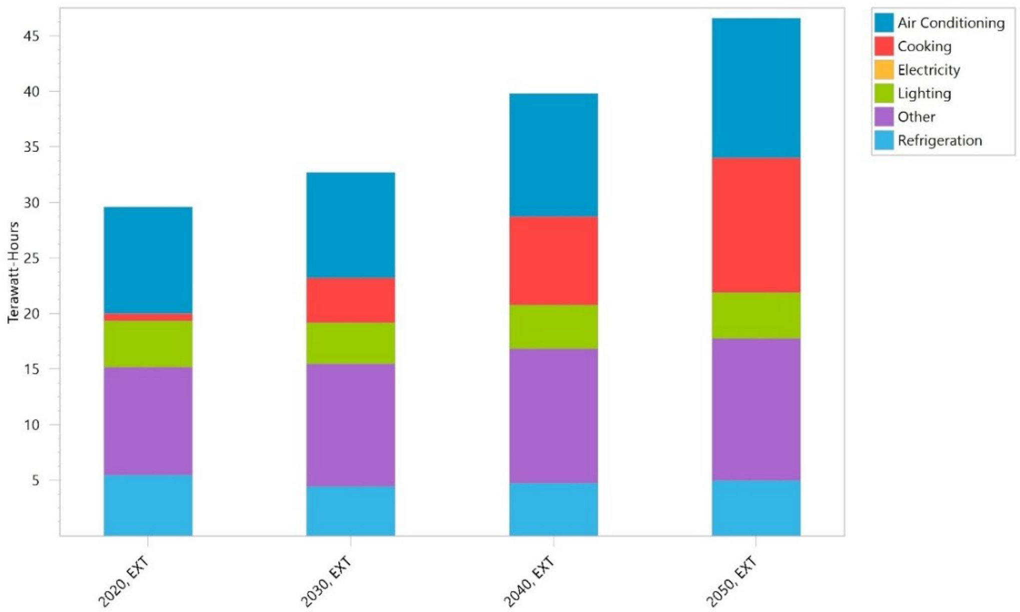

Figure 3: Historical and projected electricity demand from the residential sector under Existing Policy (2020 – 2050)

- **Industry.** Malaysia's growing industry faces a dual challenge: rising energy demand and reducing emissions. Industry drives 41% of the projected electricity demand increase by 2050 (Figure 2). While electrification helps with the latter, it increases power consumption. The National Energy Transition Roadmap aims to address both by improving industrial energy efficiency by 23% but overcoming business hurdles and accelerating electricity sector decarbonisation remain crucial.
  - **Demand drivers:** Industrial expansion, population growth, urbanisation, infrastructure development, technological advancements, and climate control needs contribute to rising demand for energy.
  - **Energy consumption:** The industry sector is the second largest energy consumer in Malaysia (26% in 2019) after the transport sector (Malaysia 4th Biennial Update Report Under the United Nations Framework Convention on Climate Change 2022).
  - **Energy efficiency measures:** Implementing measures like efficient heating, ventilation, and air conditioning (HVAC) systems[29], high-efficiency equipment[30], and process optimisations[31] can significantly impact demand.

[28] The Sustainability Achieved Via Energy Efficiency (SAVE) programme offers rebates for purchases of energy-efficient appliances.
[29] Efficient chiller, variable speed drive, thermal energy storage
[30] Compressor, motor
[31] Heat recovery, co-generation

- **Incentives:** Tax incentives exist for energy-efficient equipment and projects[32], but have not significantly spurred adoption.

- **Barriers to adoption:** Businesses cite short-term focus, upfront costs, complexity, and lack of awareness as barriers to investment (Goh, Chai and Goh 2019).

- **Energy-saving services:** Despite efforts like Energy Performance Contract (EPC), financial pressure on energy-saving service companies remains a challenge[33].

- **Electrification:** As shown in Figure 4, industry's share of total electricity demand is projected to decline from 49% in 2020 to 42% in 2030, remaining flat thereafter. Industry's electrification, while increasing, is typically slower than the service sector's. Malaysia's ongoing urbanisation creates a denser customer base, encouraging new businesses and their expansion. This, coupled with electrification as a catalyst for business growth, leads to a surge in new businesses requiring power. This surge in new businesses and their electricity needs is a key reason why the service sector's electricity demand share is projected to increase during 2020-2030, whist displacing industry's share during the same period, which is the initial stage of electrification for industry.

Due to the shift towards electrification, industry's absolute electricity demand is projected to rise steadily all the way to 2050 (Figure 5). The underscores the ultimate success of electrification in reducing emissions hinges on the pace of transitioning to clear energy sources for power generation.

[32] Waiver of import duty and sales tax on energy efficient equipment, and accelerated capital allowances or pioneer status for investment in energy efficient technologies and projects. These incentives were enhanced over the years. (National Energy Efficiency Action Plan 2015)

[33] Energy saving service companies use their own funds for energy-saving retrofit and sharing energy-saving benefits with industrial enterprises.

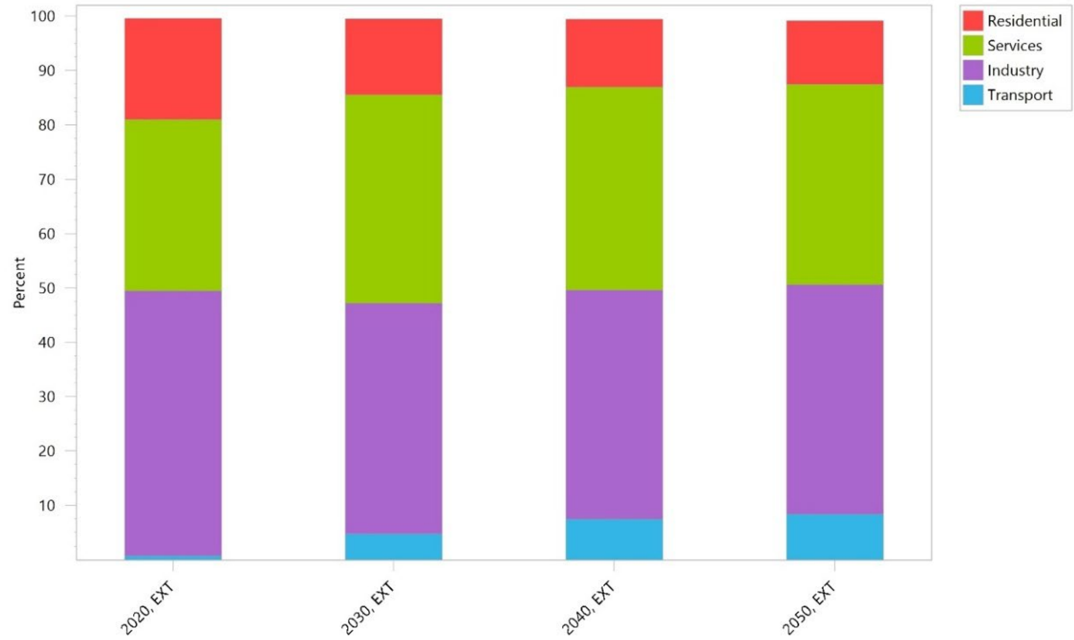

Figure 4: Historical and projected electricity demand share amongst demand sectors under Existing Policy (2020-2050)

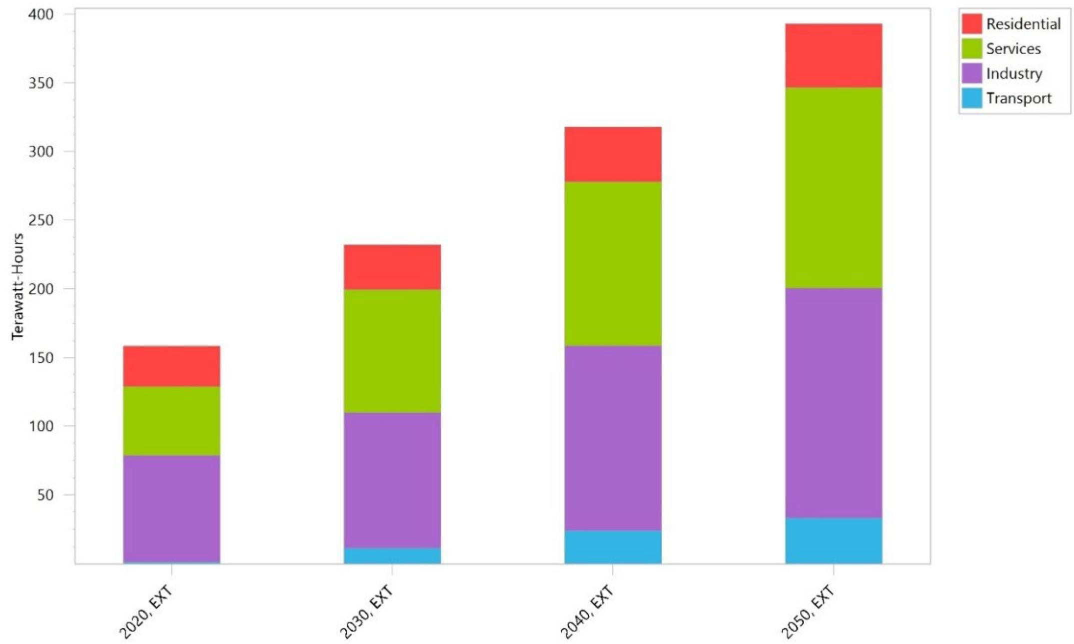

Figure 5: Historical and projected electricity demand under Existing Policy (2020-2050)

- **Commercial / services.** While mandatory building codes and government retrofits aim to improve efficiency, challenges like financing limitations and weak regulation enforcement hinder progress. Despite electrification's role in reducing emissions, soaring demand – a projected 192% increase by 2050 – could significantly outpace efficiency gains.

- **Main driver:** Buildings (cooling and equipment) account for most energy use, driving 41% of projected demand increase by 2050 (Figure 2).

- **Growth factors[34]:** Economic growth, technological advancements, changing work environments, and data centres contribute to rising demand.

- **Efficiency measures:** Mandatory building codes [Uniform Building By-Laws, MS 1525) and government building retrofits aim to improve efficiency (National Energy Transition Roadmap 2023).

- **Challenges:** Limited financing options for Energy Performance Contract (EPC) in public buildings, weak enforcement of regulations and relatively low electricity tariffs for commercial buildings hinder progress (National Energy Efficiency Action Plan 2015).

- **Electrification:** Electrification is a significant driver of change in the commercial / services sector. Figure 4 illustrates a rise in the sector's share of electricity demand, climbing from 32% in 2020 to 37% by 2050. This trend is mirrored in Figure 5, which projects an increase in electricity demand within the commercial / services sector – a 192% growth, from 50 TWh in 2020 to 146 TWh by 2050.

- **National target:** The National Energy Transition Roadmap (2023) aims to achieve a 23% energy efficiency improvement; however, the expanding services sector and its growing economic value is projected to result in a 98 TWh increase in electricity demand by 2050 (Figure 2).

- **Transport.** Malaysia pushes for electric vehicles (EVs) with an 80% target for all vehicles to be electric or plug-in hybrids (xEVs) by 2050. This green shift will strain electricity grids, as demand is projected to surge from 1 TWh in 2020 to 33 TWh by 2050. While initiatives like charging stations and tax breaks support EV adoption, policy focuses on infrastructure and incentives, neglecting total vehicle numbers. Future used vehicle and fuel subsidy policies could hold the key, while promoting public transport and active travel offer additional avenues for demand management.

  - **National targets:** To achieve its ambitious environmental goals, Malaysia has embarked on a bold EV adoption strategy. By 2050, 80% of four-wheelers and two-wheelers are targeted to be electric or plug-in hybrids (xEVs). This significant shift towards cleaner transportation, while commendable, presents the challenge of increased electricity demand. As illustrated in Figure 6, transport electricity consumption is projected to rise from 1 TWh in 2020 to a staggering 33 TWh in 2050, driven largely by the surge in EVs.

    Furthermore, the country's commitment to increase public transport usage, with a target modal share increasing to 60% by 2050, will also contribute to this demand rise. Rail electricity demand is expected to jump from 0.4 TWh in 2020 to 13.2 TWh in 2050 due to public transport (Figure 6).

[34] These growth factors are not directly modelled in LEAP but are underlying factors behind the service sector's GDP contribution, energy intensity and fuel share growth that is driving the 255% increase in electricity demand towards 2050 (Figure 5).

- **Government initiatives:**
  - Charging infrastructure: Low Carbon Mobility Blueprint (2021) targets 10,000 public charging stations by 2025.
  - Tax incentives: Budget 2022 offers tax exemptions[35] for local EV assembly/imports and tax relief for individuals for subscription of charging facilities or EV charging installation.
- **Existing policy:** No control/reduction of total vehicles on the road.
- **Behavioural changes:** Public transport and active travel alternatives could reduce overall transport electricity demand.
- **Future policy:** End-of-life vehicle policy (2025) and potential fuel subsidy removal might influence trends.

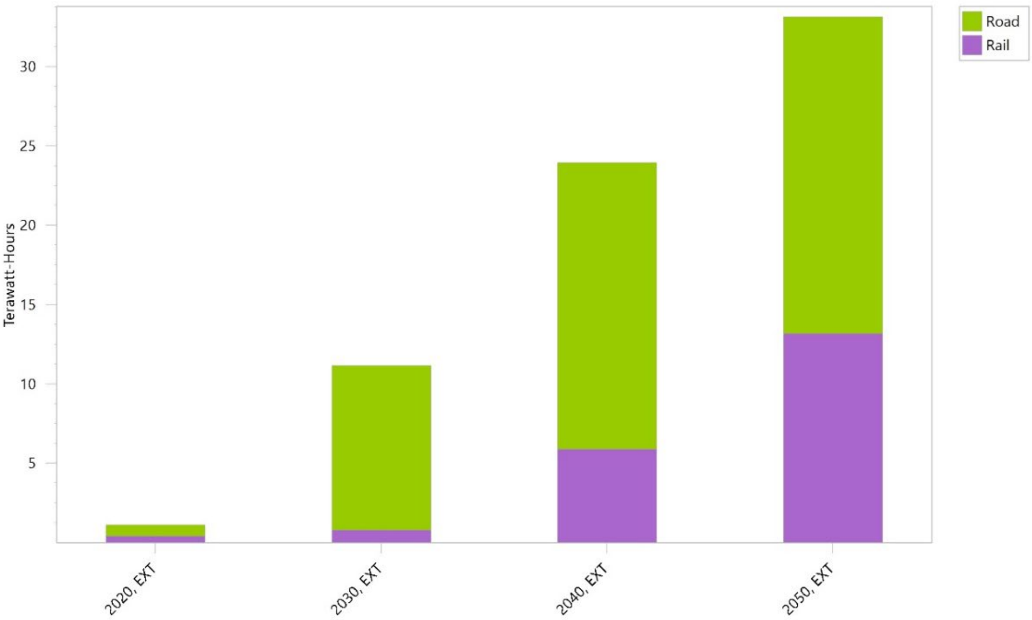

Figure 6: Historical and projected electricity demand in the road and rail sectors under Existing Policy (2020-2050)

b) Variable renewables

Variable renewables (i.e. solar and wind) have a key role to play in the decarbonisation of electricity generation because they can provide zero-carbon electricity generation at low cost.

- **The National Energy Transition Roadmap (NETR)** (2023) **prioritises unlocking Malaysia's abundant solar potential while strategically reducing reliance on coal-**

[35] Full exemption on import duty, excise duty and road tax for locally assembled EVs or imported as completely built-up, as well as full exemption for sales tax for EVs assembled locally. To encourage the growth of the EV charging network in Malaysia, the government is offering individuals RM2,500 in yearly income tax relief through to 2027 for the installation, rental, and purchase of EV charging equipment or subscription fees. (Muhammad 2024)

fired generation. However, this shift necessitates a substantial increase in deployed solar capacity to compensate for the inherent variability of solar energy compared to the consistent output of coal.

- The 2021 Malaysian Renewable Energy Roadmap published by the Sustainable Energy Development Authority (SEDA) envisions Malaysia's solar power capacity potential at 269 GW. This clean energy source holds immense promise compared to the mere 1.5 GW installed in 2020 (SEDA Malaysia 2021).

- NETR charts an ambitious course for renewable energy in Malaysia, with solar power at the forefront. Compared to the pre-NETR forecast [7.8 GW by LEAP in the AGF-MY 2.1 report (Woo, et al. 2023)], NETR aims for a staggering sevenfold increase in solar capacity to 56 GW in 2050.

However, a key question remains: can Malaysia achieve this target? While the LEAP model projected a higher solar generation capacity of 72 GW by 2050 (Figure 7), exceeding NETR's target by 29%, achieving either level of deployment will require significant investments in infrastructure, grid modernisation, and enabling policies.

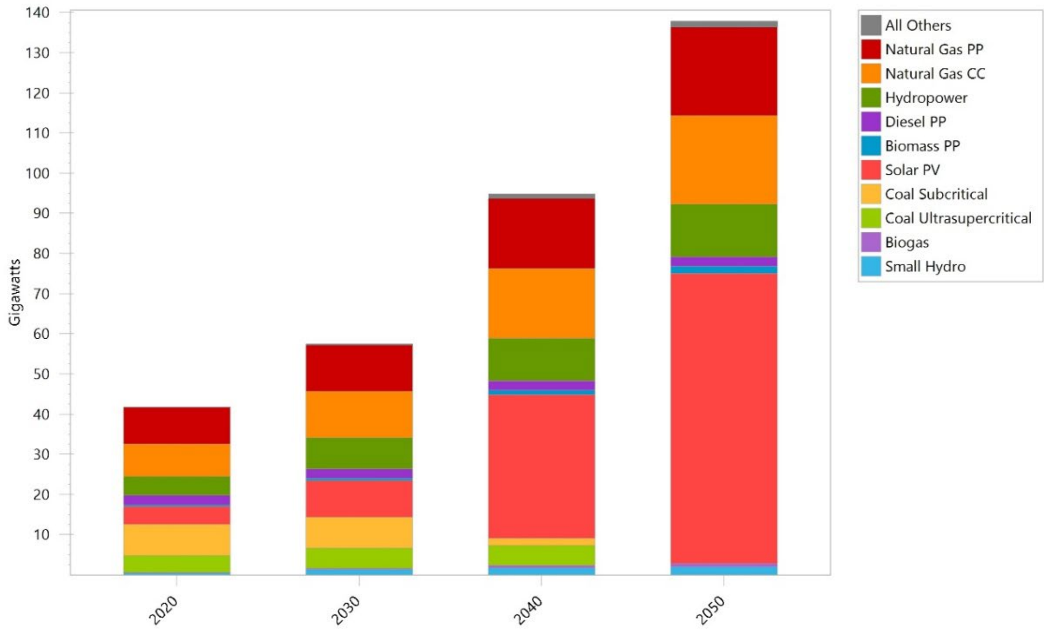

Figure 7: Installed and projected generation capacity by technology under Existing Policy (2020-2050)

- In 2019, solar energy contributed a modest 1.5 TWh (0.9% of total generation) according to the National Energy Balance 2019 (Energy Commission 2022). However, LEAP projections anticipate a dramatic rise to 94 TWh by 2050 (Figure 8), representing a 62-fold increase from 2019 figures. This surge will propel solar's share in Malaysia's total generation mix to 21% (Figure 9).

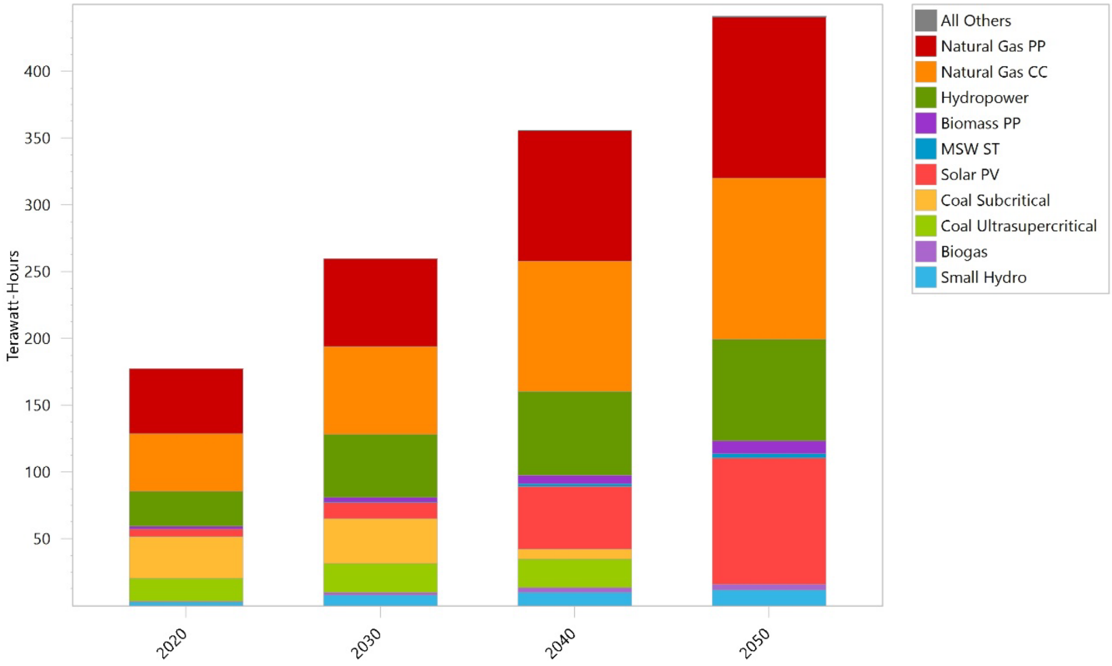

Figure 8: Historical and projected power generation by fuel under Existing Policy (2020-2050)

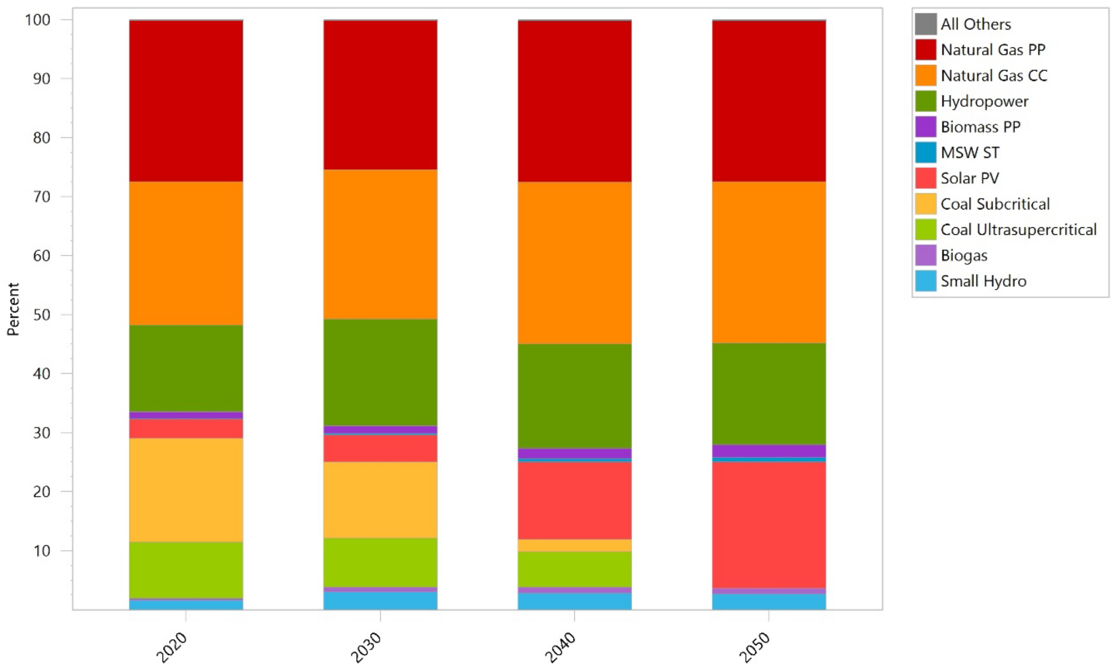

Figure 9: Historical and projected power generation share by fuel under Existing Policy (2020-2050)

c) Dispatchable low-carbon generation

NETR establishes targets for various low-carbon generation sources beyond solar PV, leveraging Malaysia's abundant resources. This includes expanding the capacity of hydropower and diverse bioenergy forms (Figure 7 and Figure 8). Notably, NETR incorporates hydrogen into the mix, acknowledging its variable carbon footprint based on production methods.

- **Hydropower: the cornerstone of grid flexibility for renewables**
  - Hydropower plants are not only a cornerstone of renewable power generation, but also a crucial enabler for integrating other variable renewable sources like solar and wind. This is due to their inherent capabilities to provide a range of grid flexibility services (XFLEX HYDRO 2022):
    - **Fast frequency control:** Hydropower plants can rapidly adjust their output to counterbalance fluctuations in grid frequency caused by intermittent renewables.
    - **Fast start/stop and transition modes:** They can be quickly brought online or taken offline to meet changing energy demands and can even switch between generation and pumping modes for energy storage.
    - **High ramping rate:** Hydropower plants can rapidly increase or decrease their output to accommodate sudden changes in demand.
    - **Inertia emulation:** They can mimic the inertial response of traditional fossil-fuel generators, which is critical for maintaining grid stability.

- **NETR sets a target of 11 GW of hydropower by 2050, focusing on maximising this clean energy source. Hydropower is projected to contribute 20% of total Malaysian power generation in 2050. Achieving this target will require further development of both large and small hydropower plants. Hydropower's vulnerability to drought highlights the need for diversification.**
  - The 2021 Malaysian Renewable Energy Roadmap published by the Sustainable Energy Development Authority (SEDA) indicates a potential for Malaysia to deploy 16.1 GW of hydropower capacity, comprising of 13.6 GW of large hydro (>100 MW) and 2.5 GW of small hydro (up to 100 MW). In 2020, the installed capacity stood at 5.7 GW for large hydro and 0.5 GW for small hydro (SEDA Malaysia 2021).
  - Hydro remains the largest source of clear power globally (Ember 2024) and NETR reaffirms the crucial role of hydropower in Malaysia's long-term energy strategy. NETR sets a target of 11 GW of hydropower capacity by 2050, which aligns closely with the pre-NETR forecast of 11.8 GW[36] from LEAP in the AGF-

[36] Large hydro: 10.6 GW; small hydro: 1.2 GW

MY 2.1 report (Woo, et al. 2023). This represents approximately 11% of the total projected installed capacity in 2050.

- However, even with this continued emphasis on hydropower, achieving this target will require strategic planning and investment. LEAP's post-NETR modelling suggests that 15 GW[37] of hydropower capacity might be necessary to meet anticipated demand in 2050 (Figure 7). This revised projection highlights the potential need for additional hydropower capacity beyond NETR's current target.

- Furthermore, projections indicate that 15 GW of hydropower capacity could generate 88 TWh of electricity by 2050 (Figure 8), contributing 20% of Malaysia's total electricity generation (Figure 9). This underscores the importance of optimising hydropower's potential as a clean and reliable source of renewable energy. However, its dependence on rainfall presents a vulnerability, underscored by the recent global decline in hydropower generation due to droughts (Ember 2024), highlighting the importance of resilience planning.

- Policymakers should consider this vulnerability when planning for a long-term energy mix. Strategies to mitigate the impact of droughts on hydropower might include:

    - **Diversification of the renewable energy portfolio:** Invest in complementary renewable sources like solar to reduce reliance on a single resource during droughts.

    - **Improved water management:** Explore measures to optimise water storage and usage in hydropower dams.

    - **Demand-side management:** Implement programmes to encourage energy efficiency and reduce overall demand during peak drought periods.

By acknowledging the limitations of hydropower and planning for its potential vulnerabilities, Malaysia can ensure a more resilient and sustainable long-term energy strategy.

- **Enhancing bioenergy's role in Malaysia's energy transition**

    - NETR sets a target of 1% bioenergy installed capacity (0.97 GW) by 2050. This falls short of the potential outlined in the 2021 SEDA Malaysia bioenergy assessment, which estimates a national bioenergy potential of 3.6 GW. Further supporting this higher potential, the LEAP model currently projects a bioenergy capacity of 2.56 GW (1.76 GW biomass, 0.80 GW biogas) in 2050.

- **Policy considerations for increased bioenergy adoption**

    - This gap between NETR's bioenergy target and SEDA's estimated bioenergy potential highlights an opportunity to increase bioenergy's contribution to Malaysia's clean energy future. Policymakers should consider the following:

[37] Large hydro: 13.07 GW; small hydro: 2.14 GW

    - **Revising bioenergy targets:** NETR's bioenergy goals could be revised to reflect the higher potential identified by SEDA Malaysia and LEAP modelling.
    - **Developing enabling policies:** Policies that incentivise bioenergy development and address potential sustainability concerns are crucial to unlock this potential. Examples include feedstock development programmes, renewable energy certificates specific to bioenergy, and robust sustainability certification schemes.
  - By strategically increasing bioenergy's role in the energy mix, Malaysia can enhance its energy security, diversify its renewable energy portfolio, and contribute to its decarbonization goals.

- **Malaysia's abundant forestry and agriculture resources suggest potential for expanding biomass power to support grid stability in a system increasingly reliant on variable renewables. Build up Malaysia's forest and land carbon stores and increase the local supply of sustainable harvested biomass.**
  - Despite abundant forestry and agricultural resources, Malaysia's installed biomass power capacity [50-96 MW between 2012-2020 (National Biomass Action Plan 2023-2030)] falls short of the potential estimated by SEDA (2021) at 2.3 GW. This gap presents an opportunity to leverage biomass for grid stability and accelerate Malaysia's clean energy transition.
  - Recent assessments using the LEAP model paint a promising picture. Whilst pre-NETR projections estimated a 998 MW of biomass power generation capacity by 2050 (Woo, et al. 2023), post-NETR LEAP projections indicate an even more optimistic outlook, with projections reaching 1.8 GW in 2050, generating 9.6 TWh and representing 2.2% of total generation (Figure 8 and Figure 9). This significant upward revision underscores the potential of biomass to contribute meaningfully to Malaysia's clean energy future.
  - Challenges and policy opportunities:
    - Seasonal fluctuations in feedstock availability: develop a diversified feedstock strategy and storage solutions to address seasonal variations.
    - Low combustion efficiency: promote research and adoption of advanced conversion technologies for high-moisture biomass.
    - Geographic constraints and high transportation cost
    - Policy recommendations:
      - Implement escalating co-firing mandates with coal, starting with 20% biomass and gradually increasing.
      - Establish a certification system for sustainable biomass harvesting practices.

- Potential benefits:
  - Competitive feedstock costs: Malaysia's forestry and agricultural sectors offer a potential cost advantage for biomass feedstock compared to the global average[38].
  - Environmental considerations: Sustainable biomass harvesting and plantation establishment on degraded land can promote carbon sequestration and ecosystem restoration (Leong, Woo and Platts 2023, Committee on Climate Change 2018).
  - Global business opportunities: Wood pellet production from biomass can create export opportunities.
- Exploring advanced technologies:
  - Research and development efforts should explore the feasibility of biomass with carbon capture and storage (BECCS) for net-negative emissions.

● **Biogas holds untapped potential in Malaysia.**

- Biogas offers a largely untapped source of renewable energy in Malaysia. Despite a modest installed capacity of just 71 MW in 2020 (National Biomass Action Plan 2023-2030), a 2021 SEDA analysis suggests a tenfold potential, reaching 736 MW. NETR acknowledges this potential, with Existing Policy projections indicating a significant increase to 801 MW by 2050, surpassing the pre-NETR estimate of 406 MW (Woo, et al. 2023).
- Currently, biogas contributes minimally to the national grid, generating only 0.5 TWh in 2020. However, future projections outlined in the Existing Policy scenario of the NETR paint a promising picture. By 2050, biogas is expected to contribute 4.4 TWh, representing 1% of the total generation mix (Figure 9). This substantial growth underscores the potential of biogas to play a more significant role in Malaysia's clean energy future.

● **The balance act: clean gas power with carbon capture**

- Malaysia's projected reliance on natural gas for power generation (estimated at 55% in 2050) necessitates exploring carbon capture and storage (CCS) technologies to mitigate emissions. Without CCS, natural gas plants are projected to emit a significant amount of greenhouse gases (108 $MtCO_2e$) in 2050, representing nearly all (99.8%) of the power sector's emissions (Figure 10).
- **Promising potential for storage.** Fortunately, Malaysia possesses significant potential for carbon storage. Petronas estimates depleted oil fields hold a massive 46 trillion cubic feet of storage capacity, and the Malay Basin offers geological storage potential of 84-114 $GtCO_2$ (Battersby 2020, Dayang, et al. 2020). This creates a strong foundation for deploying CCS and decarbonising the natural gas power sector.

[38] While the global LCOE for biomass power is estimated at 118 USD/MWh (International Energy Agency, OECD Nuclear Energy Agency 2020), influenced by factors like feedstock cost, infrastructure, and operation expenses, Malaysia's cost could be lower due to its advantage in fuel cost from its forestry and agricultural sectors.

- **Leading the way with Kasawari CCS.** PETRONAS Carigali's Kasawari CCS project, the world's biggest offshore CCS initiative to date, received final investment approval in November 2022. Located off Sarawak, it will capture and store 71-76 $MtCO_2$ in total or reduce carbon dioxide emissions due to flaring by 3.3 $MtCO_2e$ annually (Offshore Engineer 2023). This pioneering project demonstrates Malaysia's commitment to CCS technology and its potential role in a cleaner energy future.

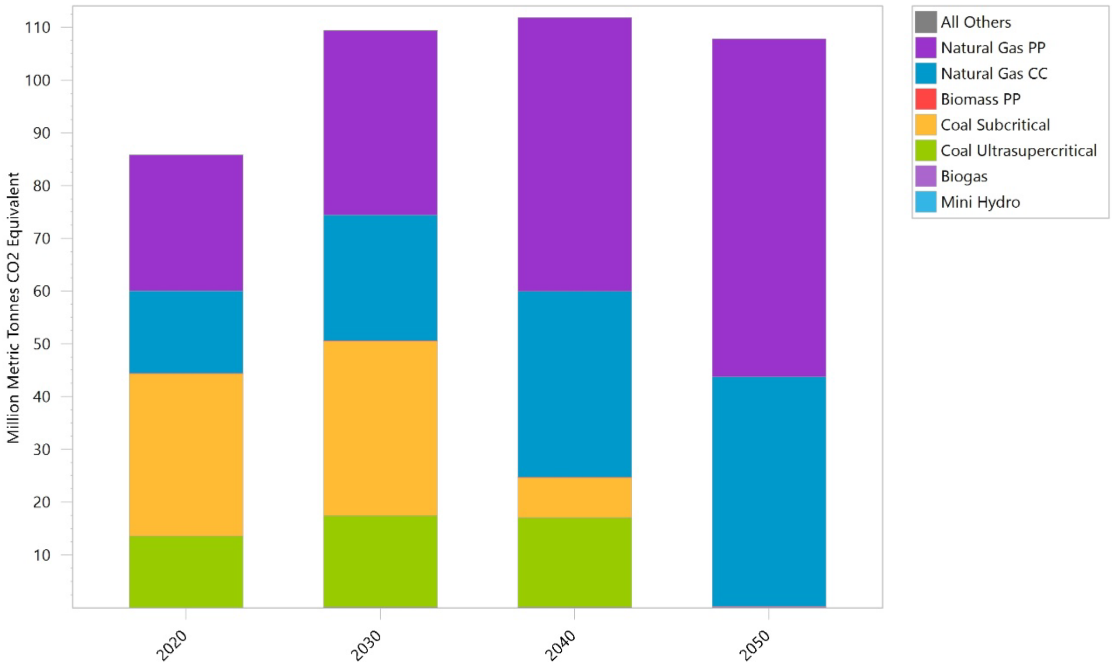

Figure 10: Historical and projected GHG emissions from power generation by source (2020-2050)

- **Cost considerations.** CCS technology faces cost challenges. Capture costs vary depending on the CO_2 source, ranging from USD 15-25/t for concentrated streams (like ethanol production) to USD 40-120/t for dilute streams like cement production and power generation (International Energy Agency 2021). Recent estimates from the International Institute for Sustainable Development (2023) and National Energy Technology Laboratory (2023) confirm these ranges. Transportation and storage costs also vary based on volume, distance, and storage conditions. While onshore pipeline transport in the US costs USD 2-14/t CO_2 and onshore storage generally falls below USD 10/t CO2 (International Energy Agency 2021), overall costs require further reduction.

- **Persistently high costs and the need for innovation.** The International Institute for Sustainable Development (2023) highlights that CCS costs remain persistently high, with slow cost reductions compared to the rapid decline in solar and wind energy costs. A hypothetical "model project" in Indonesia estimates an overall cost of USD 63/t CO_2 (capture, transport, and storage) under ideal conditions (ERIA 2022). This provides a glimpse into potential Southeast Asian costs but underscores the need for further research and development to bring CCS costs down.

- **Risk of leakage.** Substantial leakage could negate the climate benefits of CCS by returning captured CO_2 to the atmosphere, exacerbating global warming. High concentrations of CO_2 can also pose asphyxiation risks to humans and animals. Furthermore, leaked CO_2 can acidify groundwater, potentially damaging ecosystems. Finally, leakage can undermine the economic viability of CCS projects, particularly those relying on carbon credits, by incurring financial penalties or invalidating credits

- **Beyond natural gas: embracing a cleaner energy future**
  - While Figure 9 projects an increase in natural gas generation from 52% (2020) to 55% (2050) in Malaysia, this approach might not be the most sustainable long-term strategy. Unlike economies like the US, which transitioned from coal to gas in recent years (2015-2023), major Asian countries like China and India are prioritising renewables over gas (Ember 2024).
  - **The risk of stranded assets.** The rapid pace of clean technology advancements poses a significant risk of asset stranding for investments in new natural gas power plants. These stranded assets could have significant negative consequences for Malaysia's financial system. (Rocky Mountain Institute 2024)
  - **Harnessing abundant solar potential.** Given Malaysia's exceptional potential for solar power generation, the country should focus on modular clean technologies with steep learning curves. Examples include mass-produced solar PV modules and batteries, alongside the mass customisation of rooftop solar installations. These technologies offer several advantages over traditional fossil fuels because costs fall over time on learning curves, they have universal applicability, and they grow quickly. (Rocky Mountain Institute 2024)
  - By focusing on these innovative and cost-effective solutions, Malaysia can position itself for a cleaner, cheaper and more secure energy future.

d) Firm power high-carbon generation

- **Malaysia targets complete coal power phase-out by 2050 and diesel power phase-out by 2045.**
  - The category of "firm power high-carbon generation" encompasses coal and diesel generation, both traditionally designed for continuous operation. Malaysia has established phase-out targets for these sources, aiming for a complete coal power phase-out by 2050 and a diesel power phase-out by 2045. This approach is driven by the natural retirement of existing plants, coupled with a commitment to abstain from constructing new coal or diesel-fired facilities.

e) Overall power generation and demand (all fuels) observations

- **The path to a renewable future.** The National Energy Transition Roadmap (NETR) presents a transformative vision for Malaysia's energy sector. Pre-NETR projections anticipated a renewable energy capacity of 36% by 2050 (Woo, et al. 2023). However, the NETR framework, prioritising accelerated renewable energy development, significantly increases this projection. Through LEAP modelling, the Existing Policy scenario projects[39] a renewable energy capacity of 66% by 2050, approaching the ambitious NETR target of 70%.

- **NETR's dual benefit: clean energy and reduced emissions.** Beyond expanding renewable energy sources, the NETR framework promises significant reductions in greenhouse gas (GHG) emissions from the demand sectors. Pre-NETR projections estimated combined emissions from power generation and demand (for all fuels) exceeding 300 MtCO2e in 2050 (Woo, et al. 2023). With NETR implementation, these emissions are projected to decline to 219 MtCO2e by 2050 (Figure 11).

    - Figure 11 highlights the near-equal contribution of power generation and demand sectors to GHG emissions in 2050.
        - Power generation: transitioning away from natural gas and embracing renewable energy sources offer a clear path to decarbonisation.
        - Demand sectors: increasing electrification and robust energy efficiency measures can significantly reduce emissions in these sectors.

- **Addressing challenges with innovative solutions.** For certain industrial processes and heavy-duty transportation segments that are difficult to electrify, renewable fuels such as green hydrogen, biomethane, and bio-LNG offer a promising solution. These clean alternatives can contribute to a comprehensive decarbonisation strategy.

[39] Although NETR targets act as input data for the model's Existing Policy scenario, LEAP and NEMO can adjust these targets to maintain energy balance.

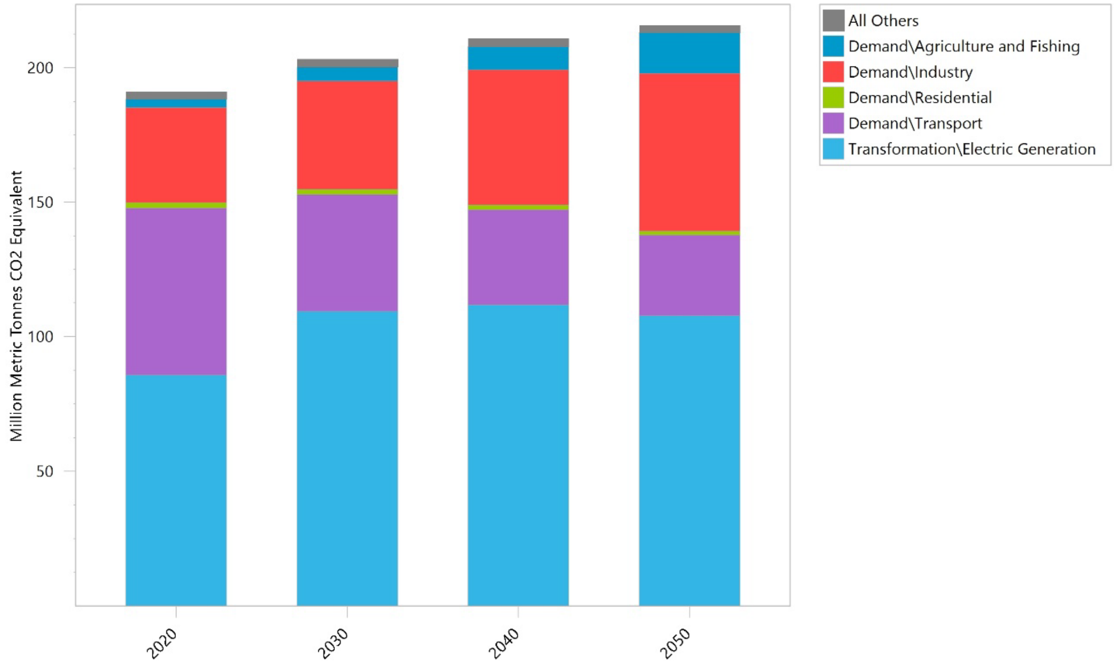

Figure 11: Historical and projected GHG emissions from the power generation and demand sectors for all fuels under Existing Policy (2020-2050)

f) System flexibility

Integrating variable renewables requires a flexible grid, achieved through consumer demand-side management, increased storage, and improved interconnection (Department for Business, Energy and Industrial Strategy, and Office of Gas and Electricity Markets 2021).

- **The Malaysian government acknowledges the potential of battery energy storge system (BESS) for grid stability and renewable energy integration. Several pilot projects are underway to test the feasibility and benefits of BESS in the Malaysian context. Foreign companies are also setting battery storage manufacturing facilities here.**
  - The first quarter of 2024 marks a significant milestone for Malaysia's energy landscape with Tenaga Nasional Bhd launching the nation's first utility-scale BESS pilot project. The 400-megawatt-hour (MWh) system is designed to address the intermittency challenges associated with renewable energy integration. (Adam 2024)
  - Sabah Energy Roadmap and Master Plan 2040 (2023) outlines plan to install a 100 MW BESS scheduled by 2026.
  - In September 2023, Sarawak Energy Bhd launched a pilot 60 MW BESS at its Sejingkat coal fired power plant. The initiative aims to provide critical grid services, such as peak shaving as well as spinning reserve, optimise plant operations and potentially reduce carbon emissions associated with coal generation. (Malaysian Investment Development Authority 2023)

- Malaysia inaugurated its first BESS-integrated EV charging station in October 2023. A 300kW/300kWh Pixii unit on the North-South Expressway paves the way for seven more, bringing total capacity to 2.4MW/2.4MWh. The units will also be paired with onsite solar PV arrays. (Colthorpe 2023)
- Citaglobal Genetec BESS unveiled Malaysia's first locally made BESS at Genetec's EPIC plant in April 2023. The 1MW MYBESS prototype, operational since December 2022, now supports the plant's energy needs. (Chong 2023)
- Citaglobal and PETRONAS signed a June 2023 MOU to collaborate on RE solutions including BESS, biogas, biomass, waste to energy (WTE), heat to energy (HTE) and carbon capture and utilisation (CCU). (The Star 2023)
- Chinese lithium battery maker Eve Energy plans to set up an energy storage company in Malaysia and acquire new land parcels to begin construction of an energy storage plant (Lei 2024).

● **Batteries are many orders of magnitude too small and costly for storing solar energy for daily balancing and dispatch purposes** (Leong, Platts and Amran 2021)

- While the planned 100MW annual battery installations (2030-2034) will enhance grid stability within the Malaysian power system, it's important to note that this technology is currently best suited for shorter-term energy storage (seconds to hours), not overnight and longer energy storage. Lithium-ion batteries, which dominate the stationary storage market (99% of recent deployments), typically have durations of four hours or less (Denholm, Cole and Blair 2023).

● **Pumped storage hydro (PSH): a key enabler for Malaysia's renewable energy integration.**

- **Mature technology.** PSH is a mature, off-the-shelf technology that thrives on significant elevation differentials between its water source and discharge point. This concept, known as head, plays a crucial role in optimising the cost per unit of energy production. Ideally, PSH targets head heights exceeding 500 meters. (Blakers, Pumped Hydro Energy Storage Atlases)
- **Dominant technology for long term storage.** PSH comprises about 96% of global storage power capacity and 99% of global storage energy volume in grid scale applications globally because of its low cost (Sandia National Lab). The current storage volume of PSH stations is at least 9,000 GWh, whereas batteries amount to just 7-8 GWh (Campbell and Ellis 2022).
- **A symbiotic trio: PSH, floating solar, and fisheries.** PSH combined with floating solar panels offers a compelling example of a symbiotic system. Floating solar generates renewable energy and, when paired with PSH, provides reliable, dispatchable power. These panels also offer shade, reducing evaporation and benefiting the aquatic environment, potentially boosting fish populations. Furthermore, PSH operations can improve water quality through oxygenation and create new habitats. This integrated approach maximises land and water use, presenting opportunities for sustainable energy development, enhanced fisheries, and enhanced ecosystem health, However, careful environmental assessment, technical design, and regulatory frameworks are essential for successful implementation.

- **Flexibility and grid stability through PSH.** PSH's inherent flexibility and rapid response capabilities play a crucial role in smoothing fluctuations in renewable energy supply and demand. This, in turn, allows for more efficient operation of thermal generators, reducing the need for frequent ramping and ultimately enhancing overall grid stability.

- **Learning from global trends.** Malaysia can learn valuable lessons from international efforts like the European Commission's XFLEX HYDRO initiative and Australia's capacity building programme (Australian Government 2023). These initiatives highlight the growing importance of PSH for grid flexibility in modern power markets with high renewable energy penetration.

- **Unlocking Malaysia's potential.** Studies (Weber, et al. 2024) indicate significant potential for off-river PSH development in Malaysia, with over 4,000 potential sites identified. However, unlocking this potential requires addressing challenges.

- **Barriers to private investment.** Currently, PSH development around the world is primarily driven by the public sector due to uncertainties around the business model and long lead times. Policy frameworks need to address these concerns to attract private sector investment.

- **Cost considerations for energy storage.** The upfront capital expenditure (CAPEX) for different energy storage technology varies significantly. PSH has an average capex of USD511/kWh, while lithium-ion battery storage is lower at USD270/kWh for and lead acid battery storage is at USD330/kWh (Mongird, et al. 2020).

    - **Balancing costs and benefits.** While PSH boasts a substantially higher upfront cost, it also offers a much longer technical lifetime of 40 years compared to batteries' 10–12-year lifespan (Mongird, et al. 2020). This translates to lower long-term operational costs for PSH.

    - **Policy considerations for a sustainable future.** Despite PSH's long-term benefits, policymakers might need to consider financial incentives like grants, subsidies, or tax breaks to bridge the initial cost gap and encourage investment in PSH projects.

    However, it's important to acknowledge that battery storage costs are projected to decline over time due to learning curves (Rocky Mountain Institute 2024). This raises the possibility of battery storage becoming a more cost-competitive alternative to PSH in the future.

- **Environmental impact.** While the development of PSH facilities may pose localised ecological concerns, the implementation of off-river configurations can serve to mitigate these potential impacts. In formulating energy storage policy, decision-makers should undertake a comprehensive assessment of the environmental burdens associated with both battery storage and PSH technologies. This comparative analysis should encompass the entire life cycle of each technology, including particular attention to the challenges of battery disposal and recycling.

- **Water consumption.** Achieving a fully renewable energy grid could necessitate a daily water allocation of approximately three litres per capita for reservoir filling and evaporation compensation. This volume equates to roughly 20 seconds of a standard morning shower. Notably, once the reservoir reaches its operational level, the water can be cycled and reused for extended periods, potentially exceeding 50 years, with minimal replenishment solely to counteract evaporative losses. (Blakers, Nadolny and Stocks 2022)

- **Land requirements.** The land footprint associated with PSH implementation is relatively modest. An estimated three-square meters per person, equivalent to the area of a double bed, would be submerged for reservoir construction. (Blakers, Nadolny and Stocks 2022)

- **Interconnections, crucial for variable renewable energy integration, are becoming a growing policy focus as Southeast Asia transitions toward a more connected and flexible regional grid.**
  - Expanding transmission infrastructure plays a crucial role in facilitating large-scale integration of renewable energy sources. High-voltage direct current (HVDC) technology offers significant advantages in this regard:
    - **Reduced storage needs:** Efficient long-distance transmission allows for balancing renewable energy supply and demand across wider geographical regions, reducing the need for large-scale energy storage solutions (DNV 2024).
    - **High-capacity, long-distance transmission:** State-of-the-art HVDC lines can transmit gigawatts of power at megavolts over thousands of kilometers (km). For example, lines can operate at 1100 kilovolts (kV), spanning 3000 km, transmitting 12 GW of power, while experiencing only a 10% energy loss during transmission. This enables the utilisation of geographically dispersed renewable resources. (Blakers)
  - Previously limited to bilateral arrangements[40], the Lao PDR – Thailand – Malaysia – Singapore Power Integration Project (LTMS-PIP) marks a shift towards increased multilateral power trade. (International Energy Agency 2019)
  - Current interconnections between Malaysia and neighbouring countries are as follows (Tenaga Nasional Berhad 2023, Lian 2021):
    - Malaysia-Thailand: 300 MW high-voltage direct current (HVDC) + 80 MW high-voltage alternating current (HVAC)
    - Malaysia-Singapore: 500 MW x 2 (HVAC)
    - Sarawak-West Kalimantan: nominated capacity is 80 MW (off-peak) and 110 MW (peak) HVAC with room for further negotiation

[40] Trade arrangements mostly limited to unidirectional power trades under power purchase agreements (PPAs) or bidirectional trading of electricity without financial compensation.

- AGF phase 2.3 will investigate the role of regional transmission line interconnection in facilitating decarbonisation across Southeast Asia.

- **National transmission lines are the backbone for enabling electricity exchange across borders. Malaysia has varied levels of preparedness** (Figure 12, Figure 13 and Figure 14)**.**

  - Peninsular Malaysia and Sarawak possess well-developed electricity grids featuring 500 kV transmission lines. These high-voltage lines facilitate efficient long-distance power transfer within these regions. In contrast, Sabah currently relies on a sole 275 kV backbone grid to transfer power from the west coast to the east coast. This represents a potential bottleneck for bulk power transmission across the state. Upgrading Sabah's grid infrastructure could be crucial for optimising power distribution and integration.

Figure 12: Peninsular Malaysia's power generation and grid infrastructure
(Source: Global Energy Network Institute)

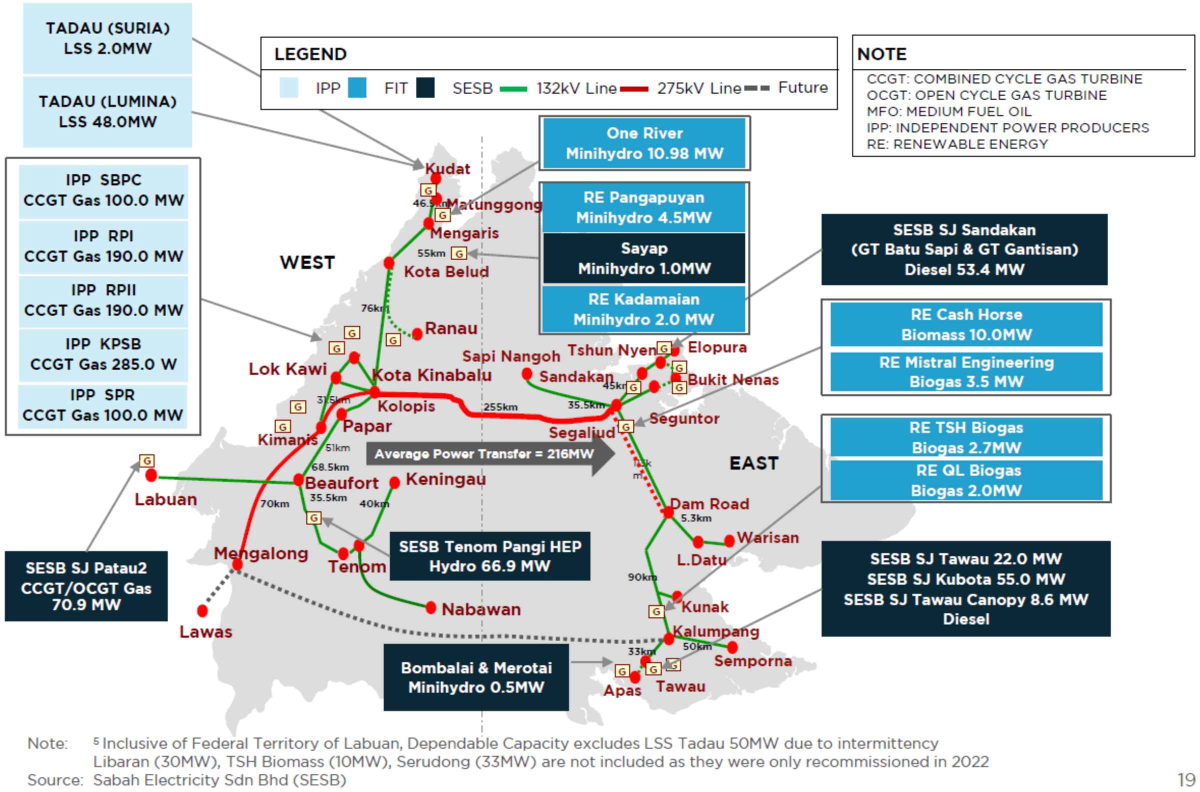

Figure 13: Sabah's power generation and grid infrastructure
(Source: Sabah Electricity Sdn Bhd)

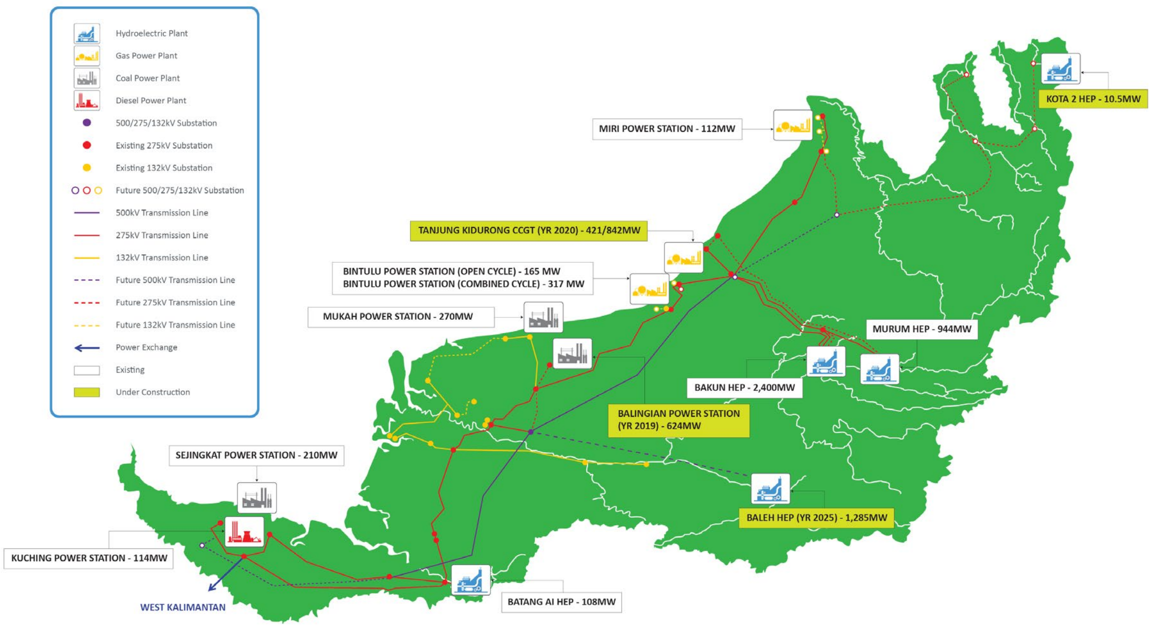

Figure 14: Sarawak's power generation and grid infrastructure
(Source: Sarawak Energy Berhad)

- Sabah's current power development plan prioritises the construction of 275 kV transmission lines. This strategic choice reflects a focus on:
    - **Cost-effectiveness:** 275 kV lines offer a balance between transmission capacity and affordability, catering to Sabah's current power needs within the state. Upfront costs for building and maintaining 500 kV lines are significantly higher.
    - **Addressing immediate needs:** The 275 kV lines will strengthen Sabah's internal grid and facilitate the planned interconnection with Sarawak's 275 kV grid, enhancing regional energy security.
- However, a **regional** energy planning approach might prioritise a higher voltage transmission line from a long-term perspective. This could involve:
    - **Futureproofing for power exchange:** A 500 kV grid could accommodate a larger volume of electricity exchange between interconnected grids in the future.
    - **Transmission efficiency:** for very long-distance power transmission across regions, 500 kV lines offer greater efficiency, minimising energy loss during transmission.
- The optimal solution likely lies in **balancing** immediate state-level needs with a long-term vision for regional power interconnection.

3.2 Optimised existing policy

Comparison between the Optimised Existing Policy, Existing Policy and NETR scenarios will be made on the following fronts:

a) Capacity and generation
b) Cost: investment and production
c) Greenhouse gas (GHG) emission

3.2.1 Capacity and generation

The impacts of optimisation on the power generation mix from 2020 to 2050 are visualised in Table 3, Figure 15 and Figure 16.

- **Variable renewables:** The optimised scenario strategically refines the projected solar PV capacity, achieving the NETR target of 56.3 GW by 2050, whilst maintaining a generation factor of 1.3 TWh/GW.

Table 3: Comparing power generation capacity and generation in Existing Policy, Optimised Existing Policy and NETR targets (2050)

	2050 EP		2050 OEP		2050 NETR
	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (TWh)	Capacity (GW)
Share of RE					
Large hydro	13.07	76.02	9.47	84.07	10.67
Small hydro	2.01	11.69	1.22	10.82	
Solar PV	72.26	94.39	56.26	73.49	56.26
Biomass	1.76	9.61	0.97	2.20	0.97
Biogas	0.80	4.37	0.58	4.80	
MSW ST	0.82	3.40	0.18	1.13	
Batteries	0.50	0	0.76	0	
Pumped storage hydro					
Wind onshore	0	0	0	0	
Wind offshore	0	0	0	0	
All others	0.14	0.79	0.06	0.50	
Subtotal	91.36	200.27	69.50	177.01	
Share of fossil fuels					
Natural gas	44.12	240.96	53.38	264.63	28.13
Diesel	2.34	0.00	2.34	0.00	0
Sub-total	46.46	240.96	55.72	264.63	
Total	**137.82**	**441.23**	**125.22**	**441.64**	

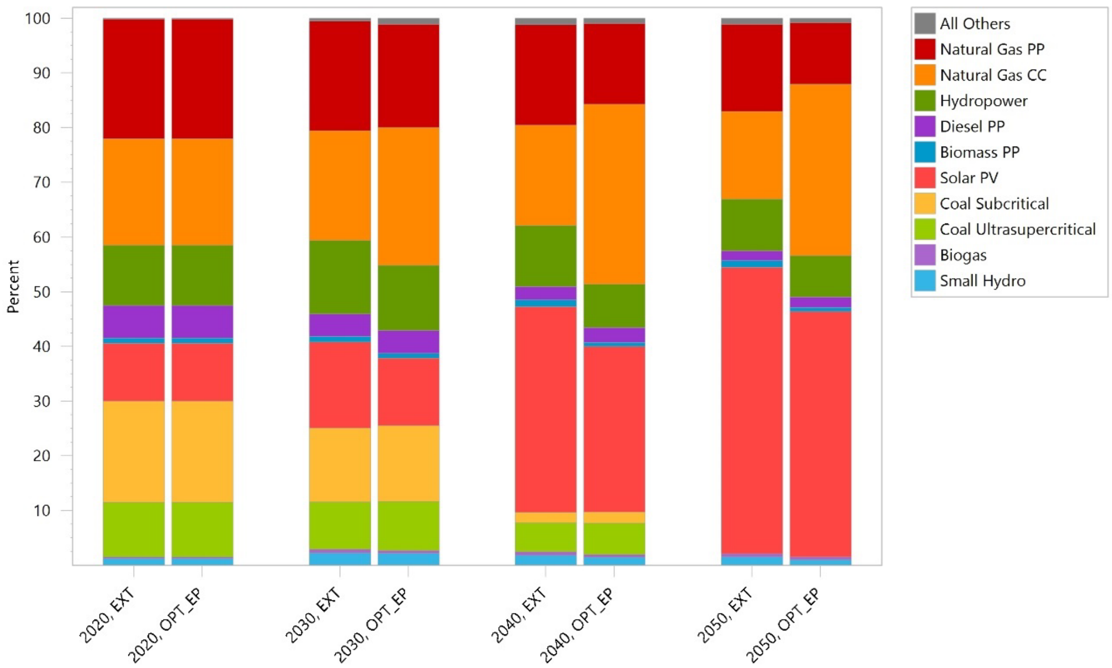

Figure 15: Comparing power generation capacity share in Existing Policy and Optimised Existing Policy scenarios (2020-2050)

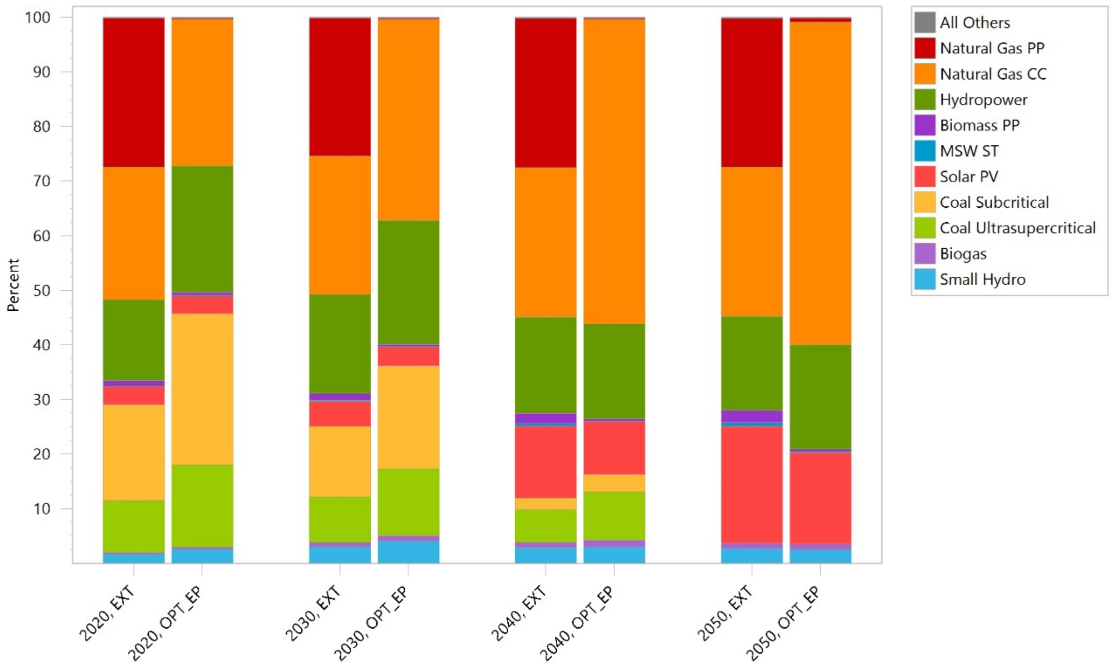

Figure 16: Comparing power generation share in Existing Policy and Optimised Existing Policy scenarios (2020-2050)

- **Dispatchable low-carbon generation:** the optimised power scenario prioritises efficient generation over sheer capacity for most renewable sources. This strategy leads to:

  - **Large hydro:** Significant capacity reduction (-28%; from 13.1 to 9.5 GW) but a surprising increase in generation (+11%; 76.0 to 84.1 TWh) due to improved utilisation (generation factor jumps from 5.8 to 8.9 TWh/GW).

  - **Small hydro:** Similar to large hydro, a capacity decrease (-67%; from 2.0 to 1.2 GW) is offset by a slight decline in generation (-7.7%; from 11.7 to 10.8 TWh) and a significant rise in generation factor (5.9 to 9.0 TWh/GW).

  - **Biomass:** This sector faces the most significant decrease in both capacity (-45%; from 1.8 to 1.0 GW) and generation (-77%; from 9.6 to 2.2 TWh). Generation factor decreases from 5.3 to 2.2 TWh/GW. Further investigation is needed to understand the cause and potential mitigation strategies.

  - **Biogas:** Shows promise with a slight decrease in capacity (-28%; from 0.8 to 0.6 GW) but an increase in generation (+9.8%; from 4.4 to 4.8 TWh) and a substantial jump in generation factor (5.5 to 8.3 TWh/GW).

  - **Natural gas presents a unique case:** The optimised scenario proposes a significant capacity increase (almost double the NETR target) with a moderate rise in generation compared to the un-optimised Existing Policy scenario (+9.8%; from 241.0 to 264.6 TWh). However, the generation factor shows a slight decline (from 5.5 to 5.0 TWh/GW). This suggests that the additional capacity might not be fully utilised, requiring further analysis of cost-effectiveness.

  - Overall, the optimised scenario prioritises efficient use of existing renewable capacity and highlights the potential of biogas. However, the significant decline in biomass generation requires further investigation. The proposed increase in natural gas capacity needs careful consideration to ensure cost-effectiveness.

  - Table 8 in the Appendix provides a detailed explanation of how LEAP handles generation capacity and generation output differently in the simulation (Existing Policy scenario) and optimisation (Optimised Existing Policy scenario) modes.

- **Firm power high-carbon generation:** The Optimised Existing Policy scenario aligns with the NETR target by phasing out coal and diesel generation entirely by 2050.

- While the **ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025** sets an aspirational target of 35% for the share of RE in ASEAN's installed power capacity by 2025, Malaysia's Existing Policy and Optimised Existing Policy scenarios suggest an installed RE capacity share of 25% in 2025, falling short of the regional target.

3.2.2 Cost

- A critical aspect of evaluating multi-decade plans lies in presenting a comprehensive picture of their financial impact. The two key cost metrics are:

  - **Real cost:** Provides a straightforward view of the total expenditure throughout the plan, highlighting the immediate budgetary requirements.

  - **Discounted cost:** Reflects the present-day value (in 2019, the first scenario year) value of all future costs, accounting for the time value of money. This approach acknowledges that future expenditures have a lower present value, providing a more accurate assessment of long-term economic burden.

- By presenting both real and discounted costs, stakeholders gain greater transparency into the financial implications of the plan. They can understand the immediate budgetary needs alongside the project's long-term economic footprint.

- This analysis employs both real and discounted cost approaches to assess the optimised configuration's financial performance compared to the non-optimised approach (Figures 14, 15, 16, and 17).

- The optimised configuration demonstrates consistent advantages in terms of real and discounted cumulative investment costs (Figure 17 and Figure 18) throughout the evaluation period until 2050.

- The optimised scenario consistently yields lower real and discounted electricity production costs compared to the unoptimized approach (Figure 19 and Figure 20). This translates to a substantial 18% cost reduction in 2050, with production costs falling from 8.8 US cents/kWh to 7.2 US cents/kWh (Table 5).

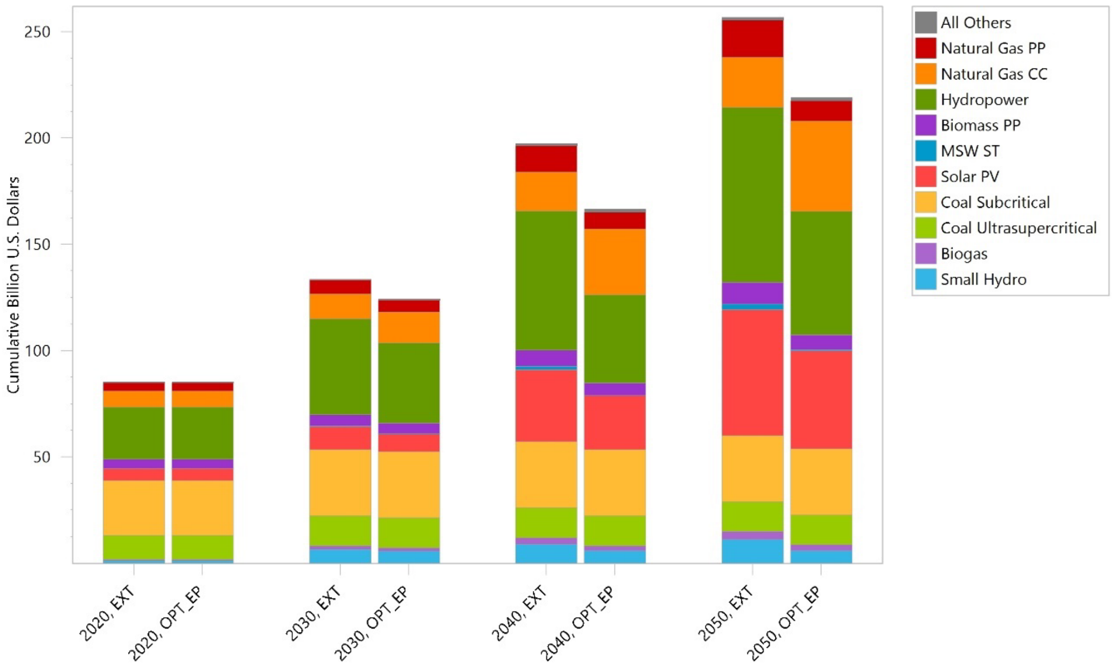

Figure 17: Comparing power generation capacity cumulative real investment cost in Existing Policy and Optimised Existing Policy scenarios (2020-2050)

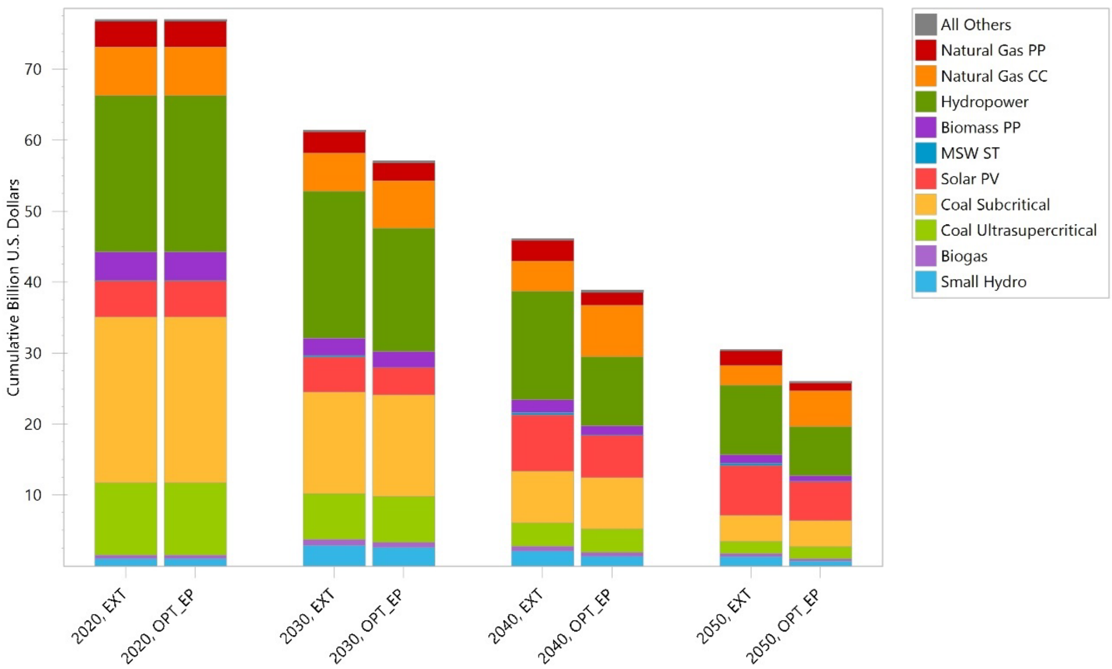

Figure 18: Comparing power generation capacity cumulative discounted investment cost in Existing Policy and Optimised Existing Policy scenarios (2020-2050)

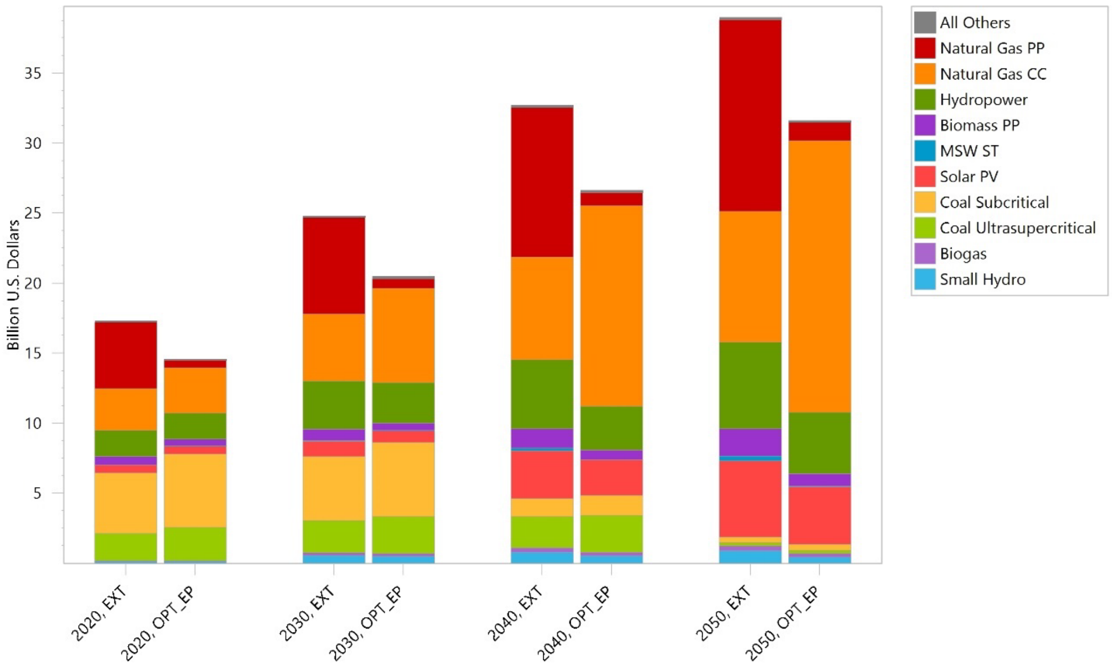

Figure 19: Comparing real power production cost between Existing Policy and Optimised Existing Policy (2020-2050)

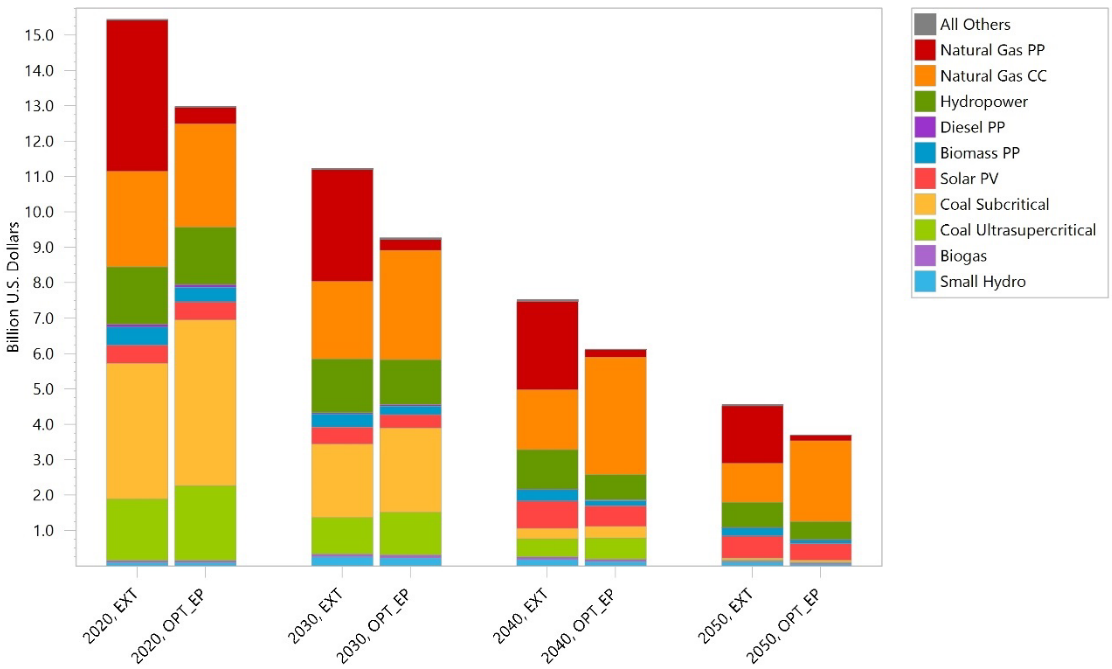

Figure 20: Comparing discounted power production cost between Existing Policy and Optimised Existing Policy (2020-2050)

3.2.3 GHG emissions

- The Optimised Existing Policy scenario offers a significantly more favourable pathway towards decarbonisation. Compared to the Existing Policy scenario, it achieves a 11% improvement in emissions reduction (Figure 21 and Figure 22) at a more cost-effective rate, incurring a 15% lower cumulative real investment cost by 2050.

- However, both scenarios fall short of achieving the ambitious goal of near-zero emissions for the power sector. This underscores the necessity for exploring more ambitious policy measures, which will be discussed in detail in the following section 3.3.

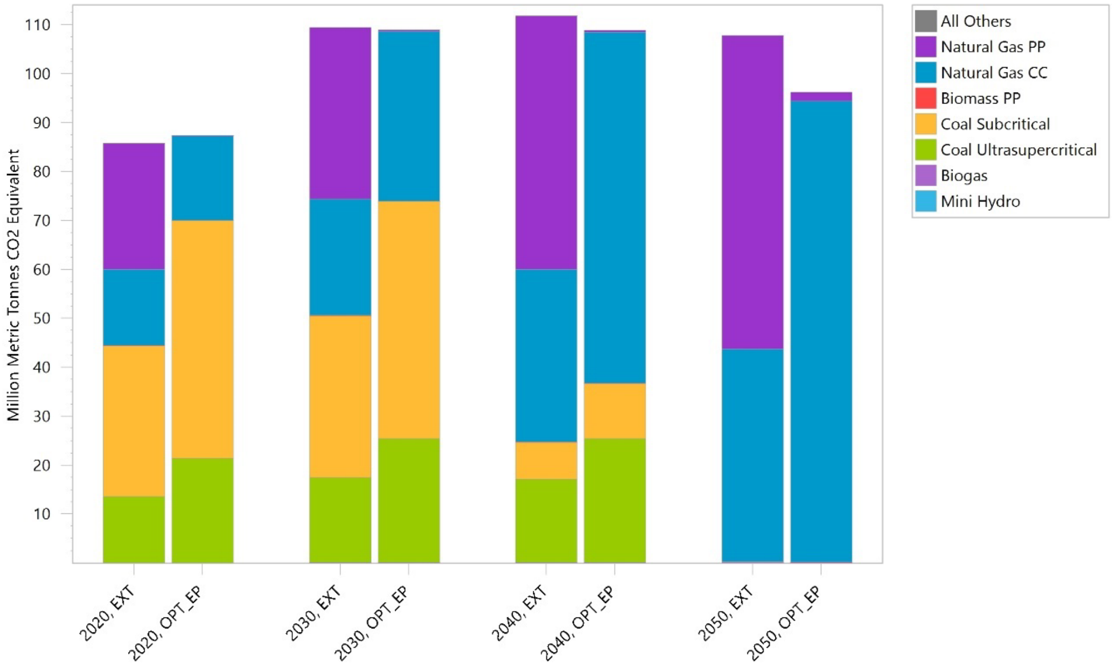

Figure 21: Comparing power generation GHG emissions in Existing Policy and Optimised Existing Policy scenarios (2020-2050)

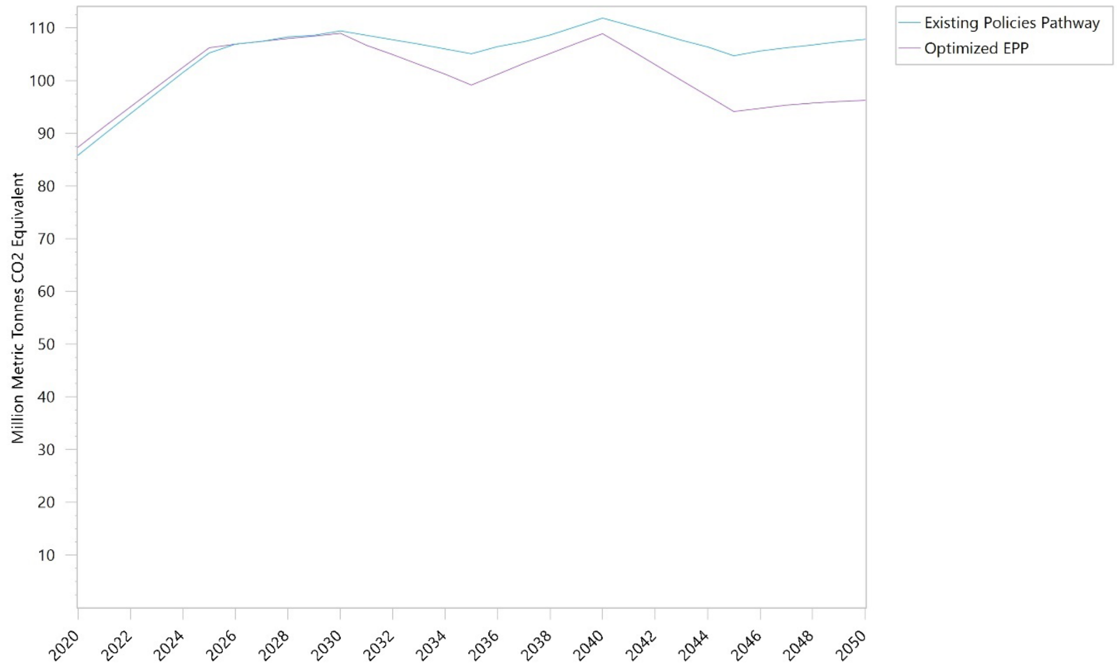

Figure 22: Power generation GHG emissions trajectories in Existing Policy and Optimised Existing Policy scenarios (2020-2050)

3.3 Optimised more ambitious policy

The More Ambitious Policy scenario hinges on two key pillars:

- **Demand-side efficiency:** This strategy prioritises reducing overall electricity consumption through efficiency measures in the demand sectors.
- **Decarbonised generation:** This approach focuses on transitioning the power sector towards cleaner energy sources with lower carbon emissions.

3.3.1 Demand and energy efficiency

- While demand side efficiency measures have increased, it's important to acknowledge that electricity demand is still projected to increase by 137% from 2019 to 2050, reaching 369 TWh (Figure 23).

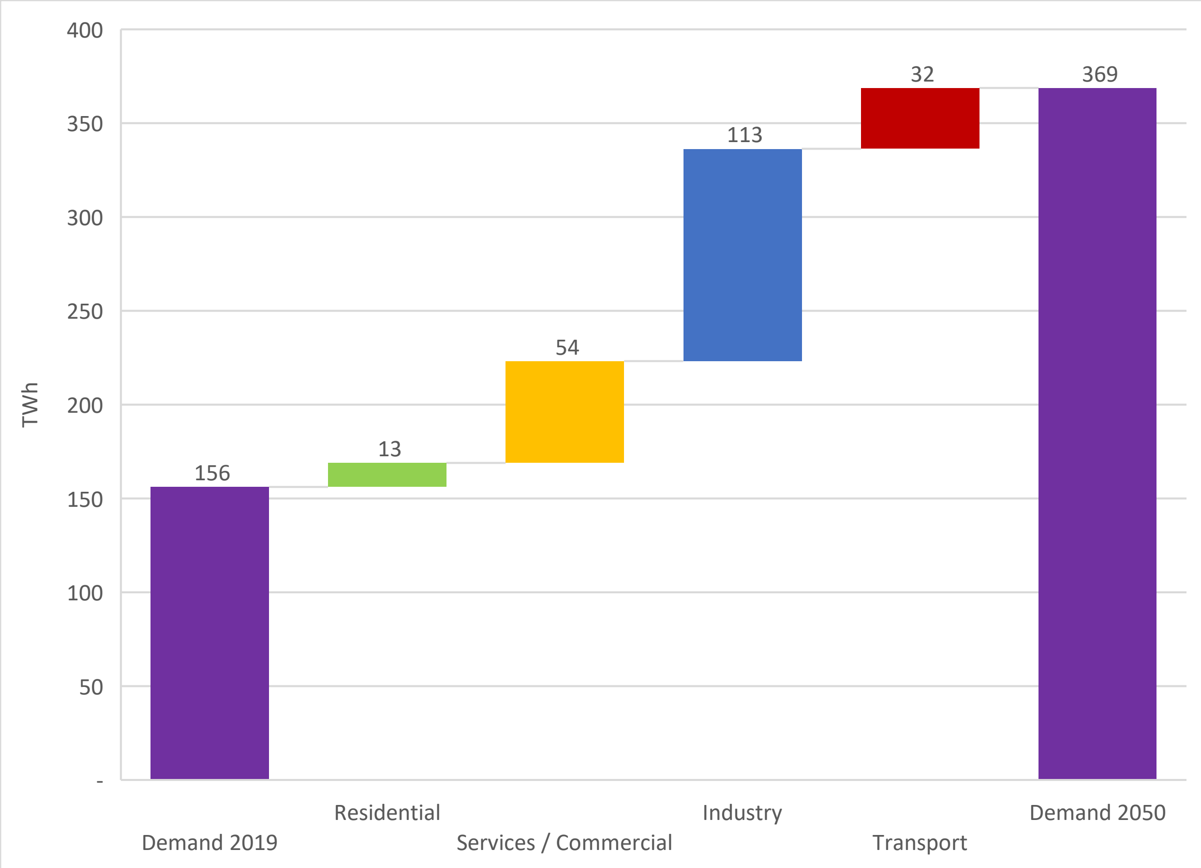

Figure 23: Contribution by sectors to increase electricity demand in the More Ambitious Policy scenario (2019-2050)

- Figure 24 illustrates the comparative electricity demand across various demand sectors under the Existing Policy and More Ambitious Policy scenarios in 2050.

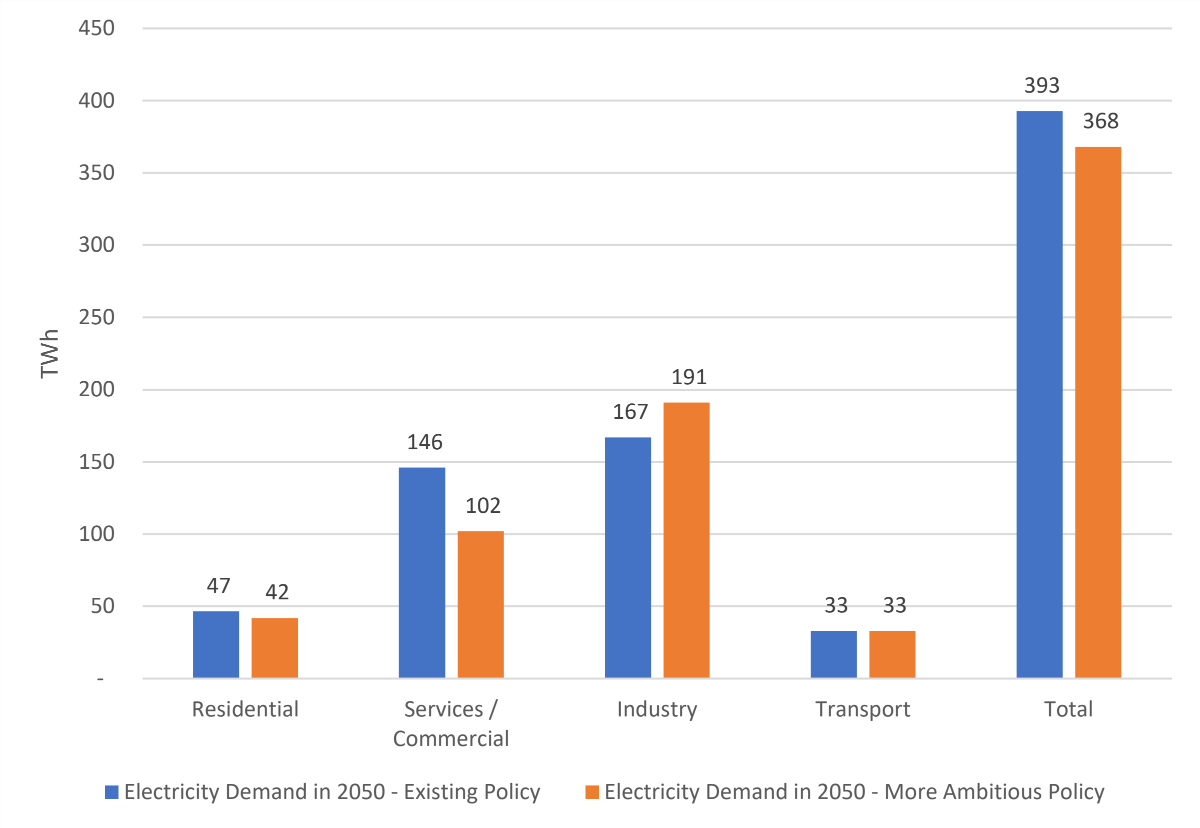

Figure 24: Comparing electricity demand in 2050 under Existing Policy and More Ambitious Policy

- **Residential.** The More Ambitious Policy scenario in the LEAP model assumes a significant increase in energy-efficient household devices (lighting, refrigeration, and air conditioning) to 100% penetration by 2060, along with a shift towards electric cooking. This strategy is projected to reduce residential sector electricity demand from 47 TWh to 42 TWh in 2050, representing an 11% improvement compared to the Existing Policy scenario.

- **Commercial/services.** The More Ambitious Policies scenario prioritises aggressive energy efficiency improvements, doubling the savings target to 46%. This enhanced focus is necessary because the current Energy Efficiency and Conservation Act covers a limited portion of commercial consumption (21%) and a negligible share of total users (less than 1%). Despite this ambitious target, the continued electrification and growth of the sector still lead to a projected demand increase of 54 TWh by 2050 compared to 2019. However, this represents a significant 30% reduction compared to the 98 TWh increase anticipated under the Existing Policy scenario, highlighting the effectiveness of the efficiency measures.

- **Industry.** The More Ambitious Policy scenario for the industrial sector projects a significant increase in electricity demand by 2050. Compared to the Existing Policy scenario, the additional demand is projected to be 113 TWh (26% higher) in 2050. This rise is driven by a strategic shift towards electrification, with the fuel share of electricity rising from 39% (Existing Policy) to 46% (More Ambitious Policy) by 2050.

- **Transport.** The transport sector maintained its existing policies (no more ambitious policy implemented). Consequently, the projected increase in electricity demand remains unchanged at 32 TWh across both the More Ambitious Policy and Existing Policy scenarios.

3.3.2 Power generation

The LEAP model incorporates two key assumptions to achieve the More Ambitious Policy scenario:

- **No new fossil fuel capacity additions after 2030:** This policy restricts the construction of new power plants reliant on fossil fuels.

- **Phased retirement of fossil fuels:** The scenario assumes a complete coal phase-out by 2040, followed by natural gas and diesel by 2050.

To assess the More Ambitious Policy scenario's effectiveness, comparisons are made across the following dimensions with the NETR, Existing Policy, and Optimised Existing Policy scenarios:

- Capacity and generation: This analysis compares the projected power generation capacity and output under each scenario.

- Cost: This evaluation considers both investment costs and production costs across the scenarios.

- Greenhouse gas emissions: This comparison assesses the impact of each scenario on greenhouse gas emissions from the power generation sector.

3.3.2.1 Capacity and generation

- The Optimised More Ambitious Policy scenario significantly elevates the role of renewables in the 2050 power generation mix, as detailed in Figures 25-26.

    - **Variable renewable:** This scenario strategically increases projected solar PV capacity to 81.0 GW by 2050, exceeding both the NETR target of 56.3 GW and the capacity projected under the Optimised Existing Policy scenario (also 56.3 GW) by 44%. This translates to a projected solar PV generation of 105 TWh, exceeding the 74 TWh projected under Optimised Existing Policy by approximately 42%.

Table 4: Comparing capacity and generation in Existing Policy, Optimised Existing Policy, NETR targets and Optimised More Ambitious Policy (2050)

	2050 EP		2050 OEP		2050 NETR	2050 OMAP	
	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (TWh)	Capacity (GW)	Capacity (GW)	Generation (TWh)
Share of RE							
Large hydro	13.07	76.02	9.47	84.07	10.67	13.60	120.69
Small hydro	2.01	11.69	1.22	10.82		4.22	37.46
Solar PV	72.26	94.39	56.26	73.49	56.26	81.02	104.82
Biomass	1.76	9.61	0.97	2.20	0.97	23.93	125.24
Biogas	0.80	4.37	0.58	4.80		0.71	4.17
MSW ST	0.82	3.40	0.18	1.13		1.53	6.87
Batteries	0.50	0	0.76	0		4.50	0
Pumped SH						8.01	0
Wind onshore	0	0	0	0		2.50	3.22
Wind offshore	0	0	0	0		2.80	11.37
All others	0.14	0.79	0.06	0.50		0.36	2.30
Subtotal	91.36	200.27	69.50	177.01		143.18	416.14
Share of fossil fuels							
Natural gas	44.12	240.96	53.38	264.63	28.13	0	0
Diesel	2.34	0.00	2.34	0.00	0	0	0
Sub-total	46.46	240.96	55.72	264.63		0	0
Total	**137.82**	**441.23**	**125.22**	**441.64**		**143.18**	**416.14**

- **Dispatchable low-carbon generation:** Optimisation of the More Ambitious Policy scenario prioritises dispatchable low-carbon sources:

  – **Large hydro:** The scenario increases the capacity from 9.5 GW (Optimised Existing Policy) to 13.6 GW (+44%), with generation rising correspondingly from 84.1 TWh to 120.7 TWh (+44%). This significant increase in large hydro development warrants further environmental impact assessments.

  – **Small hydro:** The scenario prioritises small hydro development, with capacity increasing from 1.2 GW (Optimised Existing Policy) to 4.2 GW (3.5x), and generation rising proportionately from 10.8 TWh to 37.5 TWh (3.5x). This suggests that NETR should give greater consideration to small hydro power development.

  – **Biomass - a significant increase in projected capacity and generation:** The scenario proposes a substantial increase in biomass capacity, from 1.0 GW to 23.9 GW (14x), with generation rising from 2.2 TWh to 125.2 TWh (57x). This suggests significant, potentially under-recognised potential for biomass power generation in Malaysia. However, to ensure sustainability, this finding should be triangulated with a land-use study to determine the maximum amount of biomass that can be harvested sustainably.

Beyond traditional biomass sources. Biomass availability should not be limited to traditional sources like forestry and agricultural residues. The scenario would benefit from considering the sustainable development of tree plantations as a dedicated source of wood for various purposes, including energy production.

- **Biogas:** The scenario shows a modest increase in biogas capacity from 0.6 GW to 0.7 GW (+17%). Generation decreases slightly from 4.8 TWh (Optimised Existing Policy) to 4.2 TWh (-13%).

- The Optimised More Ambitious Policy scenario suggests an installed RE capacity share of 30% in 2025, falling short of the aspirational target of 35% for the renewable energy share in ASEAN's installed power capacity by 2025 as outlined in the **ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025**.

- **Malaysia needs 1.96 GWh of storage per million people for 100% renewable electricity.**

  - Analysis for Malaysia suggests an approximate need for 250 MW of storage capacity per million people, assuming a four-hour discharge duration for batteries and a ten-hour discharge duration for pumped storage hydro to achieve 100% renewable electricity. This translates to 1.96 GWh of storage per million people. [41]

  - However, this is significantly lower than storage requirements observed in countries like Australia (20 GWh) and the US (21 GWh). A rough approximation of the storage required to support 100% renewable electricity for an advanced economy is 20 GWh per million people. The Australian data point reflects a 20-hour storage assumption, highlighting the influence of factors such as power demand, renewable energy variability, and existing infrastructure on storage needs. (Blakers, Lu, et al. 2022)

  - As the share of variable renewable energy increases, storage requirements are projected to rise. Studies suggest a minimum of eight hours of storage capacity is necessary for higher renewable energy penetration (Silverstein 2024). In the US context, achieving 80% renewables may require storage durations ranging from 12 to 120 hours, with researchers optimistic about reaching 12-hour lithium-ion battery capabilities by 2050 (Carrie 2022).

[41] The Optimised More Ambitious Policy scenario in 2050 projects a battery storage requirement of 4.5 GW and pumped storage hydro of 8.0 GW for Malaysia to achieve 100% renewable electricity, assuming a population of 50 million. This translates to a storage capacity of 250 MW per million people, providing approximately 1.96 GWh of storage per million people with a 4-hour discharge duration for batteries and 10-hour discharge duration for pumped storage hydro.

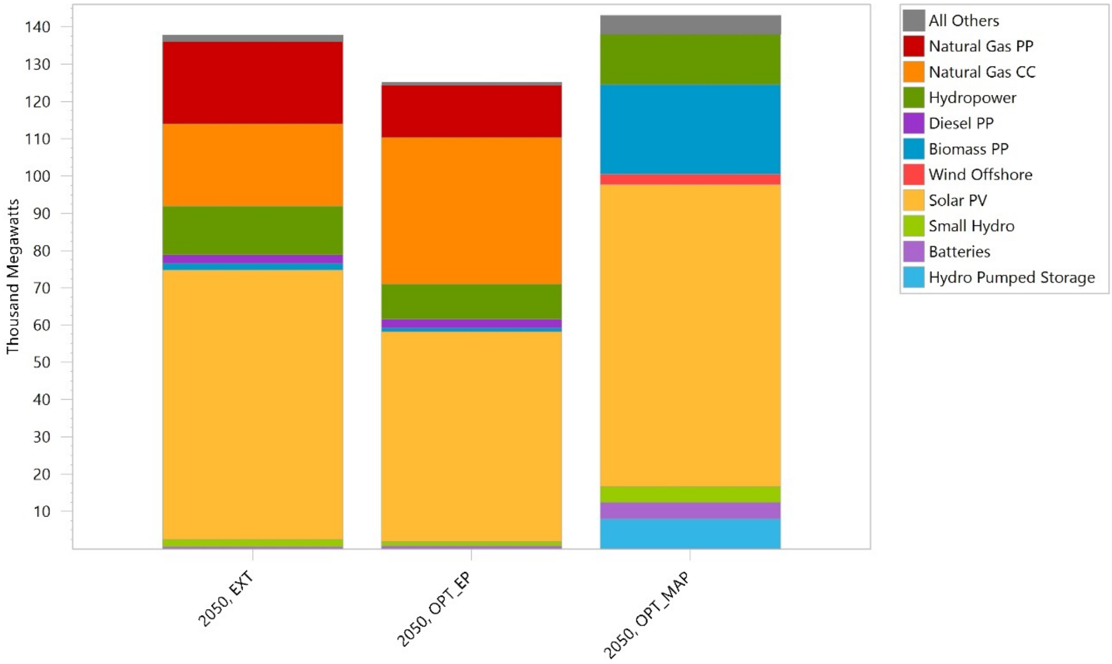

Figure 25: Comparing generation capacity between Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy (2050)

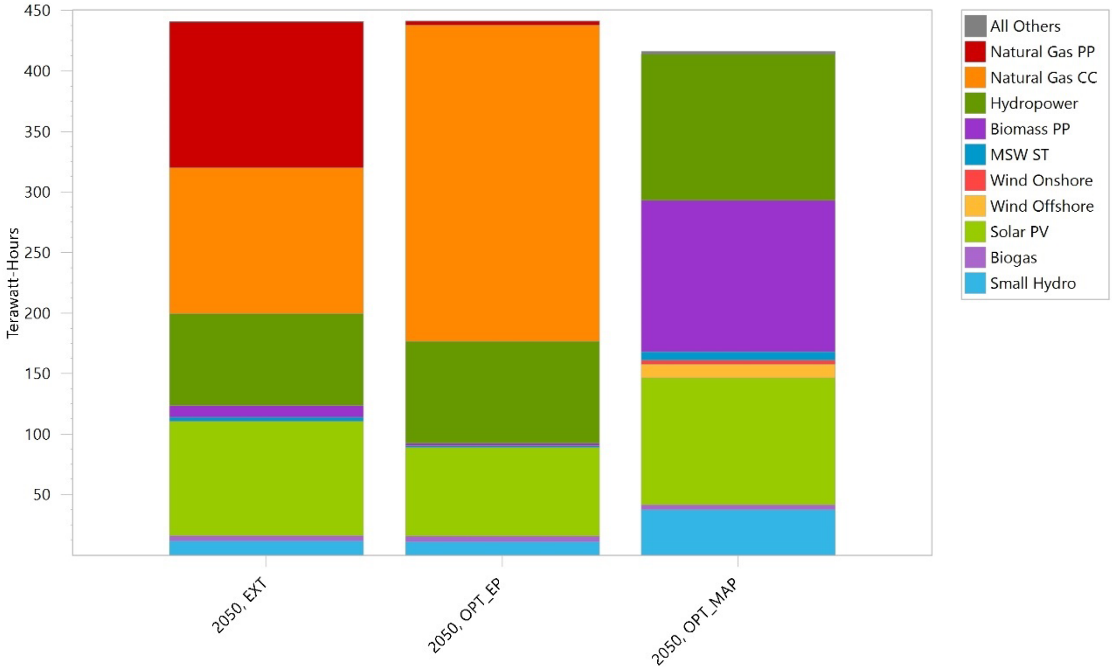

Figure 26: Comparing generation between Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy (2050)

3.3.2.2 Cost

- The Optimised More Ambitious Policy scenario requires **1.8x increase in cumulative real / discounted investment costs** for renewable power generation compared to the Optimised Existing Policy scenario (Table 5).

While the Optimised More Ambitious Policy incurs a projected 20% increase in electricity generation costs by 2050 (10.6 US cents/kWh compared to 8.8 US cents/kWh under the Existing Policy scenario), the transition to renewable energy offers substantial long-term benefits, including:

- **Improved public health and reduced healthcare costs:** Transitioning away from fossil fuels reduces air pollution, leading to improved public health outcomes and potentially lower healthcare expenditures for the government.

- **Energy security through reduced reliance on imports:** By increasing reliance on domestic renewable energy sources, Malaysia lessens its vulnerability to price fluctuations in the global fossil fuel market, enhancing energy security.

Table 5: Cost and emission comparisons between Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy scenarios

	Power generation capacity cumulative investment cost, 2001-2050 (USD billion)		**Production cost of electricity in 2050** (US cents / kWh)		**Power generation emission in 2050** (million metric tonne CO_2 eq)
	Real	Discounted	Real	Discounted	
Existing Policy	257	31	8.8	1.03	108
Optimised Existing Policy	219	26	7.2	0.84	96
Optimised More Ambitious Policy	393	47	10.6	1.24	2

- By 2050, the discounted cost of electricity generation is projected to range from 0.84 to 1.24 US cents/kWh (Table 5). It's important to note that this cost excludes transmission and distribution expenses, which are additional factors affecting the final price consumers pay.

- Current residential electricity tariffs, even after subsidies, range from 4.6 to 12.0 US cents/kWh (Table 6). As an illustration, the Malaysian government recently allocated RM2 billion to subsidise electricity costs for consumers in Peninsular Malaysia during the first half of 2024 (Malay Mail 2024).

Table 6: Malaysia's current electricity tariff (TNB)

	Electricity Tariff Range (US cents / kWh)
Residential	4.6 - 12.0
Commercial	4.6 – 10.7
Industrial	4.2 – 9.2

Exchange rate: 1 MYR = 0.21 USD

- **Integrating the cost of carbon bolsters the case for optimised More Ambitious Policy scenario.**

    - Social cost = production cost of electricity + cost of carbon.

      Estimates for the cost of carbon vary widely, for example USD 54 (Wang, et al. 2019), USD 185 (Rennert, et al. 2022) and USD 417 (Ricke, et al. 2018), as shown in Table 7. This variability stems from differing assumptions about future emissions, climate impacts, and the valuation of these damages.

        - Factoring in the cost of carbon reveals a compelling economic advantage for the Optimised More Ambitious Policy. With rising carbon costs, this policy becomes progressively cheaper than both Existing Policy and Optimised Existing Policy, driven by its significant emissions reduction.

Table 7: Social cost comparisons between Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy scenarios

	Production cost of electricity in 2050 (real) (USD cents / kWh)	**Cost of carbon**			**Social cost in 2050**		
		USD 54 / tonne CO_2 eq	**USD 185 / tonne CO_2 eq**	**USD 417 / tonne CO_2 eq**	**USD 54 / tonne CO_2 eq**	**USD 185 / tonne CO_2 eq**	**USD 417 / tonne CO_2 eq**
		(USD cents / kWh)			(USD cents / kWh)		
Existing Policy	9.84	1.48	5.08	11.46	10.28	13.88	20.26
Optimised Existing Policy	7.23	1.10	3.76	8.46	8.30	10.96	15.66
Optimised More Ambitious Policy	9.46	0.02	0.07	0.17	10.62	10.67	10.77

- Singapore has implemented a carbon tax schedule, currently the highest in Asia. The tax is set to increase from SGD25 (USD18) per tonne of CO_2 equivalent (tCO_2e) in 2024/25 to SGD45 (USD33) in 2026/27, and further to SGD50-80 (USD37-59) by 2030.
- Malaysia will introduce a carbon tax targeting the iron and steel industry as well as the energy sector starting from 2026 onwards (Ministry of Finance 2024). The new tax is also seen as a measure to prevent tax leakage in light of the implementation of the European Union's Carbon Border Adjustment Mechanism (CBAM) in January 2026. The carbon tax collected will fund green energy research and development, further fostering sustainable practices.

3.3.2.3 GHG emission

- Compared to the Existing Policy and Optimised Existing Policy scenarios, the More Ambitious Policy achieves a dramatic reduction in GHG emissions from the power sector, reaching just 2 $MtCO_2$-eq in 2050 (compared to 108 $MtCO_2$-eq and 96 $MtCO_2$-eq, respectively) (refer to Table 5 and Figure 27).

- While a focus on decarbonsing the electricity grid, as seen in the Optimised More Ambitious Policy scenario is crucial, it cannot single-handedly achieve complete decarbonisation across all sectors. 98% of Malaysia's overall energy sector GHG emissions remain outside the power generation sector in the Optimised More Ambitious Policy scenario in 2050 (Figure 28). Industries and transportation, in particular, pose a challenge due to the difficulty of electrifying certain processes and vehicles. This underscores the critical need to develop and increase the share of green hydrogen, biomethane, and bio-LNG used in these sectors to achieve comprehensive decarbonisation.

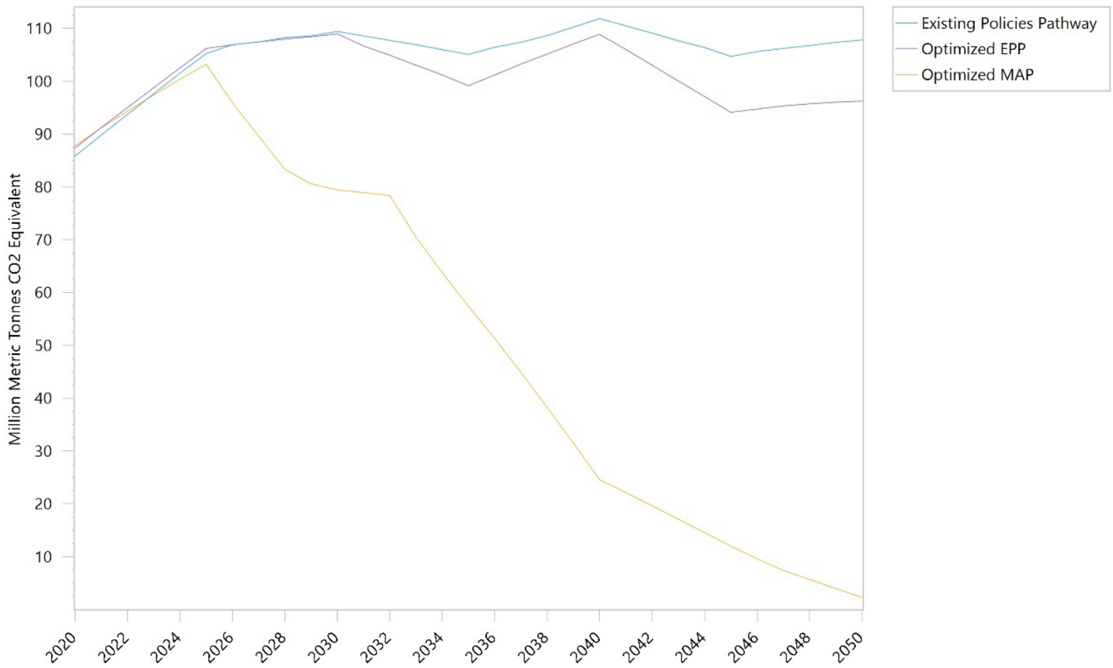

Figure 27: Power generation GHG emission trajectories in Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy scenarios (2020-2050)

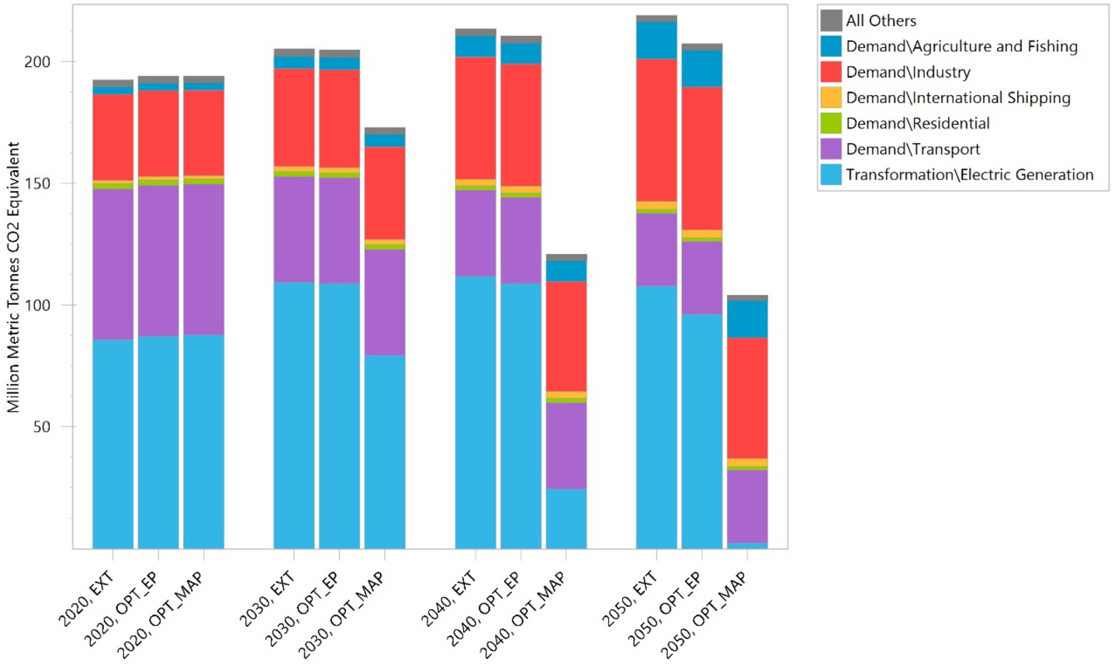

Figure 28: Comparing GHG emission of power generation and demand sectors in Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy scenarios (2020-2050)

4. POLICY RECOMMENDATIONS

4.1 Power generation

- **Reassessing the role of natural gas**

  - **Reduce dependence on natural gas for baseload power:** While previously seen as a cost-effective transition fuel, rising natural gas prices due to geopolitical instability necessitate a strategic shift.

  - **Explore alternatives for grid integration:** Although natural gas emits less carbon than coal (490 gCO_2-eq per kWh), it will not lead Malaysia to a decarbonised electricity system.

    Solar is increasingly limited only by how fast it can be connected to the grid due to the excess of solar panel supply and the rapid drop in battery storage costs

- **Prioritise dispatchable renewables and link biomass production with ecosystem healing**

  - Malaysia should prioritise developing dispatchable renewables like wood pellets, offering a baseload alternative to coal.

  - **Link ecosystem healing with biomass production:** Encourage the use of deforested or degraded land for tree plantations to establish a sustainable supply chain for wood pellet production.

  - **Government incentives for sustainable biomass:**

    - Infrastructure support: Tree plantations in remote areas often require significant investments in transportation, energy, and communication infrastructure. The government should provide support for infrastructure development to facilitate plantation establishment, not solely relying on private investment.

    - Financial incentives: Implement tax reforms and royalty discounts to incentivise sustainable biomass production.

    - Regulatory framework: Design supportive policies and regulations to ensure sustainable practices:

      - Implement soil restoration practices for degraded land, emphasising the importance of soil microbes for long-term fertility.
      - Support research and development for sustainable plantation management practices.

- **Biogas: a sustainable power source with ecosystem benefits**

  - Encouraging the development of the biogas industry offers a multifaceted solution, promoting renewable energy generation while fostering environmental restoration. The anaerobic digestion process used to produce biogas yields valuable byproducts:

    - The liquid byproduct enriches irrigation water with essential nutrients, potentially reducing reliance on synthetic fertilisers and improving crop yields.

    - The solid byproduct can be used to enhance soil carbon content and fertility. This improves water retention capacity and reduces fertiliser needs, leading to improved water quality downstream

  - To maximise biogas production and its associated benefits, consider policy measures that incentivise farmers to cultivate secondary crops after their main harvest. These secondary crops, along with animal waste and farm residues, can be used as feedstock for the anaerobic digesters, promoting a closed-loop system within farms.

  - Furthermore, the ability to generate their own electricity through biogas offers farmers financial security. Biogas production can provide a source of income during periods of crop failure or price fluctuations in agricultural commodities and electricity markets.

4.2 Storage

- **Promote hybrid pumped storage hydro (PSH)-battery systems to leverage long-term storage (PSH) and short-term flexibility (battery) for a robust grid.**

  - Given their different response characteristics and round-trip cycle efficiencies, PSH and battery systems can complement each other in a cost-effective and reliable power system (Krüger, et al. 2021).

  - Policies can incentivise the development of hybrid systems that leverage the strengths of long-term storage (overnight or several days) for PSH and short-term (minutes to hours) flexibility for batteries for a more robust and flexible grid.

- The International Forum on Pumped Hydro Storage offers valuable policy recommendations, which can encourage PSH development in Malaysia:
  - **Early needs assessment:** Conduct long-term storage needs assessments to identify and prioritise the most efficient options.

  - **Technology-neutral evaluation:** Ensure fair comparisons between PSH and other energy storage and flexibility solutions. Allow the most cost-effective and efficient solution to be chosen based on the specific application and grid needs.

  - **Remuneration for flexibility services:** Develop mechanisms to compensate providers of essential grid flexibility services like PSH.

- **Streamlined permitting:** Utilise internationally recognised sustainability tools to expedite licensing and permitting processes.

- **Long-term revenue visibility:** Establish long-term revenue visibility with risk-sharing mechanisms to attract investment.

- **Strategic site assessment:** Identify and map existing hydropower assets with PSH potential, while exploring new prospective sites.

- **Green finance integration:** Support and incentivise PSH development through green recovery programmes and green finance mechanisms.

4.3 Carbon capture, utilisation and storage (CCUS)

- **The challenge and opportunity of carbon capture**
  - Southeast Asia, including Malaysia, is heavily reliant on natural gas as a transitional fuel for power generation. While this approach offers some near-term benefits of lower carbon, achieving long-term decarbonisation goals necessitates exploring CCUS technologies. CCUS presents a crucial opportunity to manage emissions from essential industrial processes, particularly those that require intense heat or involve chemical processes that generate CO_2, such as cement, chemicals, fertilisers manufacturing, and waste incineration.

- **Building a sustainable carbon management ecosystem**

  - The pace of industrial decarbonisation hinges on the development of robust carbon capture and storage infrastructure. CCUS stands out as one of the few viable solutions for capturing emissions from these "hard-to-abate" sectors. Furthermore, by building a network for transporting and storing captured CO_2, CCUS can facilitate not only industrial decarbonisation but also the production of clean electricity through CCUS-equipped power plants.

- **CCUS hubs: a cost-effective and scalable approach**

  - Supporting the development of regional CCUS hubs, rather than isolated projects, has emerged as the most cost-effective strategy for large-scale industrial decarbonisation. These hubs leverage economies of scale to drive down costs and promote risk management across the entire CCUS value chain. This approach can significantly aid governments in achieving both their interim and long-term climate targets.

  - Beyond enabling industrial decarbonisation, CCUS hubs can accelerate the commercialisation of CCUS technologies and foster the development of a thriving carbon management industry. Governments can play a critical role in supporting this transition by implementing tailored policy measures. These might include:

    Establishing a supportive regulatory framework

    - Clear and stable regulations: Developing clear and consistent regulations for CCUS projects is essential. This includes outlining permitting processes, establishing liability guidelines, and defining monitoring requirements. Predictable regulations will provide companies with the confidence needed to invest in CCUS technologies.

- Financial incentives: Offering tax credits, grants, or loan guarantees can make CCUS projects more financially attractive. This can help offset the initial investment costs and encourage wider adoption of the technology.

Invest in CCUS infrastructure development

- R&D funding: Allocating resources for R&D of efficient and cost-effective capture technologies is crucial. This will help to reduce the long-term costs of CCUS and improve its overall performance.

- Storage site development: Supporting the identification and development of safe and secure geological storage sites for captured CO2 is essential. Geological surveys and assessments are crucial to ensure long-term, secure storage.

- Transportation infrastructure: Investing in the development of transportation infrastructure, such as pipelines, is necessary to efficiently move captured CO2 from emission sources to storage locations.

Unlocking *the* potential of CCUS in Southeast Asia

- Given Malaysia's significant geological storage capacity, this strategic investment in CCUS infrastructure can unlock a new cross-border industry, positioning Malaysia as a leading carbon management player in Southeast Asia.

4.4 Transmission lines and interconnections

- **Invest in strategic transmission line expansion and modernisation.**

  – Conduct a national assessment to identify key renewable energy zones and prioritise transmission line upgrades and construction to connect these zones to load centres.

  – Modernise existing transmission infrastructure to handle the variable nature of renewable energy sources like solar. This may involve integrating smart grid technologies for improved grid management and power flow optimisation.

- **Foster regional interconnection and collaboration.**

  – Develop collaborative agreements with neighbouring countries to establish regional power grids. This allows for the sharing of renewable energy resources and reduces reliance on fossil fuels for balancing purposes.

  – Standardise regulations and technical specifications for interconnection to facilitate seamless integration of regional power grids. This ensures efficient power exchange and minimises technical hurdles.

4.5 Transport

- **Shift freight to rail** (Leong and Woo 2023)
  - **Increase rail's modal share**
    - Prioritise long-distance freight for rail transport
    - Develop targeted incentives for businesses and shippers to shift from road to rail
  - **Develop targeted incentives for businesses and shippers to shift from road to rail**
  - **Enhance regional connectivity**
    - Develop standardised regulations and infrastructure specifications for seamless regional rail interconnection.
  - **Attract investment**
    - Implement strategies to capture the economic value of improved access and reduced pollution.
    - Utilise captured benefits to create a risk-sharing mechanism, making rail projects more attractive to investors.

- **Biofuels production: increasing demand and overcoming challenges**
  - **Mandate for biofuel blending:** Implement regulations requiring fuel retailers to blend a specific and gradually increasing quota of biofuels (beyond biodiesel) into their transport fuels. This policy will directly stimulate demand for biomethane and bio-LNG, contributing to greenhouse gas emissions reduction.
  - **Supporting small biogas producers:** Recognise the significant capital investment required for small biogas plants (<500kW) to upgrade biogas to biomethane. Explore policy options to facilitate cost-sharing mechanisms or subsidies for the upgrading equipment.
  - **Large-scale liquefaction and bio-LNG volume tracking:** For economic viability, bio-LNG production often requires larger volumes of biomethane than small plants can produce. Investigate the feasibility of large-scale biomethane liquefaction facilities that could serve multiple small producers, or liquifying biomethane together with natural gas derived from fossil fuels. The latter will require establishing a mass balance approach to accurately calculate and track the actual volume of bio-LNG involved within these facilities.

4.6 Industry

- Ensure that electricity generated from renewable energy is affordable so that there is financial incentive for firms to adopt electrified industrial heating processes.
- Reduce demand for carbon-intensive materials such as cement and steel through circular economy measures such as material substation and efficient design that uses less material, shared use of products and extending product lifetime, and reuse and recycling initiatives.

- Execute and track NETR's energy efficiency measures for the industrial sector, including public awareness programmes, expansion of the Minimum Energy Performance Standards (MEPS) and 5-star rating bands, and enforcing mandatory audits for large industrial buildings.

- Increase fuel share for electricity to 46% by 2050 to align with the IEA's target for achieving net zero by 2050.

- Explore the feasibility of carbon pricing as a mechanism to discourage continuous investment in fossil-fuel based industrial heating processes, while considering the impact on the competitiveness of Malaysian industrial firms and jobs.

4.7 Commercial

- Increase NETR energy efficiency target of 23% for this sector as the current Energy Efficiency and Conservation Act only covers 21% of commercial consumption and less than 1% of total users.

- Execute and track NETR's energy efficiency measures for the commercial sector, including public awareness programmes, green building codes, and enhancing the ESCO ecosystem to coordinate public building retrofits.

- Continue with improving behavioural changes and building norms such as the government announcement in August 2023 that government premises will be raising air conditioner temperatures above frigid cold and changing the dress code to suit Malaysian weather. These steps should also be encouraged in the private sector, and can reduce electricity demand from air conditioning, which is a significant source of power demand in this sector.

- New buildings should be required to adhere to green standards, such as the Merdeka 118 which achieved triple green platinum certification for Leadership in Energy and Environmental Design (LEED), Green Real Estate (GreenRE), and Green Building Index (GBI); and the Exchange TRX which is LEED and GBI accredited.

4.7 Residential

- The International Energy Agency (International Energy Agency 2021) highlights that enhancing standards and labelling programmes for energy efficient appliances is highly effective and cost efficient, with typical society benefit/cost ratios of 4:1, while also delivering improved air quality and health outcomes.

- Hence, focusing on the strategy of increasing penetration of energy efficient appliances is recommended. Since the current National Energy Efficiency Action Plan expires in 2025, Malaysia should continue efforts towards 100% penetration by 2060.

- Malaysia's Sustainability Achieved via Energy Efficiency (SAVE) programme that provided cash rebates for purchase of energy efficient appliances in 2011 and 2021 was successful in increasing penetration of energy efficient appliances and should be continued.

- Offer financing options to cover capital costs for residential rooftop solar installation, which can be paid back over time through cost savings from lower electricity bills.

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APPENDIX

Residential[42]

Urbanisation rate increases from 76% in 2018 to 90% in 2060 (Affairs 2018).

For reference, the urbanisation rate of Japan and Korea have plateaued at around 90% and 80% respectively. Malaysia's urbanisation trends might follow other more developed countries in Asia.[43]

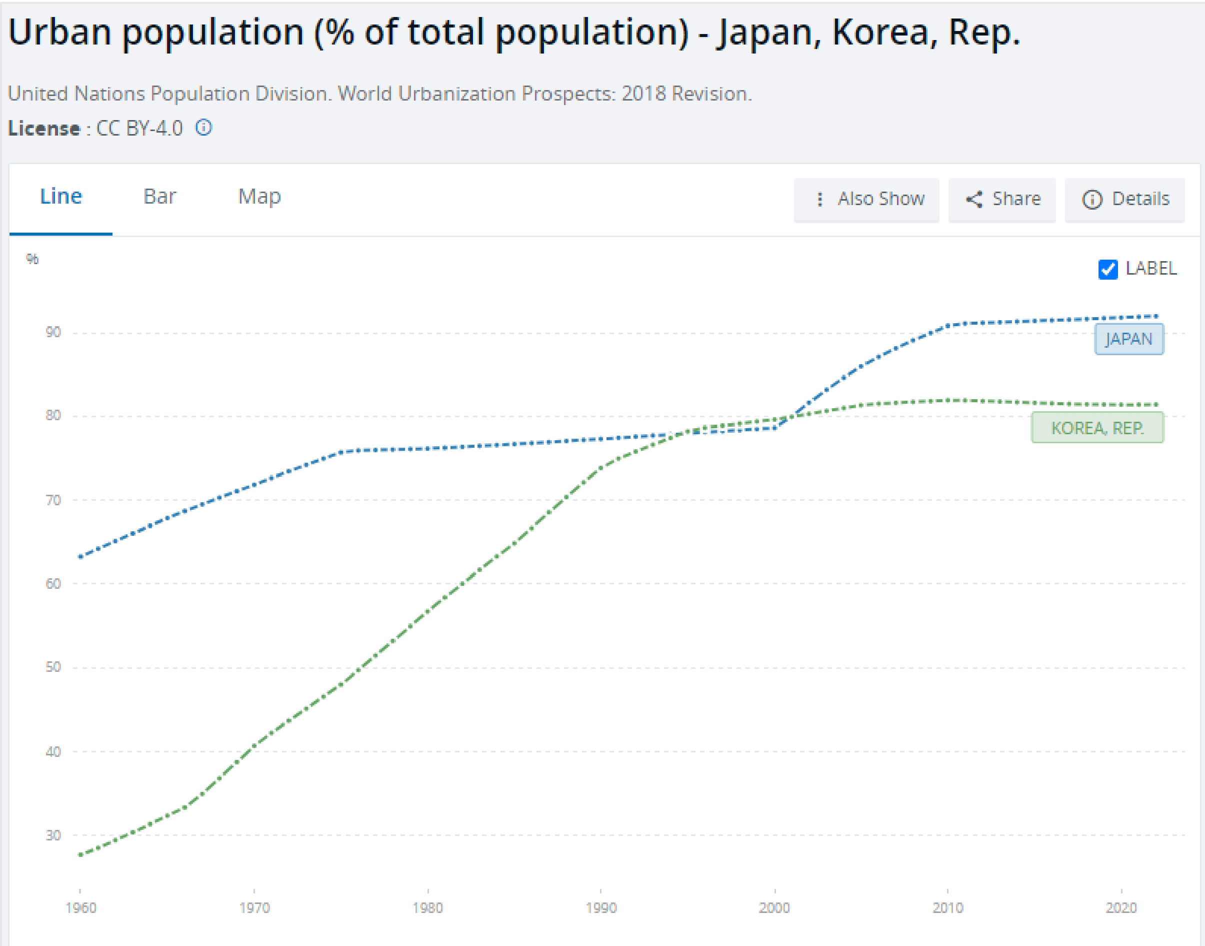

Figure 29: Urbanisation rate for Japan and Korea (1960-2020)

[42] LEAP's native modelling of the residential sector follows a bottoms-up approach, which does not allow for a top-down target to be modelled. The NETR has a 20% energy efficiency improvement target for this sector. Our projections in LEAP follow the NEEAP targets for individual appliances and our calculations show that its outcome is not too far off from the NETR target of 20%.

[43] While urbanisation has been a dominant trend, there is an emerging potential "reverse migration" phenomenon globally, where individuals may choose to relocate from cities to rural areas. This trend, if it materialises, could influence future urbanisation patterns in Malaysia and globally. However, this trend might also be moderated by the continued development of rural areas, which might cause reclassification as urban areas.

Existing Policy:

- For urban:
    - Penetration rates for cooking, lighting, and other appliances are 100% in 2018 and remain constant
    - Cooking uses 95% LPG and 5% wood in 2018, changing to 60% electric and 40% LPG in 2060
    - Lighting uses 100% electricity, which remains constant. Efficient lighting increases from 10% in 2018 to 55% in 2025, then remains constant.
    - Penetration rate for refrigeration is 99% in 2018 and remains constant. Efficient refrigeration increases from 30% in 2018 to 90% in 2025, then remains constant.

- For rural:
    - Penetration rate for air conditioning is 54% in 2018 and increases to 90% in 2060. Efficient air conditioning increases from 10% in 2018 to 55% in 2025, then remains constant.
    - Penetration rates for cooking, lighting, and other appliances are 100% in 2018 and remain constant
    - Cooking uses 90% LPG and 10% wood in 2018, changing to 40% electric and 60% LPG in 2060
    - Lighting uses 100% electricity, which remains constant. Efficient lighting increases from 10% in 2018 to 55% in 2025, then remains constant.
    - Penetration rate for refrigeration is 99% in 2018 and remains constant. Efficient refrigeration increases from 30% in 2018 to 90% in 2025, then remains constant.
    - Penetration rate for air conditioning is 54% in 2018 and remains constant. Efficient air conditioning increases from 10% in 2018 to 55% in 2025, then remains constant.

More Ambitious Policy:

- For urban:
    - Penetration rates for cooking, lighting, and other appliances are 100% in 2018 and remain constant
    - Cooking uses 95% LPG and 5% wood in 2018, changing to 60% electric and 40% LPG in 2060
    - Lighting uses 100% electricity, which remains constant. Efficient lighting increases from 10% in 2018 to 55% in 2025 to 100% in 2060.
    - Penetration rate for refrigeration is 99% in 2018 and remains constant. Efficient refrigeration increases from 30% in 2018 to 90% in 2025 to 100% in 2060.

- For rural:
    - Penetration rate for air conditioning is 54% in 2018 and increases to 90% in 2060. Efficient air conditioning increases from 10% in 2018 to 55% in 2025 to 100% in 2060.
    - Penetration rates for cooking, lighting, and other appliances are 100% in 2018 and remain constant
    - Cooking uses 90% LPG and 10% wood in 2018, changing to 40% electric and 60% LPG in 2060
    - Lighting uses 100% electricity, which remains constant. Efficient lighting increases from 10% in 2018 to 55% in 2025 to 100% in 2060.

- Penetration rate for refrigeration is 99% in 2018 and remains constant. Efficient refrigeration increases from 30% in 2018 to 90% in 2025 to 100% in 2060.
- Penetration rate for air conditioning is 54% in 2018 and remains constant. Efficient air conditioning increases from 10% in 2018 to 55% in 2025 to 100% in 2060.

Numbers and targets in the residential sector are based on the National Energy Efficiency Action Plan 2016-2025, Department of Statistics Malaysia, and World Health Organisation.

Services

Under the National Energy Transition Roadmap's Energy Efficiency (EE) initiatives (page 30), these are the ones that are relevant to the services sector:

1) Improve EE awareness
2) Improve existing Minimum Energy Performance Standards (MEPS) and 5-star rating bands
3) Enforce mandatory audits for large commercial buildings
4) Establish green building codes for energy-intensive commercial buildings
5) Establish and Energy Service Company platform
6) Launch a major EE retrofit initiative amongst government buildings

Further details of each initiative can be found in the National Energy Transition Roadmap.

Initially, LEAP's default settings for the services sector follow historical trends and projects it forward over the long term. This includes the value added from the services sector to GDP (expressed as a percentage), which was projected to reach 85% in 2060. Meanwhile, agriculture's contribution to GDP decreases all the way to 2% in 2060, with industry making up the remainder of GDP contribution.

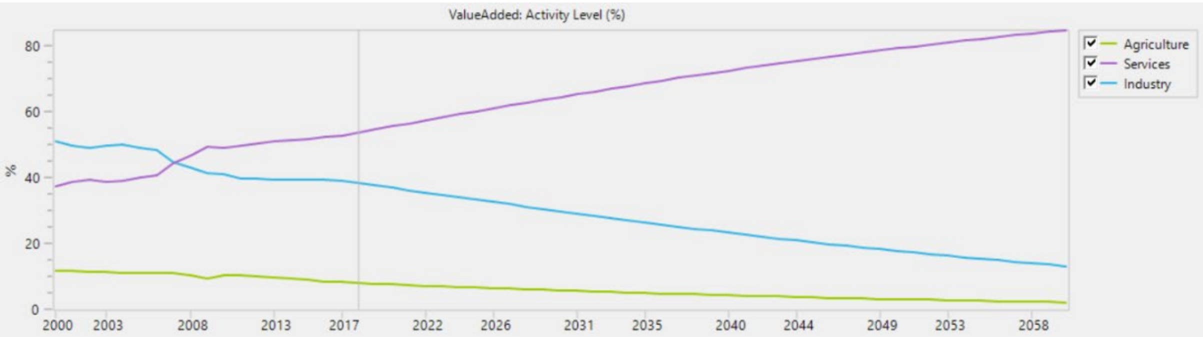

Figure 30: Value added from the agriculture, services and industry sectors to GDP in LEAP's default settings

We decided that these values were too extreme and unrealistic, and set out to introduce limits to these trends. Since there is very limited research on future projections of these GDP components, we compare Malaysia's GDP components with other countries. One of the countries we compared to was Australia, which also has a significant mining industry, and gradually achieved a long-term average of about 65% services. Singapore is a closer neighbour but its lack of natural resources and agricultural land makes it less comparable to Malaysia's situation. Even then, its services contribution appears to plateau at around 70%.

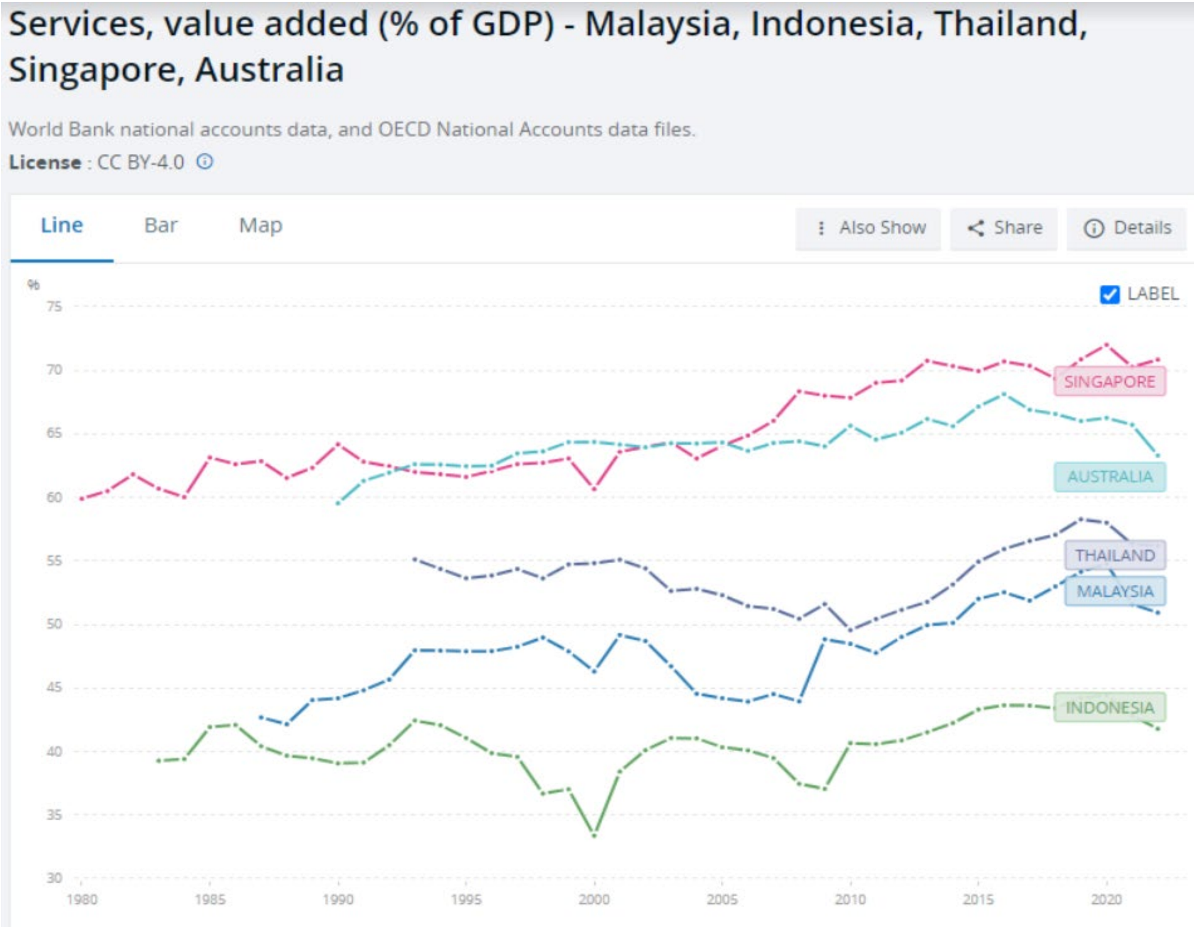

Figure 31: Value added from the services sector in Indonesia, Malaysia Singapore, Thailand and Australia

Therefore, we decided to introduce into our model an upper bound of 65% contribution to GDP for the services sector, as well as a 5% minimum bound for agriculture. These bounds are reached in 2031, after which each component is modeled to be stable at their respective bounds. This approach also has implications for the industry sector, which then makes up the remaining 30% of GDP.

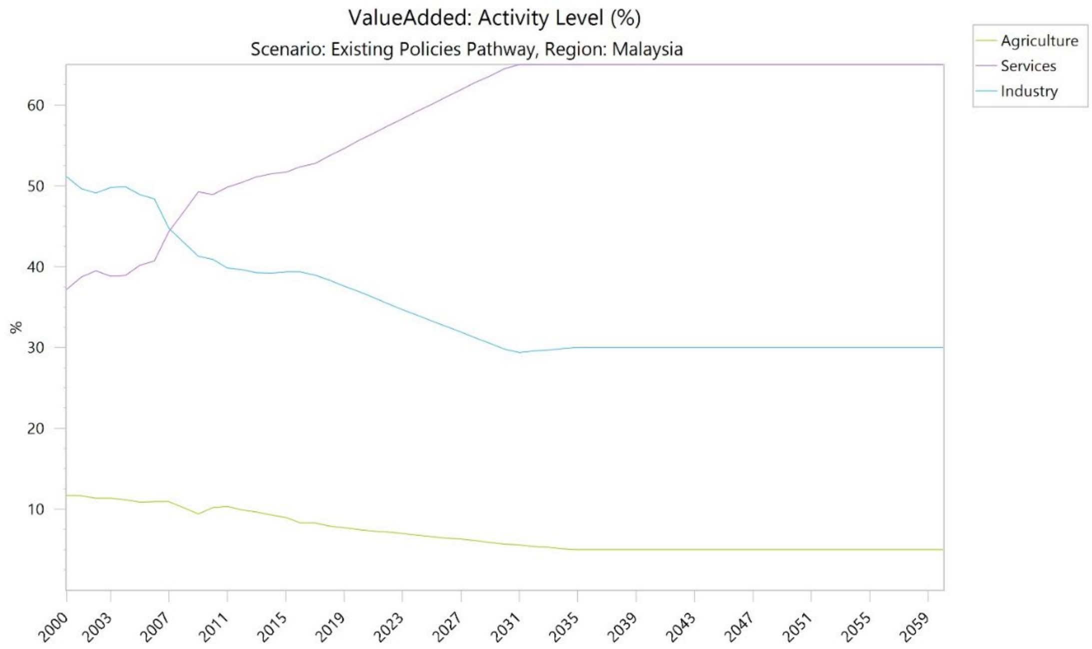

Figure 32: Value added in agriculture, services and industry sectors to GDP in LEAP's revised settings

Industry

Under the National Energy Transition Roadmap's Energy Efficiency (EE) initiatives (page 30), these are the ones that are relevant to the industrial sector:

1) Improve EE awareness
2) Improve existing Minimum Energy Performance Standards (MEPS) and 5-star rating bands
3) Enforce mandatory audits for large industrial buildings
4) Establish an Energy Service Company platform

Further details of each initiative can be found in the National Energy Transition Roadmap.

For the More Ambitious Policy scenario, the following method was used to calculate the potential demand reduction from circular economy measures in the steel sector:

> *Circular economy measures in steel (material substitution, efficient design, shared use of products and extending product lifetime, and reuse/recycling) could reduce demand by 40%* (Mission Possible Partnership 2022).
>
> *While data on steel-specific power usage is unavailable, steel's 23% share of industry GHG emissions [7,553.5 tCO_2e out of 32,853.8 tCO_2e* (Ministry of Natural Resources, Environment and Climate Change, Malaysia 2022)*] provides a proxy.*
>
> *Focusing on domestic consumption [7.03 million tonnes, 42.8% of 2022 production,* (The Edge 2022)*], estimated demand reduction through circularity translates to 4% (40% * 23% * 42.8%).*

To be clear, the modeling for the demand reduction of 4% was done through the energy intensity variable in the model as there is no other variable that can directly model a demand reduction. An energy intensity saving of 4% will result in the same amount of power savings as a demand reduction of 4%. Although the amount of steel output would technically differ for these two scenarios, this discrepancy has no impact on LEAP's output and analysis.

In the model, Existing Policy already has a 23% energy intensity savings which comes from the NETR target, and is modelled through a formula that denotes that the energy intensity is 77% of what it was in the base year. For More Ambitious Policy, we adjusted this energy intensity variable to 74%, as it includes an additional 3% of savings (4% * 77%).

Meanwhile, the increased fuel share for electricity under the More Ambitious Policy scenario is modeled through the UnscaledFuelShare variable in the model, such that fuel share of electricity increases to 46% in 2050 as outlined in IEA's projection.

Transport

Final energy intensity of electric cars

Clarke (2017) estimates the final energy intensity of electric cars to range from 0.43 to 1.55 MJ/km, depending on how the electricity consumed is produced. Meanwhile, Mackay (2009) estimates the average consumption for electric cars to be 0.54 MJ/km.

Compared to these values, LEAP's default of 0.2 MJ/km appeared too low, hence we decided to update it to 0.54 MJ/km.

Final energy intensity of electric motorcycles

Our literature review yielded a range of estimates, from 0.10 MJ/km[44] (Koossalapeerom, et al. 2018), to 0.21 MJ/km[45] (Kusalaphirom, Satiennam and Satiennam 2023), to 0.32 MJ/km[46] (Weiss, Cloos and Helmers 2020).

Since the default value in LEAP of 0.215 MJ/km sits within range of the literature, we decided to accept SEI's estimate for this model.

Modeling approach for public transport modal share

Using data from the Road Transport Department of Malaysia and estimated ridership from upcoming rail projects such as the Mass Rapid Transit Line 3 (MRT3), East Coast Rail Link (ECRL), and High-Speed Rail (HSR) projects, projections for total vehicle-kms of various transport options were calculated and tabulated.

To model the NETR target of increasing public transport modal share to 60% by 2050, we took the total vehicle-km projected for 2050, and redistributed it to meet this target. This meant 60% share for public transport and 40% share for private transport. The 60% share of public transport is split evenly between 30% rail passenger and 30% bus, while the 40% share of private transport is split into 25% cars and 15% motorcycles. These internal ratios follow historical data trends.

[44] 2.8 kWh/100km = 0.10 MJ/km
[45] 57.83 Wh/km = 0.21 MJ/km
[46] 9 kWh/100km = 0.32 MJ/km

Table 8: Comparing how LEAP handles generation capacity and generation in simulation and optimisation modes

	Simulation (e.g. Existing Policy)	Optimisation (e.g. Optimised Existing Policy)
Generation capacity	Modeller defines the amount of generation capacity to be added in the model based on policy decisions. Should further additions be required in any given year to maintain the reserve margin above the value specified in the Planning Reserve Margin, LEAP will add according to the addition order and addition size specified by the modeller.	LEAP exogenously adds the same amount of generation capacity defined by the modeller based on policy decisions. Should further additions be required in any given year to maintain the reserve margin above the value specified in the Planning Reserve Margin, LEAP will add guided by cost and maximum capacity addition per year. LEAP disregards the addition order and addition size the modeller sets in simulation mode.
Projected demand	The model considers the projected demand for electricity.	Like Existing Policy, the model considers the projected electricity demand.
Merit order	The modeller sets a specific order for how different types of generation plants are used to meet projected demand. The model prioritises dispatching variable renewable energy (like solar and wind) first, followed by plants that provide reliable and constant power (e.g., natural gas, hydropower). This prevents the constant output of baseload plants from overshadowing the contribution of variable renewables, even when their capacity is lower.	LEAP disregards the merit order the modeller sets in simulation mode. Instead, it automatically selects the lowest cost generation technology available at any given time to meet demand. This optimises the system based on cost-effectiveness.

Cost Data Tables

Table 9: Power generation costs

	Year	Capital cost (USD/kW)	Fixed cost (USD/kW-yr)	Variable cost (USD/MWh)	Source
Coal	2018	3549	78	8.46	(NREL 2023)[47]
	2030	3395	75	8.10	
	2040	3140	70	7.87	
	2050	2824	64	7.60	
	2060	2508	58	7.33	
Natural gas turbine	2018	1120	24	6.44	(NREL 2023)
	2030	1050	23	6.44	
	2040	961	22	6.44	
	2050	872	20	6.44	
	2060	783	18	6.44	
Natural gas combined cycle (NGCC)	2018	1248	31	1.96	(NREL 2023)
	2030	1161	29	1.84	
	2040	1062	26	1.72	
	2050	971	24	1.62	
	2060	880	22	1.52	
Oil	2018	1150	34.5	40	(Farnoosh 2022)[48]
	2030	1150	34.5	40	
	2040	1150	34.5	40	
	2050	1150	34.5	40	
	2060	1150	34.5	40	
Diesel	2018	1150	34.5	40	(Farnoosh 2022)
	2030	1150	34.5	40	
	2040	1150	34.5	40	
	2050	1150	34.5	40	
	2060	1150	34.5	40	
Biomass / biogas	2018	5391	157	5	(NREL 2023)
	2030	4489	157	5	
	2040	4186	157	5	
	2050	3871	157	5	
	2060	3556	157	5	
Hydro	2018	6660	33	0	(NREL 2023)
	2030	6660	33	0	
	2040	6660	33	0	

[47] 2018 data was not available, so 2021 data was used. 2060 data is extrapolated from 2050.
[48] 2018 data was not available, so 2016 data was used.

	Year	Capital cost (USD/kW)	Fixed cost (USD/kW-yr)	Variable cost (USD/MWh)	Source
	2050	6660	33	0	
	2060	6660	33	0	
Solar	2018	1291	23	0	(NREL 2023)
	2030	1038	18	0	
	2040	764	15	0	
	2050	632	13	0	
	2060	500	11	0	
Geothermal	2018	6750	114	0	(NREL 2023)
	2030	5926	107	0	
	2040	5421	104	0	
	2050	5156	104	0	
	2060	4891	104	0	
Wind onshore	2018	1363	30	0	(NREL 2023)
	2030	1150	27	0	
	2040	1037	25	0	
	2050	924	23	0	
	2060	811	21	0	
Wind offshore	2018	3711	113	0	(NREL 2023)
	2030	2975	91	0	
	2040	2696	81	0	
	2050	2528	74	0	
	2060	2360	67	0	
Nuclear	2018	9440	152	2	(NREL 2023)
	2030	7730	152	2	
	2040	7209	152	2	
	2050	6668	152	2	
	2060	6127	152	2	

Table 10: Fuel Costs

	Year	Price	Unit	Source
Coal	2018	9.80	USD/MWh	(ACE 2022)[49]
	2030	7.05	USD/MWh	
	2040	7.05	USD/MWh	
	2050	7.05	USD/MWh	
	2060	7.05	USD/MWh	
Natural gas	2018	28.40	USD/MWh	(ACE 2022)
	2030	27.90	USD/MWh	
	2040	27.90	USD/MWh	
	2050	27.90	USD/MWh	
	2060	27.90	USD/MWh	
Crude Oil	2018	27.60	USD/MWh	(ACE 2022)
	2030	52.40	USD/MWh	
	2040	61.90	USD/MWh	
	2050	61.90	USD/MWh	
	2060	61.90	USD/MWh	
Diesel	2018	10.2	USD/MWh	(ACE 2022)
	2030	13.3	USD/MWh	
	2040	14.1	USD/MWh	
	2050	14.1	USD/MWh	
	2060	14.1	USD/MWh	
Biomass	2018	0.6	USD/MWh	(ACE 2022)
	2030	0.6	USD/MWh	
	2040	0.6	USD/MWh	
	2050	0.6	USD/MWh	
	2060	0.6	USD/MWh	
Biogas	2018	2.3	USD/MWh	(ACE 2022)
	2030	2.3	USD/MWh	
	2040	2.3	USD/MWh	
	2050	2.3	USD/MWh	
	2060	2.3	USD/MWh	
Biomethane	2018	10.4	USD/mmbtu	(International Energy Agency 2020)
	2030	9.1	USD/mmbtu	
	2040	7.8	USD/mmbtu	
	2050	7.8	USD/mmbtu	
	2060	7.8	USD/mmbtu	

[49] 2018 data was not available, so 2020 data was used. 2060 data is extrapolated from 2050.

	Year	Price	Unit	Source
Nuclear	2018	3.8	USD/MWh	(ACE 2022)
	2030	7.2	USD/MWh	
	2040	10.8	USD/MWh	
	2050	14.4	USD/MWh	
	2060	17.9	USD/MWh	

For further enquiries about the ASEAN Green Future project, please contact:

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