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Optimising Malaysia's power mix for a sustainable future: a multi-scenario modelling approach

Wing Thye Woo
Liaoning University, Shenyang, China, and
Yuen Yoong Leong, Wai Sern Low, Jin Soong Liew and
Chean Chung Lee
Sunway University, Kuala Lumpur, Malaysia

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Abstract

Purpose – This study employs advanced modelling to assess the effectiveness of Malaysia's current energy policies in achieving a low-carbon future. By optimising a 100% renewable energy mix, including energy storage, the research identifies pathways to decarbonise the power sector while minimising costs. These findings will inform the development of future policies.

Design/methodology/approach – This study employs the Stockholm Environment Institute-developed Low Emissions Analysis Platform (LEAP) and Next Energy Modeling system for Optimization (NEMO) to construct and optimise a comprehensive Malaysian power sector model. The model encompasses both electricity supply, including diverse electricity generation sources and demand across key sectors. Three scenarios – existing policy, optimised existing policy and more ambitious policy (near-zero emissions) – are analysed.

Findings – Solar photovoltaic (PV) is the dominant technology, but realising its full potential requires significant grid upgrades. While natural gas expansion underpins Malaysia's decarbonisation strategy, solar and storage offer a cleaner and potentially cost-effective alternative. Rapid technological advancements in clean energy increase stranded asset risk for new gas power plants. Malaysia's abundant bioenergy resources need more tapping. This can contribute to decarbonisation and rural development. Transitioning to a fully renewable grid necessitates substantial investments in energy storage and grid infrastructure. While falling battery costs and regional interconnection can mitigate costs, careful consideration of potential disruptions and cost fluctuations is essential for resilience.

Research limitations/implications – Energy sector modelling results are inherently dependent on input assumptions, such as future technology costs, resource availability and fossil fuel prices. These factors can be highly uncertain. While this study did not conduct sensitivity analyses to explore how variations in these assumptions might affect the results (e.g. cost variations across scenarios, technology mix fluctuations), the core findings provide valuable insights into potential decarbonisation pathways for Malaysia's power sector. Future studies could build upon this work by incorporating sensitivity analyses to provide a more comprehensive understanding of how key results might change under a wider range of future possibilities.

Originality/value – This study co-optimises a 100% renewable energy mix for Malaysia, incorporating a comprehensive range of renewable resources, battery and pumped hydro storage. The research also provides a unique perspective on the interplay of philosophical underpinnings, psychological maturity and energy policy.

Keywords Decarbonisation, 100% renewable grid, Energy storage, Regional interconnection

Paper type Research paper

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1. Introduction

The philosophical underpinnings of power generation, essential to sustaining life, are deeply intertwined with broader societal, ethical and economic considerations. Table 1 categorises these underlying philosophies into three psychological maturity levels, mirroring the three degrees of working tools depicted by Jim Platts in Meaningful Manufacturing (2003). Tool proficiency reflects a craftsman's acquired skill. Similarly, the level of psychological maturity influences the impact of energy design and decisions on humanity.

The energy transition in Malaysia, like many nations, is a complex phenomenon resulting from the interplay of competing philosophies and interest. While *second* and *third-degree* philosophies, prioritising sustainability and long-term social wellbeing, drive the transition towards renewable energy, first-degree philosophies, often rooted in short-term economic gains and political stability, can hinder progress.

The ambitious goal of a 100% renewable energy system faces significant challenges. Fossil fuel stakeholders, entrenched in a legacy of oil and gas dominance, resist rapid change. Additionally, government concerns of economic disruption and potential political repercussions can lead to policy inconsistencies. This tension was evident in Economy Minister Rafizi Ramli's public shift in stance between May and July 2024.

Initially, he emphasised the need to accelerate the transition to avoid increased natural gas imports (Bernama, 2024a, b). Natural gas supply in Malaysia has been tight due to declining domestic production and increasing demand (Leong, 2022). However, in June, he signalled a more tempered approach, emphasising the continued role of oil and gas in the nation's energy mix.

The government's efforts to support the oil and gas industry, including the oil and gas service and equipment (OGSE) census and initiatives to improve access to financing, reflect a desire to balance economic stability with sustainability goals. While these measures aim to alleviate the industry's challenges, they also highlight the ongoing reliance on fossil fuels (Bernama, 2024a, b).

In September, Minister Ramli's statement on the National Energy Transition Roadmap (NETR) clarified that fossil fuels will remain a significant part of Malaysia's energy mix well into 2050. This acknowledgement of the industry's contribution to national development

Table 1. Core philosophies influencing the energy sector

Psychological maturity	Philosophies
First degree	*Utilitarianism:* Maximising overall happiness or well-being; often reflected in the pursuit of energy sources that provide the greatest benefit to the largest number of people, such as efficiency, affordability, and reliability *Economic rationality:* Maximising economic efficiency and growth; influences the choice of energy sources based on cost-benefit analysis, market forces, and economic incentives *Technological determinism:* A perspective that suggests technology drives societal change; evident in the push for innovation and the development of new power generation and energy storage technologies
Second degree	*Social justice:* Focuses on fairness and equity; relevant in the context of energy access, affordability, and the distribution of benefits and burdens associated with power generation
Third degree	*Environmental ethics:* Consider the moral relationship between humans and the environment; sustainable energy sources, renewable energy, and carbon reduction are often driven by environmental ethics *Fundamental principles/natural laws:* Put bounds on creativity and maintains balance

Source(s): Table by authors

underscores the delicate balance between economic considerations and the incentive to transition towards a more sustainable energy future. (Lim, 2024)

Malaysia's energy policy, whilst primarily shaped by domestic economic and political considerations, is deeply intertwined with the broader Association of Southeast Asian Nations (ASEAN) ecosystem. While the ASEAN Plan of Action for Energy Cooperation [1] (APAEC) outlines a path for regional energy integration, the focus on fossil fuels, particularly natural gas, remains a significant barrier to achieving a near-zero emissions power system.

As Malaysia assumes the ASEAN chairmanship in 2025, the opportunity to lead the region towards a more sustainable energy future is at hand. However, the current trajectory, heavily reliant on natural gas, falls short of the ambitious goal of a near-zero emissions power system by 2050.

The rapid advancements in solar, wind, and storage technologies have presented a compelling alternative to the continued reliance on fossil fuels. The UN Sustainable Development Solutions Network's (SDSN) and Climateworks Centre have been developing local analytical capacity of country teams in ASEAN member states to investigate a near-zero emissions power system in ASEAN and highlight the technical and economic feasibility of such a transition. This initiative improves country teams' ability to offer relevant insights to policy makers to inform climate strategies, targets and policies.

This research presents a comprehensive modelling framework that incorporates both demand and supply to evaluate a near-zero emissions power system, without carbon capture, in Malaysia. By simulating and optimising several power mix scenarios and assessing their economic, environmental, and social impacts, the study offers forward looking insights into the evolution of the Malaysia power landscape for policymakers until 2050.

Given the current policy landscape, the government may be hesitant to commission such ambitious research. However, the findings of this analysis provide a crucial guidepost for transitioning towards a more sustainable and resilient energy future. The direction of this transition is inevitable, but the speed and effectiveness of the transition depend on policymakers' choices and their ability to consider the long-term implications of their decision, including the psychological maturity framework outlined in Table 1.

2. Literature review

2.1 Malaysia's energy and climate policy journey

Malaysia's journey towards renewable energy (RE) began in 2000 with the inclusion of RE as a fifth fuel source in the 8th Malaysia Plan (2001–2005). The subsequent Renewable Energy Act of 2011 accelerated RE development, driven primarily by the Feed-in Tariff (FiT) programme for Peninsular Malaysia and Sabah, and initiatives like the Sarawak Corridor of Renewable Energy (SCORE). Launched in 2008, SCORE aimed for 12 hydropower projects by 2020, but only three are operational today and a fourth is being built (Tham, 2022).

In recent years, Malaysia has made substantial strides towards a more sustainable energy future. In 2021, the Malaysian government announced a carbon neutral commitment as early as 2050 (Channel News Asia, 2021).

In the same year, the Malaysia Renewable Energy Roadmap (MyRER) (Sustainable Energy Development Authority Malaysia, 2021) outlines strategies for achieving a clean power transition. It sets target capacities for various RE sources, including large hydro (8,062 MW), solar (7,280 MW), small hydro (1,219 MW), biomass (998 MW), biogas (406 MW) and geothermal (30 MW) in 2035.

The National Energy Policy (DTN) 2022–2040 (Malaysian Government, 2022) outlines Malaysia's strategy for achieving a net-zero energy transition. It advocates for transitioning from fossil fuels to renewable and sustainable energy sources, while also focussing on improving energy demand management and promoting green technologies.

DTN aims to create a conducive investment climate, particularly in the upstream oil and gas sector, by enhancing its competitiveness and adherence to environment, social and governance (ESG) standards. Furthermore, DTN seeks to achieve macroeconomic resilience, energy supply security, equality, social sustainability, and environmental preservation through four strategic cores: optimising energy resources, stimulating economic growth, enhancing environmental sustainability, and ensuring fiscal stability.

As a further development to MyRER, the National Energy Transition Roadmap (NETR) (2023) outlines Malaysia's plan to grow the generation capacity of RE from 27% (12 GW) in 2025, to 41% (23 GW) in 2035 and to 70% (68 GW) in 2050. With the natural retirement of existing coal power generation plants and the ban on their new construction, NETR anticipates coal-fired power generation capacity to decline from 29% (13 GW) in 2025 to 11% (6 GW) in 2035 and to zero by 2050. The absolute capacity of gas power plants would increase steadily over time, from 19 GW in 2025 to 26 GW in 2035 and 28 GW in 2050. Ceteris paribus, NETR would observe a steady increase in the amount of greenhouse gases emitted.

Malaysia's commitment to addressing climate change has been evident since the launch of its inaugural National Climate Change Policy in 2009. The recently unveiled National Climate Change Policy 2.0, spearheaded by the Natural Resources and Environmental Sustainability Ministry (NRES), represents a significant step forward in the country's transition towards a low-carbon economy.

This comprehensive policy framework serves as a unifying force, integrating various climate-related initiatives and providing a clear roadmap for governance, low-carbon development, adaptation, climate financing, and partnerships.

2.2 Decarbonisation pathways and power system modelling landscape

While previous studies (World Wildlife Fund Malaysia and Boston Consulting Group Malaysia, 2021; Shell, 2021) explored decarbonisation pathways for Malaysia, they limited their analysis to scenarios with less than 100% renewable electricity penetration, deeming it overly ambitious. DNV-GL's (2018) solar penetration limit assessment recommended caps of 24% and 20%, respectively, based on existing grid constraints.

However, these early studies often assumed a static grid and did not fully explore the potential of network evolution and management tools like demand-side response and energy export. The UK, where initial estimates suggested low renewable penetration limits, has evolved towards ambitious targets of up to 90%. Malaysia may also be able to achieve significantly higher renewable energy penetration through strategic grid modernisation and policy interventions. (Leong, 2022)

Ember's analysis of Malaysia's electricity transition roadmap highlights the continued reliance on natural gas in the power generation mix through 2050. To expedite decarbonisation, Malaysia should prioritise the expansion of solar power generation beyond the targets set in the NETR. Concurrently, investments in energy storage solutions and grid infrastructure upgrades are essential to support the integration of renewable energy. (Shabrina & Dinita, 2024)

Ember's modelling showed that solar generation costs in Peninsular Malaysia have become significantly more competitive, surpassing fossil fuel options by 53% in 2023 (Shabrina & Dinita, 2024). However, the study's modelling did not fully account for the potential impact of energy efficiency and electric vehicle adoption on electricity demand. These factors are crucial drivers of the energy transition and will influence future power demand requirements.

The 8th ASEAN Energy Outlook 20230–2050 (ASEAN Centre for Energy, 2024) offers a comprehensive analysis of Southeast Asia's energy sector. Its integrated policy modelling approach, encompassing both demand-side and power generation factors, provides valuable insights for policy makers. The introduction of a Carbon Neutrality Scenario, focussing on least cost optimisation of net-zero technologies, for example in space cooling that helped improve and make air conditioning more efficient, is a notable advancement.

However, two limitations should be acknowledged. The absence of a 100% renewable electricity scenario restricts the exploration of long-term decarbonisation pathways. Moreover, the whole-of-ASEAN regional perspective, while informative, lacks the granularity required for country-specific policymaking. Disaggregating the data by country would enable a more nuanced understanding of the energy landscape in each ASEAN member state.

While much of the existing research on achieving 100% RE has focussed on regions outside Southeast Asia, Weber, Blakers, Firnando Silalahi, Catchpole, and Nadolny's (2024) exploration of a 100% renewable electricity scenario in the sunbelt region (between ±35° latitude), where a significant portion of the global population resides, provides valuable insights for Malaysia, particularly regarding the potential of solar and pumped hydro storage.

While solar PV is undoubtedly a dominant RE source in Malaysia, modelling efforts should also consider non-solar options like biomass and biogas to ensure a balanced and diversified energy mix.

Weber *et al.*'s (2024) assumption of complete electrification across all sectors, presents a significant challenge for Malaysia. This paper offers a more realistic pathway by assessing the feasibility of electrifying transportation, heating/cooling, and industry sectors within the Malaysian context.

The co-optimisation of battery and pumped hydro storage for energy transition pathways remains understudied area. For instance, IRENA's Malaysia Energy Transition Outlook (2023) exclusively focused on battery storage within its 100% renewables scenario. Previous research by Haiges, Wang, Roskilly, and Ghoshray (2019) compared a nuclear scenario with a renewable-plus-storage scenario incorporating six renewable technologies (37.40 GW solar PV, 23.84 GW large hydro, 1.18 GW biomass, 1.10 GW biogas, 0.07 GW geothermal, 0.49 GW mini-hydro) and pumped hydro storage (0.69 GW).

The decarbonisation pathways and energy models discussed in this section can be categorised into three distinct groups: yesterday's debate, today's debate and tomorrow's debate. As the energy landscape evolves, incumbent modellers must adapt their approaches or risk becoming irrelevant. The work presented in this paper falls within the "tomorrow's debate" category, offering a forward-looking perspective on future energy transitions.

2.3 Leading change beyond modelling

The energy transition is not merely a technological shift but a profound societal transformation. As outlined in the Introduction, the obstacles encountered are typical of any change process. For transformative change to succeed, Kotter's (1996) eight-step framework provides a valuable guide. This framework, distilled from successful leadership and organisational transformation cases, emphasises:

(1) Creating a sense of urgency
(2) Building a guiding coalition
(3) Forming a strategic vision
(4) Enlisting a volunteer army
(5) Enabling action by removing barriers
(6) Generating short-term wins
(7) Sustaining acceleration
(8) Instituting change

While modelling offers an analytical foundation, it's essential to recognise that it's a starting point, not a definitive blueprint. Large-scale societal change requires widespread mobilisation around a shared vision. Effective leadership involves both learning and action, guiding society through transitions in a timely manner with pragmatism and foresight, while fostering psychological maturity.

The first step in Kotter's eight-step leading change framework, creating a sense of urgency, is crucial for accelerating energy transitions. China's experience during the Malacca Dilemma, a potential blockade of vital sea lines of communication, provides a compelling case study.

Recent trends indicate that China's reliance on foreign oil could reach 80%, and the country was on track to become 62% dependent on foreign liquefied natural gas imports by the end of the decade (Zeng, Zhang, Wang, & Wang, 2022; Wang, Li, & Li, 2018). Faced with the existential threat of energy and economic security, China swiftly and effectively implemented its energy transition. The resistance of incumbent oil and gas interests proved futile to impede policy change.

3. Research design and methodology

The objectives of the model presented in this paper are to:

(1) Assess the effectiveness of current energy policies in driving decarbonisation within the power generation sector; Identify any potential gaps or areas where existing policies might not be enough to achieve the desired emissions reduction goals.

(2) Evaluate an optimised power generation scenario within the existing policy framework;

(3) Analyse the potential of an optimised near zero emissions power generation system; provide insights and data to inform future policy decisions and ensure a successful transition to a near-zero emissions power generation sector.

The model explored least-cost pathways for power generation under three scenarios, as summarised in Table 2.

3.1 Software

This study leverages two leading energy system optimisation modelling 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). This report is informed by the LEAP model sdsn_agf_main_v3.3.5 MY-ALPHAv3.

3.2 Scope

This study'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.

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.

3.3 Time

The model uses 2019 as the base year, reflecting the most recent data available from Malaysia's Fourth Biennial Update Report (2022). The historical time period spans 2001–2018, coinciding with significant policy developments and economic changes, including

Table 2. Modelling scenarios and their policy implications

Scenarios	Explanation	Policy implications
Existing policy (EP)	Simulated power generation and demand based on current policies. This scenario assessed the effectiveness of existing policies in achieving energy and environmental goals. Key assumptions included the projected power system installed capacity mix outlined in the National Energy Transition Roadmap (NETR) (Ministry of Economy, 2023) and targets for energy efficiency, renewable energy, hydrogen, bioenergy, and green mobility	By simulating power generation and demand based on current policies, the model can identify areas where policies may be inadequate or require strengthening to accelerate the transition to a low-carbon economy. For example, the simulation can help the government understand the projected power generation greenhouse gas emissions trajectory under the National Energy Transition Roadmap (NETR) and assess the need for policy adjustments to achieve more ambitious climate goals
Optimised EP	Optimised for the least-cost power generation mix within the existing policy framework	By identifying the least-cost power generation mix, policymakers can gain insights into the cost-effectiveness of current policies and identify areas where adjustments may be necessary to achieve energy objectives at a lower cost
Optimised more ambitious policy (OMAP)	Examined the least-cost path under more stringent emission reduction targets for both demand and generation. This scenario incorporated strategies such as increased demand-side efficiency measures and a transition to cleaner energy sources, including no new fossil fuel capacity additions after 2030, a complete phase-out of coal by 2030, followed by natural gas and diesel by 2050	By analysing the least-cost pathway under this scenario, policymakers can assess the feasibility and costs associated with more ambitious climate targets and inform decision-making on future policy interventions

Source(s): Table by authors

Malaysia's Kyoto Protocol commitment, the Multimedia Super Corridor growth, and the National Automotive Policy. The study's end year is 2050.

3.4 Discount rate

This study employs a discount rate of 7% after considering the risk profile of Southeast Asia, specific risks associated with power projects such as regulatory uncertainty and fuel price volatility, and the cost of capital in the region.

3.5 Inflation rate

The model utilises a 2.7% inflation rate, aligning with the International Monetary Fund's (IMF) medium-term forecasts for ASEAN (2025–2029). While acknowledging variations among member countries (e.g. Brunei 1%, Myanmar 7.8%), the IMF's project offers a more comprehensive outlook compared to the Asian Development Bank (ADB) shorter-term forecasts of 3.2% for 2024 and 3.0% for 2025.

3.6 Source of data

The LEAP model relies on reliable data carefully curated from publicly accessible, published reports like National Energy Transition Roadmap (NETR) (2023), National Biomass Action

Plan 2023–2030 (2023) and the Hydrogen Economy and Technology Roadmap (2023). Key data points include the following:

(1) *Projected capacity mix:* The model utilised the projected power system installed capacity mix outlined in the National Energy Transition Roadmap (NETR) for the period 2025–2050 under the Existing Policy scenario.

(2) *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.

3.7 Limitations and future research directions

Energy sector modelling results are inherently dependent on input assumptions such as future technology costs, resource availability, and fossil fuel prices. These factors can be highly volatile and uncertain, and the stochastic nature of these variables should have been included to provide further bounds to the estimates. However, due to data limitations, this study has not incorporated further sensitivity analyses to explore how variations in these assumptions might affect the results (e.g. cost variations across scenarios, technology mix fluctuations). While this study provides valuable insights into potential decarbonisation pathways for Malaysia's power sector, future work could incorporate uncertainty and sensitivity analyses to provide a more comprehensive understanding of how key results might change under a wider range of future possibilities.

4. Results

The analysis examines model results across five key dimensions to inform policies for a near-zero emissions power sector in Malaysia: power generation and demand mix, greenhouse gas emissions, investment needs, electricity production costs, and social costs.

Additionally, external factors were examined to explore key decarbonisation pathways. This included assessing the potential for accelerated deployment of 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.

4.1 Existing policy

This section presents the results of simulating power generation and demand under current policy frameworks.

(1) 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 1 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 (Aziz, 2023).

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

(1) *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.

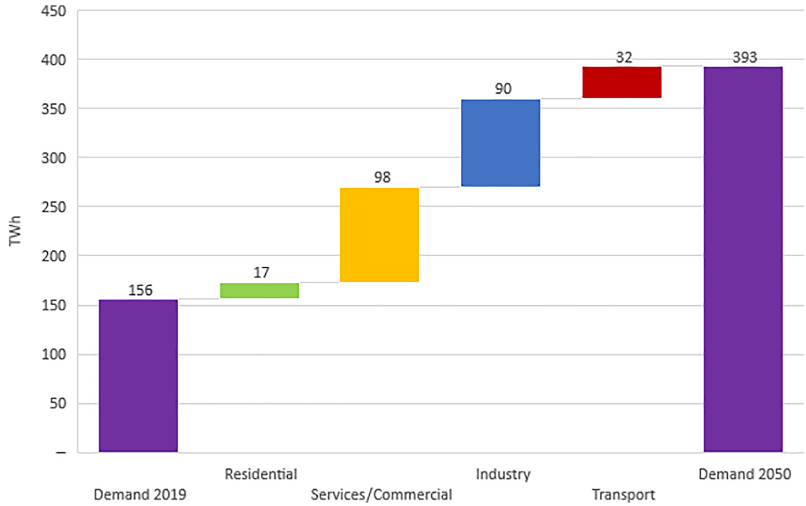

Figure 1. Contribution by sectors to increased electricity demand in the existing policy scenario (2019 and 2050)

(2) *Industry.* Malaysia's growing industry faces a dual challenge: meeting increasing energy demands while simultaneously reducing emissions. Industry drives 41% of the projected electricity demand increase by 2050 (Figure 1). 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.

(3) *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.

(4) *Transport.* Malaysia's ambitious target of 80% electric or plug-in hybrid vehicles (xEVs) by 2050 will significantly strain the electricity grid, with projected demand soaring from 1 TWh in 2020 to 33 TWh by 2050.

(2) Variable renewables

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

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 4), representing a 62-fold increase from 2019 figures. This surge will propel solar's share in Malaysia's total generation mix to 21%.

Wind power plays a negligible role in Malaysia's energy mix due to the country's low annual wind speeds, typically below 2 m per second at two metres above ground. Most wind turbines require a minimum speed of 4 m per second for efficient electricity generation (Koons, 2024).

(3) Dispatchable low-carbon generation

NETR establishes targets for various low-carbon generation sources beyond solar photovoltaics (PV), leveraging on Malaysia's abundant resources. This includes expanding the capacity of hydropower and diverse bioenergy forms (Figures 2 and 3). Notably, NETR incorporates hydrogen into the mix, acknowledging its variable carbon footprint based on production methods.

4.1.1 Hydropower. 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 (Sustainable Energy Development Authority 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 [2] from LEAP in the AGF-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 [3] of hydropower capacity might be necessary to meet anticipated demand in 2050. This

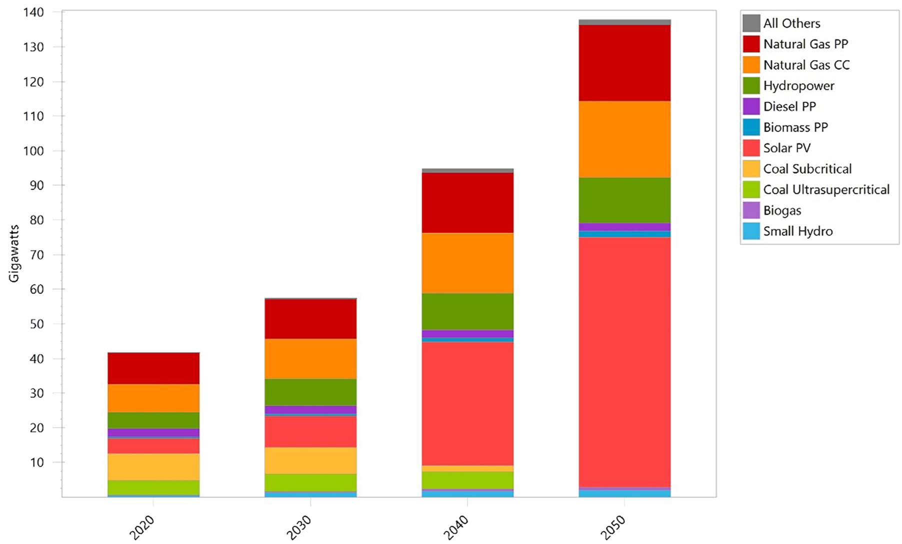

Figure 2. Installed and projected generation capacity by technology under existing policy (2020–2050)

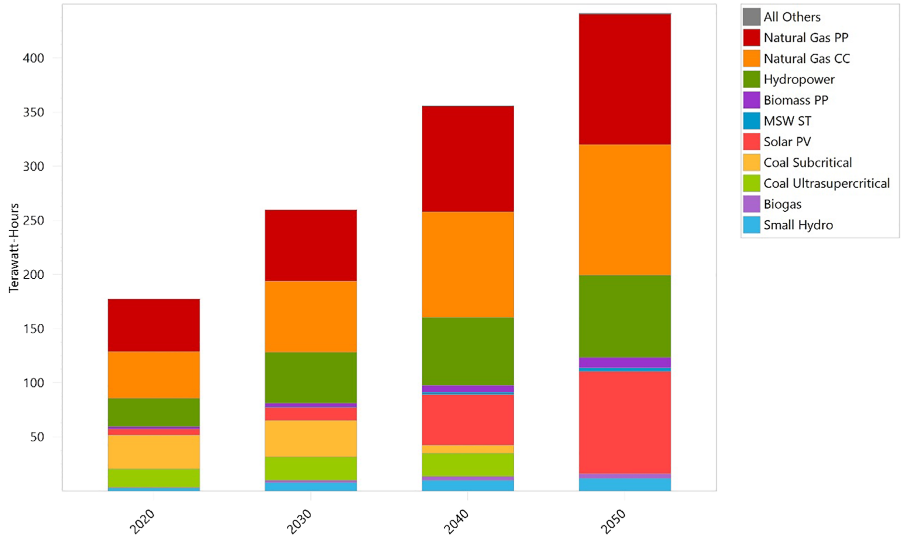

Figure 3. Historical and projected power generation by fuel under existing policy (2020–2050)

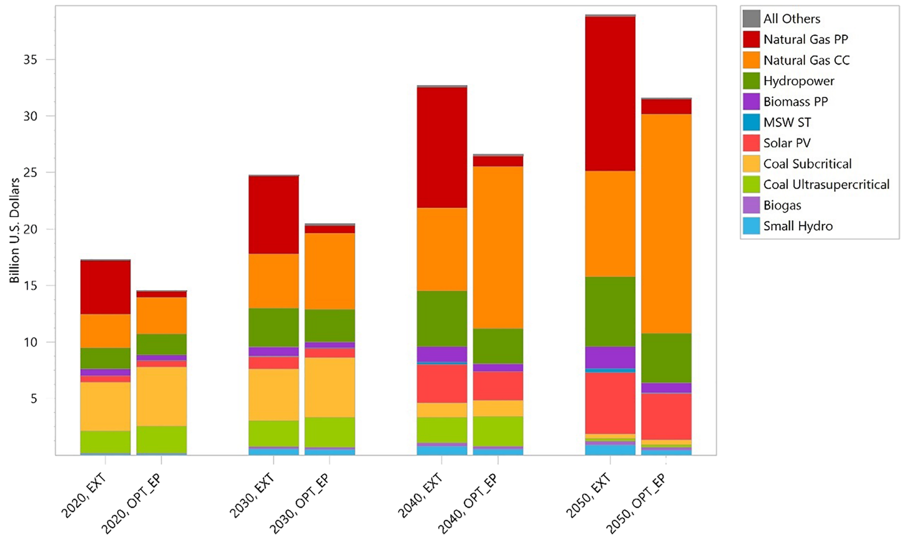

Figure 4. Comparing real power production cost between existing policy and optimised existing policy (2020–2050)

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, contributing 20% of Malaysia's total electricity generation. 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.

4.1.2 Bioenergy. 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.

Despite abundant forestry and agricultural resources, Malaysia's installed biomass power capacity [50–96 MW between 2012–2020 (Ministry of Plantation and Commodities, 2023)] 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 (Figures 2 and 3). This significant upward revision underscores the potential of biomass to contribute meaningfully to Malaysia's clean energy future.

Biogas offers a largely untapped source of renewable energy in Malaysia. Despite a modest installed capacity of just 71 MW in 2020 (Figure 2), 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 3). This substantial growth underscores the potential of biogas to play a more significant role in Malaysia's clean energy future.

4.1.3 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.

(4) Firm power high-carbon generation

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.

4.2 Optimised existing policy

This section presents the results of least-cost optimisation of the power generation mix within the constraints of current policies.

(1) Capacity and generation

The impacts of optimisation on the power generation mix from 2020 to 2050 are shown in Table 2.

(1) *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.

(2) *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.

(3) *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.

(4) 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.

(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:

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

(2) *Discounted cost:* Reflects the present-day value of all future costs, incorporating the time value of money. Future expenditures have a lower present value, offering a more nuanced perspective on the 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. The optimised scenario delivers lower real and discounted production costs across all years (Figures 4 and 5).

(3) GHG emissions

The Optimised Existing Policy scenario offers a significantly more favourable pathway towards decarbonisation. Compared to the Existing Policy scenario, it achieves an 11% improvement in emissions reduction 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.

4.3 Optimised more ambitious policy (OMAP)

This scenario explores the least-cost pathway to achieving more stringent emission reduction targets for both demand and generation. Key strategies include increased demand-side efficiency measures and a transition to cleaner energy sources. The OMAP scenario incorporates assumptions such as no new fossil fuel capacity additions after 2030 and a complete phase-out of coal by 2030, followed by natural gas and diesel by 2050.

(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 6 illustrates the comparative electricity demand across various demand sectors under the Existing Policy and More Ambitious Policy scenarios in 2050.

(1) *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

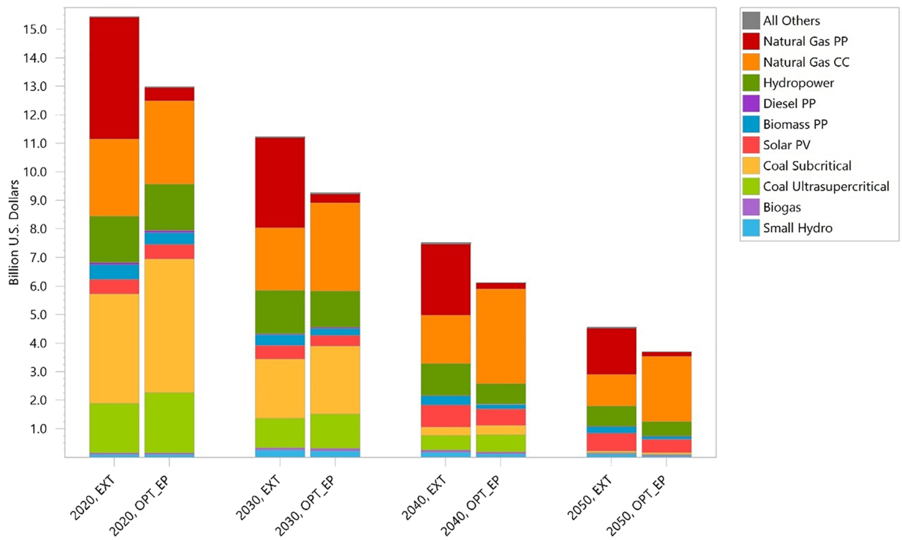

Figure 5. Comparing discounted power production cost between existing policy and optimised existing policy (2020–2050)

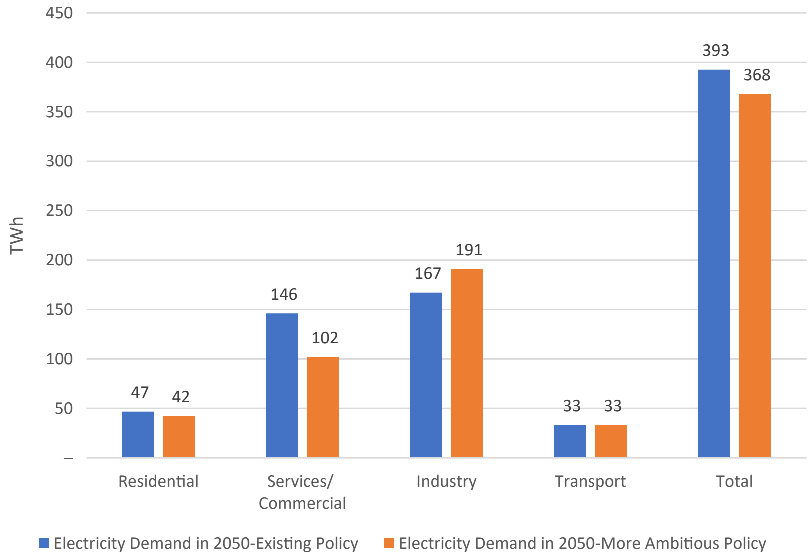

Figure 6. Comparing electricity demand in 2050 under existing policy and more ambitious policy

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.

(2) *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.

(3) *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.

(4) *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.

(2) Capacity and generation

The Optimised More Ambitious Policy scenario significantly elevates the role of renewables in the 2050 power generation mix, as detailed in Table 3.

Table 3. Comparing capacity and generation in existing policy, optimised existing policy, NETR targets and optimised more ambitious policy (2050)

	2050 EP Capacity (GW)	Generation (TWh)	2050 OEP Capacity (GW)	Generation (TWh)	2050 NETR Capacity (GW)	2050 OMAP 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

Source(s): Table by authors

(1) *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%.

(2) *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 (24x), 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.

- *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%).

(3) 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.

(4) 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 [4].
- 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-h storage assumption, highlighting the influence of factors such as power demand, renewable energy variability, and existing infrastructure on storage needs. (Blakers, Lu, Cheng, Stocks, Nadolny, & Weber, 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-h lithium-ion battery capabilities by 2050 (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.

(3) 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 4).

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:

(1) *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.

(2) *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 4. Cost and emission comparisons between NETR, Existing Policy, Optimised Existing Policy and Optimised More Ambitious Policy scenarios

	RE power generation 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

Source(s): Table by authors

By 2050, the discounted cost of electricity generation is projected to range from 0.84 to 1.25 US cents/kWh (Table 4). 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. 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).

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, Deng, Zhou, & Yu, 2019), USD 185 (Rennert *et al.*, 2022) and USD 417 (Ricke, Drouet, Caldeira, & Tavoni, 2018), as shown in Table 5. This variability stems from differing assumptions about future emissions, climate impacts, and the valuation of these damages.

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.

Table 5. 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 (USD cents/kWh)			Social cost in 2050 (USD cents/kWh)		
		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
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

Source(s): Table by authors

(4) 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 4 and Figure 7).

5. Discussion

Figure 8 provides a visual summary of the key points discussed in this section. Renewable energy generation, energy storage, and the grid are the key enablers of a resilient power system. When these components are optimally balanced, system resilience is enhanced.

5.1 Solar is a key technology in all scenarios

Malaysia's abundant solar resources position the country as a prime candidate for large-scale solar power deployment. To maximise the potential of this renewable energy source, a strategic focus on modular, rapidly scalable technologies, such as mass-produced solar PV modules and batteries, is imperative. These technologies exhibit steep learning curves, which

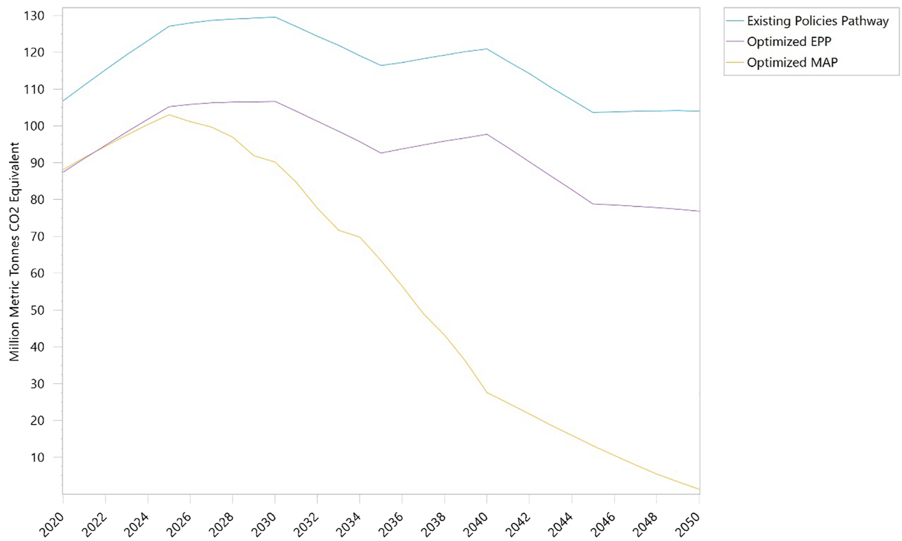

Figure 7. Power generation GHG emission trajectories in existing policy, optimised existing policy and optimised more ambitious policy scenarios (2020–2050)

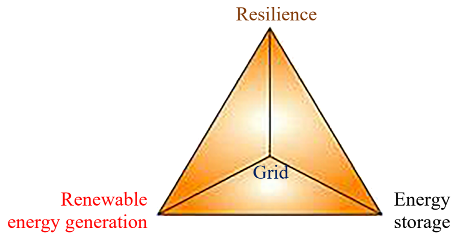

Figure 8. Key enablers of the energy transition

drive down costs and accelerate market penetration. Moreover, the flexibility and adaptability of rooftop solar installations enhance the distributed nature of solar power generation. As highlighted by the Rocky Mountain Institute (2024), these factors collectively position solar as a disruptive force capable of challenging and replacing traditional energy paradigms.

To address the intermittent nature of solar power, the integration of hybrid pumped hydro and battery storage systems is essential. These complementary technologies offer a robust solution to grid stability challenges by providing long-duration energy storage, short-term flexibility, and a range of grid services.

While both the LEAP model (72 GW) and the National Energy Transition Roadmap target (56 GW) underscore the significant solar expansion potential for Malaysia, realising these ambitions necessitates substantial investments in grid modernisation. Policymakers should explore incentives and funding mechanisms to accelerate the buildout of grid infrastructure that can effectively integrate a growing share of variable renewable energy sources, like solar, that is time-varying in supply and is generated in dispersed locations.

5.2 Leapfrogging over natural gas

While Figure 3 projects an increase in natural gas generation share 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 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)

The more sustainable and cheaper alternative to natural gas expansion is solar and storage solutions.

5.3 Expanding the roles of biomass and biogas

5.3.1 Biomass. The significant disparity between the National Energy Transition Roadmap's bioenergy target of 0.97 GW and SEDA's estimated potential of 3.60 GW underscores the untapped opportunities in this sector. This study's optimisation model further amplifies this potential, recommending a bioenergy capacity of 24.64 GW. To ensure sustainable growth, a comprehensive land-use study is crucial to inform revised bioenergy targets and develop supportive policies for feedstock development, certification and utilisation (e.g. biomass co-firing mandate escalation).

Malaysia's abundant forestry and agricultural resources position it as a prime location for biomass feedstock production. However, challenges such as feedstock variability, low combustion efficiency, and logistical hurdles hinder full exploitation. Overcoming these requires diverse feedstock sources, advanced conversion technologies, and optimised supply chains.

Dedicated, multi-use tree plantations offer a strategic pathway to scale up biomass supply sustainably. This approach must be incremental and evidence-based, integrated within a broader land-use strategy, and consider factors like carbon storage, avoided emissions, biodiversity, soil health, water requirements, and land rights. By addressing these factors and ensuring social acceptance, Malaysia can build robust and enduring biomass industry.

5.3.2 Biogas. Malaysia possesses significant untapped potential for biogas production, particularly in the agriculture and livestock sectors. While the nation has made strides in biogas generation from palm oil mill effluent, the utilisation of livestock industry waste and agricultural biomass remain underdeveloped. These two categories have the largest annual production of biomass after plantation biomass.

The National Biomass Action Plan 2023–2030 (Ministry of Plantation and Commodities, 2023) highlights Johor and Pahang as leading states in livestock manure production, surpassing 1 million tonnes annually each. Perak and Malacca follow closely with over 800,000 tonnes. Johor produces 500,000 tonnes of pineapple leaves and peel waste annually.

Despite this abundant resource, a 2018 study (Nurul, Suhaimi, Nurshuhada, Roslan, & Norazean, 2018) revealed limited biogas digester adoption in these regions – only four in Johor and two in Perak. This stark contrast underscores a substantial opportunity for biogas development in the agriculture and livestock sectors.

While biogas contributes modestly to overall renewable power generation, it offers significant benefits by closing the carbon loop. This approach reduces emissions, improves soil health, enhances agricultural yields, and strengthens the economic resilience of farmers.

To maximise biogas's value for Malaysia, a comprehensive study is needed to assess the economic feasibility and environmental impact of various biogas system configurations (e.g. combined heat and power, biomethane upgrading, direct use), considering feedstock characteristics and energy demand. This analysis will inform the development of a methodology for selecting optimal biogas systems based on site-specific conditions and policy frameworks.

5.4 The cost challenge of isolated renewable grids

Table 4 shows that the electricity production cost for a fully renewable grid in 2050 under the More Ambitious Policy scenario is 20% higher (10.6 US cents/kWh vs 8.8 US cents/kWh) than the cost of a mixed fossil fuel and renewable grid under the Existing Policy Scenario. This analysis assumes no cross-border interconnections. LEAP's calculation of electricity production cost incorporates power plant and energy storage capital, fixed and variable operation and maintenance expenses, fuel costs, plant performance metrics and financial parameters.

The intermittent nature of solar power requires flexibility solutions like energy storage to maintain grid stability. Falling battery costs could narrow this cost gap. Additionally, increased regional power interconnections can reduce the need for large-scale storage within individual countries (DNV, 2024).

Malaysia's Electricity Supply Industry 2.0 tariff (39.5 Malaysian Ringgit cents/kWh) is currently composed of fuel (42%), generation (26%), grid (29%), and retail (2%) costs. A shift to renewables is expected to reduce fuel costs but potentially increase grid expenses due to modernisation and flexibility requirements.

5.5 Regional grid integration: a necessity for renewable energy

Regional power interconnections are essential for integrating variable renewable energy sources and building a resilient, flexible power system. Expanding transmission infrastructure, especially through HVDC technology, is crucial for unlocking Southeast Asia's renewable energy potential. By enabling efficient long-distance electricity transfer, HVDC can enable optimal utilisation of geographically dispersed renewable energy generation and reduce the need for large-scale energy storage (DNV, 2024).

The Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP) is a significant step towards regional power trade. However, infrastructure disparities persist. While Peninsular and Sarawak Malaysia have robust 500 kV grids, Sabah's 275 kV grid is a bottleneck. Upgrading Sabah's grid is crucial for both intra-state power flow and regional integration.

5.6 Interpreting results with caution: resilience analysis

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 crucial to consider the resilience of different pathways in the event of potential disruptions. For example, pathways heavily reliant on hydropower or biomass could be more vulnerable to climate change impacts (e.g. droughts) and lead to poorer energy services or unexpected cost increases. Additionally, pathways that appear cost-effective under baseline assumptions might not be as economical under different circumstances, such as significant fossil fuel price spikes.

This type of in-depth analysis to assess pathway resilience was not included in the current modelling exercise. However, such considerations are essential when framing and presenting the results, as well as when developing policy recommendations.

6. Conclusion

The rapid deployment potential of solar and supporting technologies necessitates a re-evaluation of the extent to which natural gas should be relied upon as a bridge fuel as recommended in the National Energy Transition Roadmap. The rapid advancements in the technologies that harness, and store renewable energy, are likely to mean that a cheaper and cleaner energy transition can be achieved by replacing planned natural gas power plants with solar power and storage expansion.

Given the vast potential of solar power in Malaysia as well as its increasing affordability and its key role in all energy transition scenarios, Malaysia should unlock its solar power potential with coordinated investments in solar and storage technologies, and grid upgrades. Regulations on the power industry should be correspondingly updated.

The key components of the global energy transition are electrification, energy efficiency, solar, wind, energy storage, and energy transmission. Policymakers should design innovative incentives to expedite the development of smart grid infrastructure capable of integrating variable renewable energy sources.

Biomass power and biogas power should play bigger roles in the renewable energy mix. The potential scale of biomass power must be assessed in the context of a comprehensive land-use study and supply chain analysis.

Similarly, the assessment of the potential for animal waste-based biogas production must also consider benefits like circular waste management, methane emission reduction, water purity protection and poverty alleviation.

The key to unlocking the most cost-effective and reliable path to decarbonising Malaysia's power supply lies in a regional ASEAN approach. This approach prioritises strategic interconnections of national grids over isolated national expansion of renewable energy capacity to allow cost-competitive sourcing and backup power during outages. This vision necessitates a two-pronged planning approach: a long-term vision for a regional ultra-high voltage direct current backbone grid and the near-term optimisation of the current ASEAN Power Grid plan.

Notes

1. Seven focus areas: 1. ASEAN Power Grid (APG) 2. Trans-ASEAN Gas Pipeline (TAGP) 3. Coal and Clean Coal Technology (CCT) 4. Energy Efficiency and Conservation (EE&C) 5. Renewable Energy (RE) 6. Regional Energy Policy and Planning (REPP) 7. Civilian Nuclear Energy (CNE)
2. Large hydro: 10.6 GW; small hydro: 1.2 GW; Large hydropower plants typically generate over 30 megawatts (MW) of electricity; Small hydropower plants typically generate between 100 kilowatts (kW) and 30 megawatts (MW) of electricity.
3. Large hydro: 13.07 GW; small hydro: 2.14 GW.
4. 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-h discharge duration for batteries and 10-h discharge duration for pumped storage hydro.

References

ASEAN Centre for Energy (2024). *The 8th ASEAN energy outlook*. Jakarta: ASEAN Centre for Energy. Available from: https://www.partnershipsforinfrastructure.org/newsroom/potential-pumped-hydro-energy-storage-malaysia (accessed 2023).

Aziz, A. (2023). *Dewan Rakyat passes energy efficiency and conservation bill*. Available from: https://theedgemalaysia.com/node/685660 (accessed 23 February 2024).

Bernama (2024a). *Govt to review policies related to oil and gas industry, says Rafizi*. s.l.: s.n.

Bernama (2024b). *Rafizi: Malaysia faces higher gas imports if it doesn't quickly switch to sustainable energy*. s.l.: s.n.

Blakers, A., Lu, B., Cheng, C., Stocks, R., Nadolny, A., & Weber, T. (2022). Global greenfield pumped hydro energy storage atlas. Available from: https://re100.eng.anu.edu.au/global/

Carrie, H. (2022). *Power for 127 hours: The economics of long-duration energy storage*. s.l.: s.n.

Channel News Asia (2021). *12th Malaysia Plan: What you need to know about the 2050 carbon neutral goal and other green measures*. s.l.: s.n.

DNV (2024). *ASEAN interconnector study: Taking a regional approach to decarbonization*. s.l.: s.n.

DNV-GL (2018). *Consultation serivces on renewable energy penetration study for peninsular Malaysia and Sabah: Final report for peninsular Malaysia*. DNV GL Clean Technology Centre. s.l.

Ember (2024). *Global electricity review 2024*. s.l. Ember.

Energy Commission (2022). National energy balance 2019, s.l.: Energy Commission.

Haiges, R., Wang, Y., Roskilly, A., & Ghoshray, A. (2019). Unconventional fuel pathways for decarbonizing the electrical power generation in Malaysia by 2050. *Energy Procedia*, *158*, 4238–4245. doi: 10.1016/j.egypro.2019.01.803.

International Renewable Energy Agency. (2023). *Malaysia energy transition outlook*. Abu Dhabi: IRENA.

Koons, E. (2024). *Wind energy in Malaysia – potential for growth*. s.l.: s.n.

Kotter, J. P. (1996). *Leading change*. Boston, Massachusetts: Harvard Business School Press.

Leong, Y. Y. (2022). Electricity generation. In *Net Zero Pathways for Malaysia: ASEAN Green Future Phase 2 Interim Report* (pp. 7–39). s.l. UN Sustainable Development Solutions Network.

Lim, J. (2024). *NETR to phase down, not phase out, fossil fuels, says Rafizi*. s.l.: s.n.

Malay Mail (2024). *Electricity subsidies of RM1.935b for Peninsular Malaysia consumers in H1 2024*. s.l.: s.n.

Malaysian Government (2022). *National energy policy, 2022-2040*. s.l.: s.n.

Ministry of Economy (2023). *National energy transition roadmap*. Putrajaya: Ministry of Economy.

Ministry of Natural Resources, Environment and Climate Change, Malaysia (2022). *Malaysia 4th biennial update report under the United Nations framework convention on climate change*. Putrajaya: Ministry of Natural Resources, Environment and Climate Change.

Ministry of Plantation and Commodities (2023). *National biomass action plan 2023-2030*. Putrajaya: Ministry of Plantation and Commodities.

Ministry of Science, Technology and Innovation (2023). *Hydrogen economy and technology roadmap*. Putrajaya: MOSTI.

Nurul, A. M., Suhaimi, D., Nurshuhada, S., Roslan, M. Y., & Norazean, M. F. (2018). Current status of animal waste based biogas plants. *Malaysian Journal of Veterinary Research*, *9*(2), 117–121.

Platts, J. (2003). *Meaningful manufacturing*. York: Sessions of York.

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., . . . Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO2. *Nature*, *610*(7933), 687–692. doi: 10.1038/s41586-022-05224-9.

Ricke, K., Drouet, L., Caldeira, K., & Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, *8*(10), 895–900. doi: 10.1038/s41558-018-0282-y.

Rocky Mountain Institute (2024). *The cleantech revolution*. s.l. Rocky Mountain Institute.

Shabrina, N., & Dinita, S. (2024). *Solar and grid flexibility critical for Malaysia's future electricity affordability and security*. s.l. Ember.

Shell (2021). *The tree, the sky, the sun: A pathway towards Malaysia's carbon neutral future*. s.l. Shell.

Silverstein, K. (2024). *Long-duration energy storage is core to tripling renewables by 2030*. s.l. Forbes.

Sustainable Energy Development Authority Malaysia (2021). *Malaysia renewable energy roadmap: Pathways towards low carbon energy system*. Putrajaya: Sustainable Energy Development Authority (SEDA) Malaysia.

Tham, S. Y. (2022). Hydropower developmetn in Sarawak: Sensitivities over sustainability and China's involvement. *ISEAS Perspective, ISEAS Perspective 2022/45*, 28 April 2022.

Wang, Q., Li, S., & Li, R. (2018). China's dependency on foreign oil will exceed 80% by 2030: Developing a novel NMGM-ARIMA to forecast China's foreign oil dependence from two dimensions. *Energy*, November, *163*(15), 151–167. doi: 10.1016/j.energy.2018.08.127.

Wang, P., Deng, X., Zhou, H., & Yu, S. (2019). Estimates of the social cost of carbon: A review based on meta-analysis. *Journal of Cleaner Production*, *209*, 1494–1507. doi: 10.1016/j.jclepro.2018.11.058.

Weber, T., Blakers, A., Firnando Silalahi, D., Catchpole, K., & Nadolny, A. (2024). Grids dominated by solar and pumped hydro in wind-constrained sunbelt countries. *Energy Conversion and Management*, 17 April, *308*, 118354. doi: 10.1016/j.enconman.2024.118354.

Woo, W. T., Leong, Y. Y., Low, W. S., Liew, J., Lee, C. C., Fan, A. . . . Lim, J. (2023). *Simulating Malaysia's electrifying future*. Kuala Lumpur: UN Sustainable Development Solutions Network.

World Wildlife Fund Malaysia and Boston Consulting Group Malaysia (2021). *Securing our future: Net zero pathways for Malaysia*. s.l.: s.n.

Zeng, W., Zhang, X., Wang, X., & Wang, X. (2022). China's LNG import risk assessment based on the perspective of global governance. *Scientific Reports*. *12*(1), 15754. doi: 10.1038/s41598-022-20090-1.

Corresponding author
Yuen Yoong Leong can be contacted at: yuenyoong.leong@unsdsn.org