ACCEPT II
ASEAN Climate Change and Energy Project

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ENERGY AND MINES

An Energy Sector Roadmap to Net Zero Emissions for Lao PDR

ASEAN Centre for Energy
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About ASEAN Centre for Energy

Established on 1 January 1999, the ASEAN Centre for Energy (ACE) is an intergovernmental organisation within the Association of Southeast Asian Nations' (ASEAN) structure that represents the 10 ASEAN Member States' (AMS) interests in the energy sector. ACE supports the implementation of the ASEAN Plan of Action for Energy Cooperation (APAEC), a blueprint for better collaboration towards upgrading energy. The Centre is guided by a Governing Council composed of Senior Officials on Energy from each of the AMS and a representative from the ASEAN Secretariat as an ex-officio member. ACE serves in three key ways:

- *As a catalyst to unify and strengthen ASEAN energy cooperation and integration by implementing relevant capacity-building programmes and projects to assist the AMS develop their energy sector.*
- *As the ASEAN energy data centre and knowledge hub to provide a knowledge repository for the AMS.*
- *As an ASEAN energy think tank to assist the AMS in identifying and surfacing innovative solutions for ASEAN's energy challenges on policies, legal and regulatory frameworks and technologies.*

Maintaining the region's energy security, affordability, and sustainability is a fundamental concern of the ASEAN energy sector. Hosted by the Ministry of Energy and Mineral Resources of Indonesia, ACE's office is located in Jakarta, Indonesia. For more information, please visit www.aseanenergy.org.

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- Delivery of Draft Model and Results (December 2023)
- Workshop II – Consultation on Model and Results and Capacity Building on Low Emissions Analysis Platform (LEAP) and Next Energy Modelling System for Optimisation (NEMO) Energy Modelling (March 2024)
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Forewords from ACE Executive Director

As the Executive Director of the ASEAN Centre for Energy (ACE), I am honoured to present ***An Energy Sector Roadmap to Net-Zero Emissions for Lao PDR***. Developed under the ASEAN Climate Change and Energy Project (ACCEPT) Phase II with generous support from the Norwegian Government, this publication provides a strategic pathway for Lao PDR's energy sector to achieve its commitment to net-zero emissions by 2050. Lao PDR declared this commitment during COP26 in Glasgow, reflecting the nation's clear dedication to a low-carbon future in alignment with global climate objectives.

As a nation often referred to as the *"Battery of Southeast Asia"*, Lao PDR is endowed with immense renewable energy potential. Hydropower remains a cornerstone of its energy strategy, with over 25GW of development potential, positioning the county as a regional clean energy hub and distributer. However, despite its established hydropower capacity and abundant resources, the changing climate patterns present challenges in terms of ensuring the resilience of the energy infrastructure. The country's significant potential in wind, solar and biomass energy presents an opportunity to diversify its renewable energy mix, further strengthening energy security and sustainability.

Lao PDR has demonstrated strong climate leadership, becoming the first country in Asia to submit its Nationally Determined Contribution (NDC) in 2015. Given the energy sector's growing prominence in the country's overall emissions profile, as part of its commitments to climate action, Lao PDR has prioritised reducing emissions in this sector. With rising electricity demand and increasing regional interconnections, ensuring a sustainable and low-carbon energy supply will be vital for achieving the country's net-zero target.

Today, as Lao PDR advances towards decarbonisation, the road ahead is filled with opportunities and challenges, underlining the necessity for collaboration among governments, international institutions and public-private sectors. In this regard, regional cooperation will be crucial for Lao PDR to secure energy independence, economic growth, and a sustainable transition to renewable energy sources that will ensure a resilient, low-carbon future for generations to come.

This roadmap **is designed to support Lao PDR** in its ambitious pursuit of net-zero emissions, while strengthening its long-term planning, driving essential policy reforms, and addressing critical gaps in institutional capacity and financial resources. It includes a detailed presentation of the energy modelling methodology and scenario overview, analysis of energy supply and demand, exploration of cross-cutting issues, recommendations and a way forward.

Two advanced tools were employed in the energy modelling: the Low Emissions Analysis Platform (LEAP) and the Next Energy Modelling System for Optimisation (NEMO). Developed by the Stockholm Environment Institute (SEI), countries around the world are leveraging the LEAP and NEMO toolkit to design net-zero pathways as part of their Long-Term Low Emission Development Strategies (LT-LEDS).

As ASEAN looks to the future, ACE remains committed to supporting all ASEAN Member States (AMS) in their journey towards energy transition. This is an important step for our collective future, and while the path may be challenging, it is one we must take together. I would like to express my sincere appreciation to the Ministry of Energy and Mines (MEM) of Lao PDR, SEI and the Embassy of Norway for their support throughout this process. This roadmap serves not only as a strategic guide for Lao PDR, but also as a valuable resource for other nations navigating the complexities of energy transition in the face of climate change. It is my hope that it will inspire and guide countries in their efforts towards a sustainable and low-carbon future.

Dato' Ir. Ts. Abdul Razib Dawood
Executive Director
ASEAN Centre for Energy

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Executive Summary

Over the past two decades, Lao PDR has achieved remarkable economic growth, averaging 7% annually from 2000 to 2018, driven primarily by hydropower and mining. However, heavy reliance on hydropower poses risks from climate variability, such as drought-induced water shortages that threaten energy security and export revenues. The COVID-19 pandemic exposed economic vulnerabilities, including rising public debt and a depreciating currency, slowing recovery and limiting sustainable energy financing. This, combined with high external debt repayments, has intensified inflationary pressures and economic instability.

Despite the challenges, Lao PDR has set an ambitious goal to achieve net- zero greenhouse gas (GHG) emissions by 2050. This commitment reflects the country's determination to strengthen energy security, enhance economic resilience and contribute to global climate action, particularly under the Paris Agreement. The country submitted its Nationally Determined Contributions (NDC) in 2015, and was even more ambitious in 2021, targeting further emission reductions through sustainable forest management, renewable energy expansion and energy efficiency.

Lao PDR's goal of net-zero emissions by 2050 requires transforming its energy sector, which faces challenges from hydropower vulnerabilities and fossil fuel dependence in industry and transport. Despite progress in renewable energy and cross-border electricity trade, gaps remain in understanding the sector's role in achieving net-zero emissions. An integrated approach is needed to align energy transitions with national and regional goals. This roadmap employed the Low Emissions Analysis Platform (LEAP) and the Next Energy Modelling System for Optimisation (NEMO) to guide long-term decision-making, explore viable pathways and assess technology options and policy impacts. These advanced tools enable robust assessments of both baseline and transformative pathways, incorporating stakeholder input to optimise energy generation and storage at the lowest possible cost.

To assess the feasibility and implications of the emission reduction targets, we evaluated two primary scenarios: the Baseline Scenario and the Net-zero Scenario. The Baseline Scenario represents a continuation of existing practices without major policy shifts, while the Net-zero Scenario envisions comprehensive mitigation measures aimed at reducing emissions across the economy. The analysis reveals that the Net-zero Scenario significantly reduces total energy demand compared to the Baseline Scenario. This reduction is primarily driven by improvements in energy efficiency and a transition to cleaner fuels. Notably, the industrial sector is projected to become the largest energy consumer, surpassing all other sectors such as the transport, commercial and residential sectors. Renewable energy sources, particularly solar and biomass, are expected to play a critical role in achieving net-zero emissions, while coal and traditional biomass usage are gradually phased out. Additionally, electrification—including the widespread adoption of electric vehicles — and biofuels emerge as essential for reducing emissions from road transport, which is anticipated to become the second-largest energy consumer. Emissions reductions within the industrial sector are also achieved through energy efficiency measures and fuel transitions, such as adopting hydrogen and implementing carbon capture technologies.

Meanwhile, on the supply-side, Lao PDR shows that achieving the Net-zero Scenario requires significant growth in electricity generation capacity, reaching nearly 30 GW by 2030 compared to 18 GW in the Baseline Scenario, driven by increased demand, hydrogen production and direct air capture (DAC) processes. Hydropower remains dominant, with solar, wind and geothermal gradually replacing coal and biomass. Unlike the steady generation in the Baseline Scenario, the Net-zero Scenario shows dynamic patterns with energy storage playing a vital role. Electricity exports continue, while the demand for coal and biofuels increases. Petroleum imports decline as transportation adopts cleaner energy.

The GHG emissions in Lao PDR's Baseline Scenario still mainly come from agriculture, forestry and other land use (AFOLU) and industrial processes, particularly cement production. This highlights the need for comprehensive mitigation across all sectors to achieve net-zero targets. In the Net-zero Scenario, achieving conditional NDC targets, especially in the forestry sector, significantly reduces emissions between 2020 and 2030 by creating a carbon sink that partially offsets emissions from other sectors. However, residual emissions remain from industrial processes, waste, coal use and transport, requiring carbon removal, primarily through DAC. By 2050, Lao PDR must securely store over 6 million tonnes of CO_2 each year unless further emission reductions are made.

Achieving these goals will require significant investments in modernising infrastructure, particularly to enhance grid stability and efficiency. Improving grid interconnections, especially in rural areas, will be imperative for maintaining a reliable electricity supply. As electric vehicle adoption and the electrification of cooking and heating expand, the existing grid will face increased demand, necessitating upgrades and modernisation. In addition, fostering innovation in energy storage solutions—such as lithium-ion batteries and pumped storage hydro—will be critical to maintaining both energy security and reliability.

Financial and technical challenges also present substantial obstacles to achieving the net-zero target. Lao PDR's dependence on foreign investment makes it susceptible to global economic shifts, while limited technical expertise may hinder the deployment of advanced renewable technologies. Transitioning from traditional biomass cooking methods to cleaner alternatives, such as electric and LPG stoves, also requires significant changes in both behaviour and infrastructure. Addressing these challenges will necessitate comprehensive capacity-building initiatives and collaboration among multiple stakeholders to sustain progress.

The transport sector also presents challenges, particularly in terms of electrification. Limited infrastructure and high upfront costs for electric vehicles could slow adoption rates. To address this, incentives to encourage EV uptake, investments in charging infrastructure and the promotion of electric public transport systems will be essential. Furthermore, fostering regional cooperation to facilitate cross-border electricity trade and technology-sharing will help diversify Lao PDR's energy mix and strengthen economic resilience. Achieving a balanced energy transition will also require addressing socio-economic impacts, including potential job displacement and the need for workforce reskilling.

Recommendations and Way Forward:

1. **Policy Integration:** Strengthen the alignment between national development plans and climate action strategies to create a cohesive framework that integrates socio-economic growth with sustainability goals.

2. **Technology Advancement:** Accelerate the deployment of clean energy technologies, including solar, wind and bioenergy, and enhance grid resilience to accommodate increased renewable penetration.
3. **Capacity Enhancement:** Develop local technical expertise and institutional capacity to manage complex energy transitions and maintain system reliability.
4. **International Collaboration:** Foster stronger regional integration to attract investments, secure technical assistance and enhance cross-border energy trade and infrastructure development.
5. **Financial Innovation:** Explore blended finance models and leverage international climate finance to bridge funding gaps, particularly for large-scale renewable projects and electric vehicle adoption.
6. **Community Engagement:** Promote awareness and education to encourage public acceptance and participation in clean energy initiatives, particularly in rural and remote areas.
7. **Social Inclusivity:** Develop strategies to ensure that vulnerable populations are not disproportionately affected by the energy transition and facilitate workforce retraining and skill enhancement to support emerging green industries.

This roadmap offers a comprehensive and practical framework to guide policymakers, stakeholders and investors in navigating the path towards achieving net-zero emissions in Lao PDR. By fostering strategic partnerships, advancing technology adoption and ensuring inclusive community engagement, Lao PDR can balance socio-economic growth with environmental sustainability, securing a resilient and low-carbon future.

Hor Luk Mueang in Vientiane, Lao PDR

Chapter 1
Introduction

Chapter 1: Introduction

1.1. Lao PDR's Socio-Economic Context and Energy Needs

1.1.1. Overview of Lao PDR's economic growth and development trajectory.

The Lao People's Democratic Republic (Lao PDR) is a landlocked country in Southeast Asia. It is strategically positioned in the heart of the region, sharing borders with China, Myanmar, Thailand, Cambodia and Vietnam. Spanning a land area of 236,800 square kilometres, the country is characterised by its rugged mountainous terrain and its location within the Lower Mekong River Basin (LMB) area, which provides access to abundant natural resources. Notably, Lao PDR is rich in renewable energy (RE) potential, particularly hydropower, biomass, solar and wind [1], making it a key player in the regional energy landscape.

In 2022, Lao PDR had a population of 7.529 million, up from 5.852 million in 2005, and reflecting an average annual growth rate of 1.7%. There were approximately 1,327,125 households in 2022, with an average household size of 5.67 persons [2]. Among the ASEAN Member States (AMS), Lao PDR has one of the smallest populations, ranking 8th among of the 10 countries. Despite a gradual shift towards urbanisation, the majority of the population (63%) still resides in rural areas.

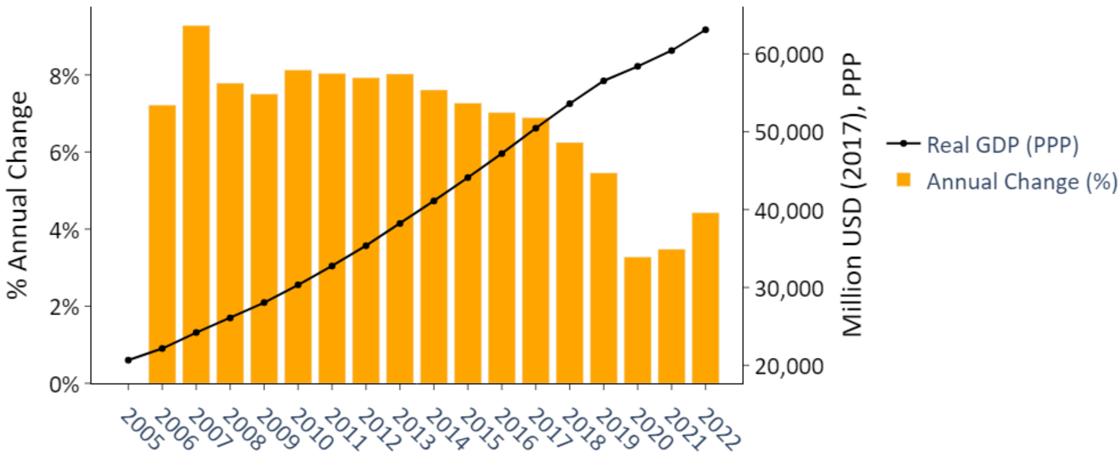
Historically, Lao PDR operated as a centralised economy until the introduction of the New Economic Mechanism (NEM) in 1986. This reform transformed the nation's agricultural focus towards a market-oriented economy. Today, the services sector constitutes approximately 47% of the country's GDP, while the industry and agriculture sectors constitute around 35% and 18%, respectively. Given its small population, the country's economy is mainly driven by the export of natural resources, particularly hydropower, mining and timber [3].

Since 2000, the country has been among the fastest growing economies in the world, achieving an average annual growth rate of 7% until 2018. This growth was primarily driven by the mining and hydropower sector with rapid infrastructure development and substantial inflows of foreign direct investment (FDI) [4]. However, when the COVID-19 pandemic hit in 2020, the country experienced a noticeable decline, with GDP growth dropping to 3.2%—its lowest rate in decades. Recovery to pre COVID-19 levels has been slow, hindered by a combination of macroeconomic challenges.

The government increased foreign borrowing to finance pandemic-related expenditures and infrastructure projects, leading to a sharp rise in public debt and strained fiscal sustainability [5]. Limited fiscal space, coupled with high external debt repayments in foreign currency, has contributed to the depreciation of the local currency, the Laotian Kip[1] [6]. A weak local currency raises import costs and amplifies foreign debt burdens, further exacerbating inflationary pressures and economic instability [7]. Figure 1 shows GDP at constant prices and its annual growth.

[1] Exchange rates for the Laotian Kip (LAK) to USD: In 2010, the exchange rate was approximately 8,254 LAK/USD; in 2022, it was 14,035 LAK/USD; and as of 2023, it stood at 17,688 LAK/USD.

Figure 1 Lao PDR GDP (at constant price, and % annual change)

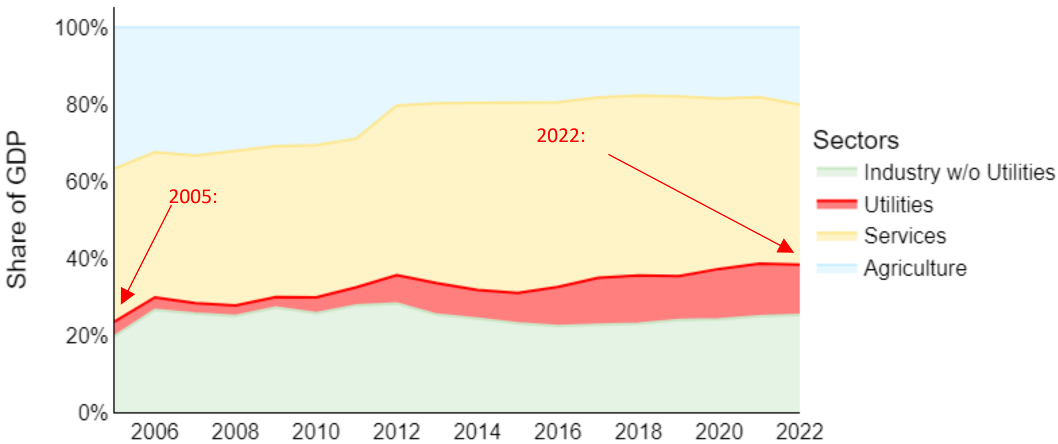


Source: ACE calculations based on data provided by multiple sources (WDI, ADB, IMF, APERC, SSP)

Electricity, as part of the utilities sector, has emerged as one of the key contributors to Lao PDR's economy. The increasing contribution of the utilities sector to the national GDP highlights its significance in the country's economic development. Utilities accounted for around 4% of the total GDP in 2005, gradually increasing over the years and reaching 13% in 2022 (Figure 2). With its abundant hydropower resources, Lao PDR has positioned itself as the regional leader in clean energy production. Hydropower development is one of the key focuses of the government's 2030 Vision and 10-Year Socio-Economic Development Strategy [8], highlighting its vital role in boosting economic growth and advancing the country's development objectives. However, the heavy reliance on hydropower presents several risks, including climate variability, such as drought-induced water shortages [9], as well as environmental degradation, socioeconomic impacts on rural livelihoods and national revenue stability concerns [10].

To capitalise on its energy potential, Lao PDR has strengthened its electricity connectivity with neighbouring countries through cross-border transmission line expansion and energy trade agreements. In 2023, the country exported 37,538 GWh of electricity, making it the 17th largest electricity exporter in the world. Electricity is the country's largest export, with Thailand and China being the primary export destinations [11].

Figure 2 Share of GDP by Sector (at Nominal Price)



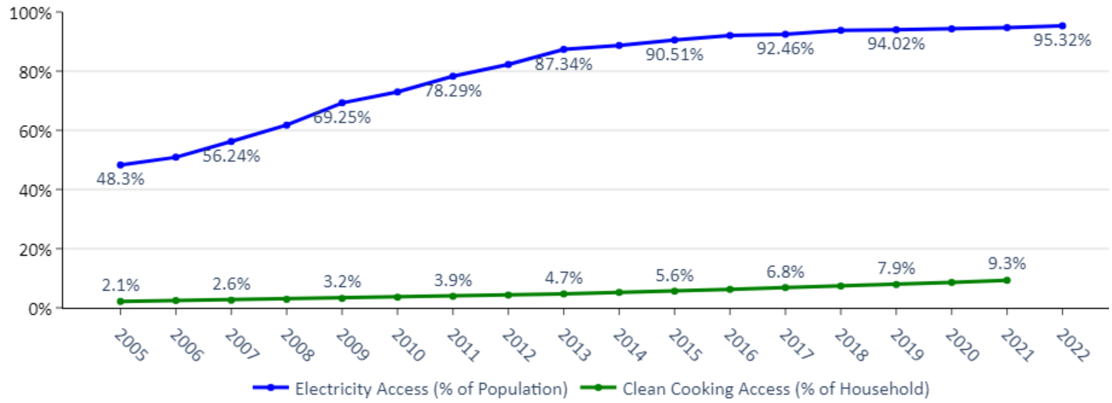
Source: ACE calculations based on data provided by multiple sources (WDI, ADB, IMF, APERC, SSP)

The growing prominence of electricity as an economic driver has also been reflected in domestic electrification progress. Access to electricity has grown rapidly from 48.3% of the population in 2005 to 95% in 2022. However, access to electricity still varies substantially by region. More densely populated and less mountainous central areas generally enjoy higher electrification rates, whereas the northern and southern mountainous regions still face challenges in accessing reliable electricity [12].

Despite its strong progress in electrification, access to clean cooking remains limited, with only 9% of the population having access to clean cooking solutions in 2022. The majority of households still rely on biomass stoves, which accounted for an average of 97% of households in 2018 in both urban and rural areas [13]. This heavy reliance on biomass stoves poses health, environmental and social challenges. Prolonged exposure to air pollution from burning fuels is a leading cause of respiratory illness.

Efforts have been made to transition households into cleaner cooking methods. With abundant electricity from hydropower generation, Lao PDR has great potential to promote the use of electric stoves. However, to support this, it is essential to ensure the reliability and quality of electricity supply through improved grid interconnections, particularly in rural areas [14]. Liquified petroleum gas (LPG) is another solution as it generates lower indoor pollution compared to traditional cooking stoves. However, widespread adoption of LPG in Lao PDR is constrained by the country's dependency on oil and gas. Currently, Lao PDR imports all of its oil products, making the transition to LPG economically challenging [15].

Figure 3 Electricity Access and Clean Cooking Share, 2005-2022



Source: ACE and WDI

1.1.2. Current energy consumption patterns across sectors

Lao PDR’s energy landscape is largely defined by its electricity generation sector, which plays a central role in national energy security and economic growth. The state-owned utility, Électricité du Laos (EDL), is responsible for managing national electricity generation, transmission and distribution, as well as electricity imports and exports from the national electricity grid [16]. Since the 1970s, the development of power generation capacity has grown at a relatively high rate of about 17% per year, driven by the neighbouring countries’ high demand for electricity imports. Around 72% of the energy generated was exported to Cambodia, China, Myanmar, Singapore, Thailand and Vietnam [17]. By the end of 2023, Lao PDR had power plants with a total installed capacity of 11,692.14 MW, generating approximately 58,884 GWh of electricity. This includes 81 hydropower plants, 1 coal-fired plant, 4 biomass plants and 12 solar power plants [18][2]. Notably, electricity generation from RE has steadily increased.

In 2020, Lao PDR's energy consumption was primarily driven by the residential sector, which accounted for 35% of total usage. This was followed by the transport sector at 28%, the industrial sector at 25% and the commercial sector at 11%. The remaining 1% was used for agriculture and other needs.

Lao PDR is often referred as the *"Battery of Southeast Asia"*[19]. This title is particularly relevant in the context of the ASEAN Power Grid (APG), a regional initiative aimed at integrating power grids across ASEAN Member States (AMS). The nation possesses an estimated hydropower potential of 26,000 megawatts (MW) [1]. Lao PDR's central location as a landlocked country provides a strategic position to serve as a transmission hub connecting energy producers and consumers across the region. Electricity was the top export commodity in 2022, accounting for 30% of total export value that year [20].

Recognising its pivotal role in regional energy trade, the Ministry of Energy and Mines of Lao PDR has set clear targets under the National Power Development Strategy (2021–2030) to enhance energy security and economic growth as follows [21].

Table 1 Lao PDR National Targets

Sector	Target
Power Development	• Develop national potential power sources with power generation mixed for domestic use and export. • Power generation mixed for domestic use from hydropower (75%), coal (14%) and RE (11%). • Promote power generation for export and power exchange among neighbouring countries.
Electric Vehicle Development	• Promote electrically powered vehicles in the transportation sector to account for 30% of the total vehicles for 2-wheelers and passenger's cars on the road by 2030.
Transmission Line System Development	• Link up the transmission line system to achieve nation-wide coverage. • Integrate export-domestic consumption systems to advance a subregional connection hub.
Electricity Distribution System Development	• The government has set electricity distribution system targets of 95% for 2020, 98% for 2025 and 100% for 2030. • Promote electricity exports among Greater Mekong Subregion (GMS) countries under the ASEAN Power Grid Memorandum of Understanding (MoU), with a focus on the Lao PDR-Thailand-Malaysia-Singapore (LTMS) project.

Source: Électricité du Laos Presentation during Workshop on An Energy Sector Roadmap to Net-zero Emissions of Lao PDR, held by ACE in October 2023 [21]

[2] The 2023 data provided is for informational purpose only and is not included in the modelling analysis, as the historical data used in the model ends in 2022.

Hydropower continues to be the backbone of electricity supply, meeting the increasing demand for clean energy. However, climate change-related challenges, such as prolonged droughts during the dry season, have raised concerns over the reliability of hydropower generation. Additionally, Lao PDR plans to continue using its existing coal-fired power plants as part of its electricity mix. This ongoing reliance on fossil fuels may present challenges to the country's international climate commitments, particularly under the Paris Agreement, which calls for a transition to low-carbon energy systems.

Ensuring alignment between Lao PDR's national energy strategy and its climate commitments is crucial. A well-integrated approach will be necessary to balance economic goals with sustainability goals, ultimately securing a mutually beneficial outcome for both national development and global climate action.

1.2. Understanding Lao PDR's Climate Commitments

1.2.1. Short term: Key targets and commitments outlined in Lao PDR's Nationally Determined Contributions (NDC)

Lao PDR was the first country in Asia to submit its NDC in 2015. According to its initial submission, the country's total greenhouse gas (GHG) emissions in 2000 were reported at 50,100 ktCO_2e, with the agriculture, forestry and other land uses (AFOLU) sector accounting for over 95% of total emissions. To complement the NDC, in 2019, the Prime Minister's Office issued the Decree on Climate Change [22] which defines principles, regulations and measures on management, and monitoring of climate issues. The Decree mandates that climate change considerations must be integrated into national socio-economic development plans, as well as sectoral and local strategies and plans.

To fulfil its climate commitments, Lao PDR set key targets in the forestry and energy sectors. One of its major pledges was to increase forest cover to 70% of the total land area by 2020. The forest cover was estimated at 58% of its total land area in 2015 [23]. Additionally, the country aimed to optimise hydropower utilisation by increasing installed capacity to 5,500 MW by 2020.

Beyond hydropower, Lao PDR also set renewable targets in its first NDC. The government committed that non-hydro RE sources would account for 30% of total final energy consumption (TFEC) by 2025. Furthermore, the share of biofuels in the transport sector was targeted to reach 10% by 2025. In addition to emission reduction efforts, Lao PDR added a rural electrification programme to its pledge. The government aimed to achieve 90% household electricity access by 2020. Noting that currently rural households consume an average of 30 litres of kerosene and diesel per year, the government is intending to increase rural electrification so that the use of these fossil fuels can be reduced, and concomitantly CO_2 emissions can be reduced by approximately 63 ktCO_2e annually.

In 2021, Lao PDR submitted an updated NDC, building on its 2015 commitments with greater ambition. The revised NDC introduced three GHG emissions projections:

1. Baseline projection – estimates emissions levels if no mitigation actions are taken.
2. Unconditional mitigation projection – outlines emission reductions based on the country's own resources and existing international support.
3. Conditional mitigation projection – details additional efforts that require enhanced financial and technical support from developed nations.

The updated NDC highlights key achievements and ongoing challenges in Lao PDR's climate commitments. Notably, the country successfully expanded its large hydropower capacity to 5,500 MW by 2020 and remains on track to reach 20,000 MW by 2030. Additionally, the rural electrification programme exceeded its initial target, achieving 94% household electricity access in 2020, surpassing the 90% goal. However, progress in other mitigation areas has been more challenging. Some targets, such as increasing forest cover and expanding non-hydro RE, have faced delays and were carried forward into the updated NDC.

The baseline projection illustrates future GHG emission levels likely to occur in the absence of GHG mitigation activities. Under the baseline projection, total GHG emissions levels in Lao PDR would be expected to reach around 82,000 ktCO_2e in 2020 and 104,000 ktCO_2e in 2030. The main sectors contributing to baseline emissions are AFOLU and energy, which includes the transport and power sectors.

Under the unconditional mitigation projection, Lao PDR commits to reducing emissions using domestic resources and existing international support. Key actions include:

- Forestry sector: Reducing emissions from deforestation and forest degradation through sustainable forest management, aiming to cut AFOLU emissions by 1,100 ktCO_2e annually from 2020 to 2030.
- Energy sector:
    - Expanding hydropower capacity by an additional 13 GW by 2030, reducing emissions by 2,500 ktCO_2e annually.
    - Distributing 50,000 energy-efficient cookstoves to reduce biomass dependency, cutting emissions by 50 ktCO_2e annually.
    - Implementing major transportation projects—including a Bus Rapid Transit (BRT) system in Vientiane and the Lao-China Railway—to achieve an annual reduction of 300 ktCO_2e.

Under the conditional mitigation scenario, Lao PDR aims to further accelerate emission reductions with increased financial and technical assistance from developed countries. Additional efforts include:

- Forestry: Expanding forest cover to 70%, reducing emissions by 45,000 ktCO_2e annually.
- Renewable energy: Installing 1 GW of solar and wind capacity and 300 MW of biomass energy by 2030, contributing to an annual reduction of 184 ktCO_2e.
- Energy efficiency: Targeting a 10% reduction in final energy consumption, leading to an annual reduction of 280 ktCO_2e.
- Transport sector: Aiming for 30% electric vehicle (EV) penetration in two-wheelers and passenger cars and maintaining a 10% biofuel share in transport fuels.

In addition to the energy, forestry and transport sectors, Lao PDR has introduced additional mitigation measures in agriculture and waste management. In the agriculture sector, efforts will focus on improving water management practices in lowland rice cultivation to reduce methane emissions, with an estimated annual reduction of 128 ktCO_2e. In waste management, the country plans to implement a sustainable municipal solid waste management system capable of processing 500 tons per day, which is estimated to reduce emissions by 40 ktCO_2e annually. Together, these measures are expected to achieve a total estimated annual emissions reduction of 168 ktCO_2e.

1.2.2. Long-term: Opportunities and challenges towards Net-Zero

Lao PDR first articulated its commitment to achieve net-zero emissions by 2050 in its updated NDC. This pledge was further emphasised by H.E. Mme Bounkham Vorachit, Minister of Natural Resources and Environment, during her statement at the High-Level Segment Ministerial Level of the UN COP 26 in Glasgow in 2021 [24] .

To support this goal, the Ministry of Natural Resources and Environment (MONRE), in collaboration with World Bank, has developed Lao PDR's Long-Term Low Emission Development Strategy (LT-LEDS) [25].

Based on this strategy, Lao PDR's pathway to net-zero emissions presents several economic and environmental opportunities. Key among these is the decarbonisation of electricity generation, with a focus on expanding RE sources apart from hydropower such as solar and wind. Then, strengthening grid infrastructure and enhancing regional interconnection to support cross-border power trade will encourage more electricity generation to be installed, and this could mean more space for RE to contribute.

With Lao PDR's abundant RE resources to generate electricity, electrification of end-uses such as replacing biomass-based cookstoves with electric alternatives and scaling up EV adoption offers significant benefits. These shifts would reduce dependence on fuel imports and enhance energy security while reducing emissions. Moreover, by investing in energy efficiency, the amounts of energy used especially by the industrial sector, and also by appliances and buildings, are expected to fall. Indeed, all measures that curtail electricity consumption from coal-fired power plants will contribute towards net-zero emissions.

Another critical pathway for Lao PDR is access to climate finance, which can provide essential funding for decarbonisation efforts. The country has been actively engaging with the Green Climate Fund (GCF) and Global Environment Facility (GEF) to secure funding for climate mitigation and adaptation projects. These international financial mechanisms play a crucial role in mobilising resources to support Lao PDR's RE expansion, energy efficiency programmes and broader sustainability initiatives [26].

Beyond these energy-related measures, Lao PDR can leverage other opportunities to support its transition towards net-zero emissions. Developing sustainable industries, such as eco-tourism and sustainable forestry, can help diversify the economy while reducing reliance on hydropower exports. The country's rich biodiversity and cultural heritage provide strong potential for eco-tourism, promoting conservation efforts while generating economic growth. Likewise, sustainable forestry practices not only support carbon sequestration but also align with the country's long-term environmental and land-use strategies.

Despite these opportunities, Lao PDR faces several key challenges in implementing its net-zero strategy. Addressing these barriers will require long-term planning, significant policy reforms, and strengthened institutional, financial and technical capacity.

One of the key challenges for Lao PDR is the need to restore macroeconomic stability and fiscal space, as financial constraints limit the government's ability to make long-term investments in clean energy and sustainability initiatives. Addressing fiscal challenges, such as public debt and budget deficits, is crucial to ensuring the financial flexibility needed for large-scale decarbonisation efforts.

At the same time, securing sufficient financial resources remains a key challenge. While international climate finance provides valuable support in bridging funding gaps, diversifying funding sources will be essential to sustaining Lao PDR's transition to a low-carbon economy. Encouraging greater private sector participation through a supportive investment climate can help unlock opportunities in clean energy projects, energy efficiency programmes, and sustainable development initiatives, contributing to long-term growth and resilience.

Beyond financial barriers, technological and infrastructure gaps remain significant obstacles to Lao PDR's net-zero ambitions. Limited access to advanced clean energy technologies, technical expertise and research capabilities constrains the adoption of modern energy solutions. Strengthening technical cooperation, research partnerships and capacity-building initiatives will be essential in bridging these gaps.

Climate vulnerability remains a major concern, as Lao PDR is highly susceptible to extreme weather events, floods and droughts, which can disrupt infrastructure and slow decarbonisation efforts. Additionally, large-scale infrastructure and energy projects must be managed carefully to minimise environmental and social impacts. Land-use competition and biodiversity loss, historically driven by agricultural expansion, infrastructure development and illegal logging, continue to threaten sustainability efforts.

Achieving net-zero emissions will require balancing conservation efforts with economic growth, ensuring that policies support both environmental and socio-economic objectives. Capacity building, workforce development and enhanced governance frameworks will be essential to drive long-term, sustainable implementation of Lao PDR's LT-LEDS.

1.3. Bridging the Energy Transition and Net-Zero Ambition

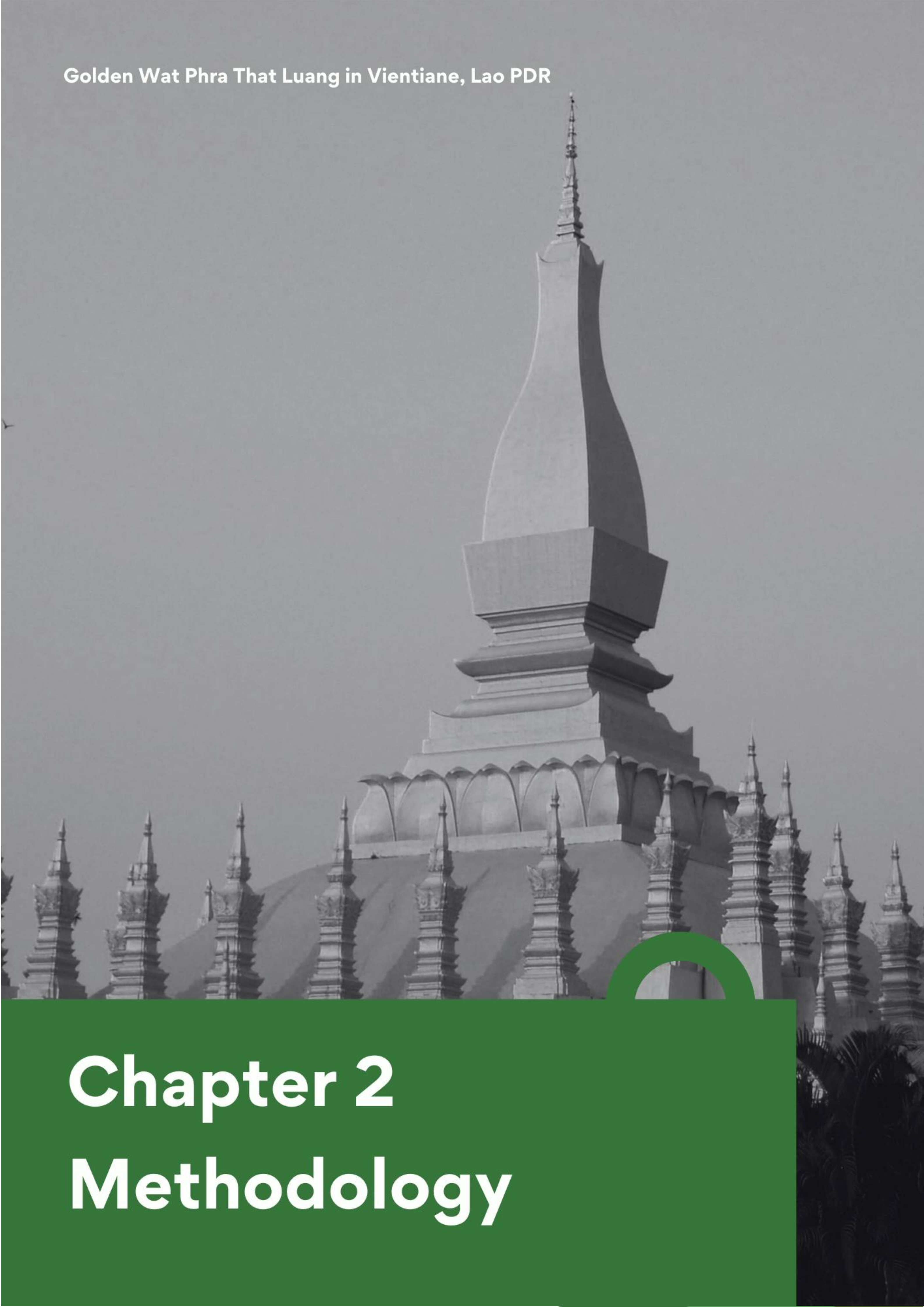
Lao PDR's commitment to achieving net-zero emissions by 2050 requires significant efforts to transform its energy sector. While the country has made notable progress in RE development and cross-border electricity trade, several challenges remain in ensuring energy security, economic resilience and sustainability. Hydropower, which serves as the backbone of the country's electricity generation, is vulnerable to climate variability, while the reliance on fossil fuels in industrial and transportation presents a barrier to full decarbonisation. The transition to cleaner energy sources should align with national development goals and regional energy integration efforts.

Despite various strategies and commitments in Lao PDR's energy and climate framework, a gap remains in understanding how the energy sector can contribute to the country's net-zero ambition. The energy transition is inherently multidisciplinary, involving interconnections between energy systems, climate policies and socio-economic considerations. A more integrated approach is needed to assess the feasibility of emission reduction strategies in the energy sector to ensure they are both practical and aligned with long-term sustainability goals.

This report aims to address this need by using energy modelling to examine a viable pathway for Lao PDR's energy sector in supporting the net-zero transition. Through scenario-based modelling, this study evaluates different technology and policy options and how they impact emissions reduction and mitigation measures to inform long-term decision-making. The key objectives of this study are:

- **Delineate a pathway for the energy sector to meet its economy-wide net-zero emissions**: This report presents *a* pathway, not *the* pathway, for Lao PDR's energy sector to meet its economy-wide net-zero emissions goal by 2050. Energy modelling is used to assess different technology and policy options and provide quantitative insights into the feasibility of a transition pathway.
- **Assessing cross-cutting issues towards achieving net-zero emissions**: This report examines technical and economic considerations, policy frameworks and regional energy integration in Lao PDR's transition to net-zero emissions. Given Lao PDR's strategic position within ASEAN, the report also explores how enhanced regional cooperation can support Lao PDR's energy security and economic resilience when transitioning towards net-zero.
- **Provide policy recommendations and a way forward:** This report offers insights to enhance Lao PDR's energy planning and inform policies that support the net-zero emissions target.

By addressing these objectives, this report provides policymakers and stakeholders with insights to support informed decision-making. It offers a structured approach to understanding how Lao PDR's energy sector can contribute to the net-zero transition while balancing economic and environmental priorities.



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Chapter 2
Methodology

Chapter 2: Methodology

2.1. Lao PDR Energy Model

2.1.1. Modelling software

The Lao PDR energy model was built using the Low Emissions Analysis Platform (LEAP) [27] and the Next Energy Modelling system for Optimisation (NEMO). These modelling tools, developed by the Stockholm Environment Institute (SEI), offer a comprehensive, flexible and user-friendly system for energy sector analysis. LEAP and NEMO are widely used for energy policy analysis, low-emission development strategies, and climate change mitigation assessments. Increasingly, countries are using the LEAP and NEMO toolkit to develop net-zero pathways within their Long-Term Low Emission Development Strategies (LT-LEDS).

LEAP is an integrated, scenario-based modelling tool designed to quantify energy consumption, production and resource requirements across all sectors of the economy under various scenarios. It also considers both sources and sinks of GHGs from the energy and non-energy sectors. LEAP serves as the primary user interface, enabling model construction and results visualisation through its graphical interface.

NEMO, a high-performance, open-source energy system optimisation tool, complements LEAP by simulating the electricity sector using mixed-integer linear optimisation. NEMO optimises the dispatch and expansion of electricity generation and storage based on demand projections from LEAP. The optimisation is conducted within a system of constraints, such as maximum and minimum capacities and capacity additions, ensuring the reasonableness of the projections.

2.1.2. Modelling scope and methods

The Lao PDR energy model used for this study is based on a broader regional LEAP and NEMO model developed by the ASEAN Centre for Energy (ACE) for their ASEAN Energy Outlook report series. SEI and ACE, collectively called the *modelling team* for this study, collaborated on the development of the model beginning with the model last used for the Seventh ASEAN Energy Outlook (AEO7) [28]. SEI implemented a set of ready-to-deploy greenhouse gas mitigation measures for the energy sector, or net-zero enabling technologies, as well as other model enhancements required to build a net-zero GHG scenario. Simultaneously, ACE worked to improve and update the model to eventually become the basis for the Eighth ASEAN Energy Outlook (AEO8) [29]. The model has continued to evolve, and at the time of this report's publication the model version was 6.08.3.

The AEO model simulates the evolution of energy demand and supply in each AMS under multiple scenarios, accounting for GHG emissions and other air pollutants that arise from energy-related activities such as fuel consumption and production. The model spans 2005 through 2022, and scenario forecasts begin in 2023 and extend to 2050. It is a multi-regional model, with one model region for each AMS, including Lao PDR. The AEO model can be calculated for all countries simultaneously or for any subset of them. The results obtained for this study are obtained by doing the calculations for Lao PDR alone within the AEO model.

Modelling of final energy demand is broken down by major sector, subsector and fuel, including energy consumption in residential and commercial buildings, industry, transportation, agriculture and other sectors. Following the methods adopted for prior AEO analyses, the model generally uses a bottom-up activity analysis to project future energy consumption based on historical and future trends in sectoral activity and energy use per unit of activity, or *intensity*. Table 2 lays out sectoral detail and units of activity that are included for Lao PDR, although the broader AEO model may represent additional sectors for other AMS that are inactive in Lao PDR.

Table 2 Final energy demand sectoral detail represented in the Lao PDR region of the AEO model[3].

Demand Sector	Subsector or End-Use Detail	Unit of Activity
Residential	Cooking, Rice Cookers	Number of households
	Lighting	Number of households
	Air Conditioning	Number of households
	Water Heating	Number of households
	Clothes Washing, Clothes Drying, Clothes Ironing, Refrigeration, Television, Computing, Fans, Other Miscellaneous	Number of households
Commercial	Cooking	Square metres of floorspace
	Lighting	Square metres of floorspace
	Air Conditioning	Square metres of floorspace
	Water Heating	Square metres of floorspace
	Refrigeration, Other Miscellaneous	Square metres of floorspace
Industry	Mining	Value added to GDP from mining
	Construction	Value added to GDP from construction
	Other Industry	GDP
Transport	Passenger	Passenger-kilometres
	Freight	Tonne-kilometres
	Rail	GDP
	Domestic Aviation	GDP
	Inland Waterways	GDP
Agriculture		Value added to GDP from agriculture

[3] This also captures historical energy consumption from non-energy use of fuels and from international aviation through 2018. However, energy consumption associated with these subsectors does not appear in the national energy statistics after that year.

Energy supply processes are simulated using a number of modules that represent the transformation of one or more fuels into another (or the transformation of one fuel into a lesser quantity of the same fuel, representing energy loss). Separate modules are used to represent energy transmission and distribution losses, production of biofuels and other alternative fuels, electricity generation and storage, and extraction and processing of fossil resources. Each module produces one or more output fuels using a specified set of production technologies, selected by following a prescribed set of rules. Table 3 lists the energy supply sectors that are represented in the Lao PDR region of the AEO model, alongside the input fuels that are transformed into output fuels by at least one production technology within that sector.

Table 3 Energy supply sectors (with input and output fuels) represented in the Lao PDR region of the AEO model.[4]

Supply Sector	Input Fuel(s)	Output Fuel(s)
Energy Sector Own Use	Electricity	Electricity
Electricity Transmission and Distribution	Electricity	Electricity
Biomethane Production	Biomass, Electricity*, Hydrogen*	Biomethane
Biogas Production	Biomass	Biogas
Biodiesel Production	Biomass, Methanol, Natural Gas*, Biodiesel*, Electricity*	Biodiesel
Renewable Diesel Production	Biomass, Hydrogen, Biodiesel*, Electricity*	Biodiesel, Sustainable Aviation Fuel
Bioethanol Production	Biomass	Ethanol
Methanol Production for Energy Use	Hydrogen, Coke Oven Gas, Blast Furnace Gas, Electricity*	Methanol
Hydrogen Production for Energy Use	Natural Gas, Electricity*, Lignite Coal, Biomass	Hydrogen
Electricity Production	Lignite Coal, Diesel, Fuel Oil, Natural Gas, Hydrogen, Large Hydro, Small Hydro, Geothermal Heat, Solar, Wind, Bagasse, Biomass, Biogas, Municipal Solid Waste	Electricity
Charcoal Production	Wood, Biomass	Charcoal
Gasoline Distribution and Handling	Gasoline	Gasoline

[4] Fuels indicated with an asterisk (*) may be either an auxiliary fuel, or both an input fuel and an auxiliary fuel. Energy from auxiliary fuels is not transformed into output fuels, but they may be required to provide process energy for the transformation of other input fuels. Some supply sectors such as natural gas production, and some input fuels such as nuclear fuel, are represented in the AEO model but they are inactive in Lao PDR and therefore not listed below.

Oil Refining	Crude Oil	Gasoline, Kerosene, Diesel, Fuel Oil, LPG, Other Oil
LNG Regasification	LNG	Natural Gas
Crude Oil Production	Crude Oil	Crude Oil
Coal Production	Lignite Coal	Lignite Coal

Any fuel requirements that are not satisfied using a transformation module are assumed to be imported. When added to modelled domestic production, they become the model's total primary energy requirements. Many of these supply sectors are used to model the production of a new fuel introduced in the Net-zero Scenario, even if they have not existed historically in Lao PDR. More information on these sectors is included in Appendix B.

In the module representing electricity production, LEAP simulates both annual capacity expansion and energy production (dispatch) during representative sub-annual time periods called *time slices*. The AEO model contains 288 time slices, one for each representative hour in each of the twelve calendar months. Two methodologies are offered: one in which capacity expansion and dispatch are simulated using a set of predetermined ordering rules (used in this study's Baseline Scenario), and one in which capacity expansion and dispatch are simulated using least-cost optimisation (used in this study's Net-zero Scenario). For the latter, LEAP connects with NEMO to provide numerical optimisation capabilities, satisfying electricity requirements using a least-cost mixture of generation and storage technologies. NEMO will attempt to find an optimal (meaning lowest net present system cost) capacity and energy mix that meets the overall system requirements: namely, that satisfies all electricity requirements, and that meets the system's minimum capacity reserve margin. Other constraints may also be specified. Using either methodology, the electricity generation sector implementation levels (capacities) for electricity technologies are specified using two separate parts, termed "exogenous" and "endogenous". Exogenous capacity reflects any specific national plans to add capacity, or to reach a minimum level by a particular year. Endogenous capacity is added to exogenous capacity at the model's discretion.

Estimates of GHG emissions associated with fuel production and consumption are calculated within LEAP, using the emission factors built into the AEO model, and expressed in carbon dioxide equivalent (CO_2-e) terms using Global Warming Potential metrics from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. The model also includes estimates of non-energy GHG emissions from industrial processes and product use (IPPU), waste and AFOLU. Historical emissions from forestry, shrubland and wetlands are taken from Climate TRACE [30]. Future values for forestry – the most significant source among all non-energy sectors – are projected using a constant value, calculated as the mean of the historical emissions between 2016 and 2022. Future values for shrubland and wetlands are held constant at their most recent values from the year 2022. Historical emissions from all other non-energy sectors are taken from the European Commission's EDGAR (Emissions Database for Global Atmospheric Research) database [31], which are then multiplied by a calibration constant to align with nationally-provided emissions from the year 2014, presented in Lao PDR's First Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC) [32]. Future values for these emissions sources are projected using a simple linear extrapolation, based on historical trends. If no historical trend is observed or only one year of historical data is available, that value is held constant for future years. Altogether, these assumptions give rise to non-energy GHG emissions that are summarised in Table 4. Since these assumptions also include forecasted values to 2050, they are used directly in the model's Baseline Scenario, which is discussed further in Section 2.2.2.

Table 4 Summary of non-energy GHG emissions used in Baseline Scenario (MT CO_2-e).[5]

Category	2015	2020	2025	2030	2035	2040	2045	2050
Industrial Processes and Product Use	0.09	0.19	0.20	0.25	0.30	0.35	0.40	0.45
Agriculture Forestry and Other Land Use	-4.61	89.7	37.5	38.6	39.7	40.8	41.9	43.0
Waste	0.54	0.58	0.60	0.62	0.65	0.68	0.71	0.73
Non-energy total	**-3.98**	**90.5**	**38.3**	**39.5**	**40.7**	**41.9**	**43.0**	**44.2**

2.2. Scenario Overview

This report presents two scenarios for Lao PDR: a Baseline Scenario derived from the forthcoming Eighth ASEAN Energy Outlook, developed by ACE with support from SEI, and a Net-zero Scenario that integrates emission constraints and low-emission technologies across various sectors, developed by SEI with support from ACE. The methods and main assumptions for each scenario are detailed in the following subsections.

2.2.1. Stakeholder input into modelling

Throughout the development of the model and two scenarios, the SEI and ACE team interacted with stakeholders in Lao PDR facilitated by the Ministry of Energy and Mines (MEM). Through these interactions, the modelling team verified the modelling approach, sought data needed to improve the model or to model specific net-zero enabling measures, and validated measure implementation assumptions and modelled results. Table 5 summarises and provides a timeline for these collaborative interactions among the modelling team, MEM and stakeholders in Lao PDR.

Table 5 Summary of stakeholder interactions and their role in the development of the model and scenarios.

Meeting or Interaction	Purpose and Outcome
Provision of Initial Data Request September 2023	At the onset of the work, SEI prepared a spreadsheet-based list of data requirements, prioritised according to their importance for conducting net-zero modelling and the availability of alternative data sources.
First In-Country Workshop October 2023	The modelling team travelled to Vientiane to propose a method for selecting net-zero enabling measures, and to gather input on which measures (and at which levels of implementation) were most appropriate for Lao PDR.

[5] Historical values (shown for 2015 and 2020) are estimated from several sources and should not be interpreted as accepted GHG inventory values.

Delivery of Draft Implementation Rates and Results December 2023	Having modelled each option individually, SEI combined these measures into a pathway that reaches net-zero greenhouse emissions by 2050. A brief characterisation of each option, its implementation level, the resulting national emissions forecast, and a set of targeted questions were delivered to MEM for reactions.
Second In-Country Workshop March 2024	Initial feedback from the December 2023 meeting was incorporated into the modelled pathway, which was presented in a more finalised format during the Second In-Country Workshop in Vientiane (with SEI attending virtually). Following the presentation of results, the modelling team guided several breakout group discussions to complete an online survey that requested specific input on the level of deployment for each net-zero option. Outcomes from the survey were carefully reviewed by the modelling team to identify changes to be included in the Lao PDR Net-zero Scenario, and changes to the model's historical data or baseline scenario assumptions. When feedback was not directed to specific measures in the Net-zero Scenario, SEI and ACE incorporated it directly into the AEO model.
Delivery of Draft Report February 2025	After incorporating all changes to the model based on feedback from the Second In-Country Workshop and from internal review by members of the modelling team, a draft report was delivered to MEM in February 2025 for official review.
Delivery of Final Report March 2025	Final report delivered to MEM.

Throughout this report, when assumptions or data inputs were provided directly to the modelling team through one of these stakeholder interactions, they were cited as such. While every effort was made to validate with stakeholders all measures and their implementation levels in the Net-zero Scenario, the requirement to meet net-zero emissions often necessitated ad-hoc adjustments to implementation rates, not all of which could be reviewed in advance.

2.2.2. Baseline Scenario

As introduced in Section 2.1.2, the model used for this analysis was developed as part of the Eighth ASEAN Energy Outlook [29]. Foundational to the AEO8 is the model's Baseline Scenario, which includes a full set of assumptions describing how the energy system may evolve over time, largely following historical trends established within each AMS. It assumes a business-as-usual level of effort put forth by each AMS, notably without meeting any established energy efficiency (EE) or renewable energy (RE) policy targets. Since many countries' power development plans (PDPs) align with these RE targets, the Baseline Scenario excludes any electricity generation capacity additions called for by Lao PDR's latest PDP. GHG mitigation commitments or measures that are described in each country's NDC are also excluded. For further detail on specific data sources and assumptions used in Lao PDR, refer to the AEO8 [29].

2.2.3. Net-Zero Scenario

The concept of net-zero emissions differs conceptually from that of zero emissions because it allows for some remaining GHG sources, so long as they are balanced by negative emissions in another sector. The Net-zero Scenario for Lao PDR envisions a pathway for the country to achieve net-zero GHG emissions economy-wide, encompassing both energy and non-energy emissions, by 2050. It is based on the AEO8 Carbon Neutrality Scenario, which is the model's most ambitious GHG reduction scenario. It includes or surpasses targets set out in the AEO8's AMS Targets (ATS[6]) and Regional Aspiration (RAS[7]) Scenarios. Together, the ATS and RAS scenarios assume that Lao PDR's national EE and RE policies are surpassed, going beyond the targets first outlined in the ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025. Together, these scenarios also assume that Lao PDR's unconditional NDC targets for the energy sector will be implemented. Finally, the scenarios assume that deployment of new electricity capacity, generation and storage will follow a least-cost trajectory, while accounting for resource constraints on RE. Planned capacity from the PDP is included. For further details about specific data sources and the assumptions used for the ATS and RAS scenarios in Lao PDR, please refer to the AEO8.

a. Scenario Assumptions for Non-Energy Sectors

Crucially, reaching net-zero GHG emissions in Lao PDR cannot be achieved without sustained and significant changes to carbon emissions from forests and land use, and methane emissions from agriculture. Assumptions about the future emissions from these sectors are necessary because they determine the remaining GHG budget for the energy sector, so that together, economy-wide emissions (energy and non-energy together) can become net-zero. Basic assumptions made for non-energy emissions are described in Section 2.1.2 and Table 4, which are also the values used for each year of the Baseline Scenario.

This analysis centres on measures that can be implemented within the energy sectors – that is, the modelling team did not consider measures that focus exclusively on AFOLU, IPPU or waste (although some measures were considered that reduce emissions from one of these sectors *as well as* energy-related GHGs). Instead, beginning with the emissions from the Baseline Scenario, the modelling team included further reductions in non-energy emissions that were informed by the conditional targets for non-energy sectors laid out in Lao PDR's NDC [33]. The NDC describes several GHG reductions that would be implemented by the year 2030, and the modelling team then assumes that these reductions would be permanent and persist for all remaining years of the scenario, 2031-2050. This includes reductions of 40,000 tonnes per year of CH_4 from waste, 128,000 tonnes per year

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[6] The ATS ensures attainment of official national policies, especially for EE and RE targets. It includes PDP installation target and firmed capacity additions and provides modelling interventions to meet energy-related unconditional targets under the various countries' NDCs.
[7] The RAS aims to explore an enhanced version of the national and regional targets outlined in APAEC 2016-2025 by escalating national EE and RE targets. RAS offers results while implementing the least-cost optimization in the power generation sector, applying RE capacity constraints, optimized electricity storage, and transmission modelling.

of CH_4 from rice cultivation, and most importantly, reductions of 45 million tonnes per year of CO_2 from forestry, turning a historical carbon source into a carbon sink. Emissions from other non-energy sectors, for which no NDC target is explicitly described, are identical to their Baseline Scenario values.

As will become clear in results presented in Chapter 3:, these are important assumptions. In the first scenario year of 2023, GHG emissions in the Baseline Scenario from AFOLU alone are over 37 million tonnes CO_2-e, larger than all energy-related GHG emissions and over 70% of national emissions. Without action in this sector, emissions from all other sectors would need to become implausibly negative for the country to reach net-zero emissions.

b. Scenario Assumptions for Energy Sectors

Whereas GHG emissions in non-energy sectors are largely assumed by the modelling team, the Net-zero Scenario outlines specific implementation levels for energy-related mitigation technologies (also called "net-zero enabling measures") that are represented within the AEO model. This scenario builds on the Baseline Scenario by incorporating emission constraints, adopting low-emission technologies and fuels on the demand side, and exploring alternatives for low-emission power generation. It also includes carbon capture and storage (CCS) in the electricity sector and relevant production processes on the supply side to support the production of required low-emission fuels. Net-zero enabling technologies were selected from the International Energy Agency's Energy Technology Perspectives (ETP) "Clean Energy Technology Guide" [34]. SEI conducted a literature review to explore the impacts of each option on energy consumption and resulting GHG emissions, while assumptions about the implementation level for the Laos PDR Net-zero Scenario were developed by SEI and validated through consultations with stakeholders in Lao PDR.

The ETP Clean Energy Technology Guide is a comprehensive database of technologies across the entire energy system that contribute to achieving net-zero emissions. It categorises each measure and includes brief descriptions of the technology, its maturity level (characterised by a Technological Readiness Level, or TRL), and key countries or regions where the technology is or may play a role.

From the approximately 550 technologies represented in the database, SEI initially selected a group with TRL ≥ 7: technologies classified as either mature, or in the market uptake or demonstration phases of development., Those that were only in the prototype or conceptual phases of development were excluded. From this group, technologies that were associated with a key country (according to the database) namely, China, Korea, any AMS, or that were left blank were admitted.[8]

One final and more subjective filter was then applied, eliminating net-zero enabling technologies on the basis that they were not sufficiently additional to, or distinct from, other net-zero measures that were included (and would thus be difficult to distinguish from one

[8] Some exceptions were included, notably solid direct air capture (solid DAC, or S-DAC). The level of end-use detail provided in the AEO model for Lao PDR does not easily permit modeling of some technologically-detailed, bottom-up mitigation measures. As a result, the modeling team expected that within the model, residual CO_2 would need to be removed using some other top-down technology.

another in an integrated energy system model like the AEO model), or they applied to an overly specific energy-related process to be resolved in the energy system model.

The resulting 135 technologies were then grouped into similar categories to be modelled together, given the relatively aggregated level or detail in the AEO model. For example, while the Clean Energy Technology Guide included multiple technologies that consume hydrogen for specific process elements within iron or steelmaking, the modelling team grouped these into a single measure under which hydrogen is introduced to the iron and steel industrial subsector. For each individual measure or group of similar measures, the model was updated with technical details that characterise the measure (such as rates of combustion or transformation efficiency, avoided fuel consumption and GHG emissions) and an implementation schedule through the year 2050.

In some cases, the net-zero enabling technology was already represented in the AEO model, such as electricity generation from solar photovoltaics or electric passenger vehicles. In these cases, the modelling team deferred to any existing assumptions used to characterise the technology in the model, modifying only the implementation level in the Net-zero Scenario. All data, sources and assumptions used to develop net-zero enabling technologies are documented and cited within the model itself.

Generally, the measures represented in the model include technologies related to:

- Electrification and fuel switching to solar energy, biofuels, biomethane, hydrogen, ammonia, methanol and sustainable aviation fuel for selected sectors and end-uses,
- Energy conservation and efficiency in lighting, cooking, space cooling, water heating, air and road transport, cement production, and some manufacturing processes,
- Carbon dioxide utilisation for iron and steel manufacturing,
- Clean electricity production from hydro, solar, geothermal, wind, biofuels and waste,
- CCS for thermal power plants, and bioenergy with CCS (BECCS),
- Electricity storage from pumped hydro and lithium batteries.

Generation and storage technologies are specified using two separate parts (exogenous and endogenous). The input assumptions provided to NEMO, including the planned (exogenous) capacity additions and the maximum (endogenous) capacity that may be added, are detailed in Appendix B (section on electricity generation and storage). The actual number of megawatts of endogenous capacity are part of the model's results and are presented in Section 3.2.1. Figure 4 lists the measures considered for the Lao PDR's Net-zero Scenario, grouped by sector. More information on the measures, including their assumptions and adoption levels, are included in Appendix B.

Figure 4 Measures included in the Net-Zero Scenario for Lao PDR.

Residential sector (R)

- R1. Improved and clean cooking
- R2. Heat pump space cooling
- R3. Reflective coatings and cool roof technologies
- R4. Programmable thermostats
- R5. Optimal building orientation
- R6. Heat pump water heaters
- R7. Solar water heaters
- R8. Gamification of electricity use

Commercial sector (C)

- C1. Improved and clean cooking
- C2. Heat pump space cooling
- C3. Heat pump water heaters
- C4. Solar water heaters
- C5. Efficient refrigerators
- C6. Light-emitting diode (LED) lighting

Industrial sector (I)

- I1. Reduced clinker in cement
- I2. Electric heat pumps for low-temperature heat
- I3. Biomass circulating fluidized bed boilers for low- and high-temperature heat
- I4. Biomethane boilers for low- and high-temperature heat
- I5. Hydrogen boilers for high-temperature heat
- I6. CO_2 capture and utilization in iron and steel production
- I7. Solid direct air capture and sequestration
- I8. Hydrogen displacement of coal and gas

Transport sector (T)

- T1. Improved aviation efficiency
- T2. Electric taxiing and ground operations at airports
- T3. Sustainable aviation fuel (SAF)
- T4. Hydrogen fuel cell aviation
- T5. Biodiesel and bioethanol blending
- T6. Biomethane vehicles
- T7. Battery electric vehicles
- T8. Hydrogen fuel cell electric vehicles (FCEV)
- T9. Hydrogen combustion for trucking
- T10. Autonomous electric taxis
- T11. Fuel economy improvements

Electricity generation and storage (E)

- E1. Large hydro
- E2. Small hydro
- E3. Onshore wind
- E4. Ground mount solar PV
- E5. Rooftop solar PV
- E6. Floating solar PV
- E7. Concentrating solar power
- E8. Geothermal
- E9. Biomass combustion
- E10. Biomass gasification
- E11. Biogas digestion
- E12. Waste
- E13. Supercritical coal with CCS
- E14. Ultrasupercritical coal with CCS
- E15. Bioenergy with CCS
- E16. Lithium-ion batteries
- E17. Pumped storage hydro

Other supply (S)

- S1. Hydrogen production from electrolysis
- S2. Conventional hydrogen production with CCS
- S3. Biomethane production from anaerobic digestion
- S4. Biogas production from anaerobic digestion
- S5. Biodiesel production from FAME
- S6. Biodiesel production from HVO
- S7. Ammonia and methanol production from hydrogen

At the core of the definition of “net zero” is an assumption that a small amount of residual emissions may be unavoidable, but that they may be balanced using sinks. GHG emission sinks, or carbon dioxide removal (CDR) technologies, are a key component of most countries’ net-zero plans. In fact, according to the Net Zero Tracker, only two countries (1.4% of those reporting) do not include some form of CDR in their national plans.

As stated earlier, actions to reduce or reverse, non-energy emissions in Lao PDR, especially from livestock, forests and croplands, are critical for reaching net zero emissions. This study assumes that some of these necessary actions will be implemented – at least those called for in Lao PDR’s NDC. But to reach net zero GHGs in this study, the remainder of the emissions gap is closed using energy-sector CDR: bioenergy with carbon capture and sequestration, and energy-consuming direct air capture (DAC) processes. Through these negative emission technologies, the model is able to meet a negative emissions constraint applied to the energy sector. Therefore, implementation of CDR technologies like BECCS and DAC in the Lao PDR Net Zero Scenario should be viewed as an absolute upper limit, only necessary in the absence of other measures.

Box 1 The role of carbon dioxide removal technologies in the Lao PDR Net Zero Scenario

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Chapter 3

Lao PDR Energy Supply and Demand

Chapter 3: Lao PDR Energy Supply and Demand

In this chapter, the modelled results are presented systematically by moving through the components of an energy balance table, from final consumption through resource production. This also mirrors the way that LEAP calculations are performed, first by specifying final energy demands (Section 3.1), conducting energy transformation analysis to meet each fuel's requirement (Section 3.2), and concluding with total primary energy requirements. Appropriate sectoral details are provided where appropriate, especially within the electricity sector where capacity, sub-annual dispatch and energy storage and release are modelled. The chapter concludes with projected GHG emissions and sinks from the energy sector, and from the Lao PDR economy as a whole (Section 3.3).

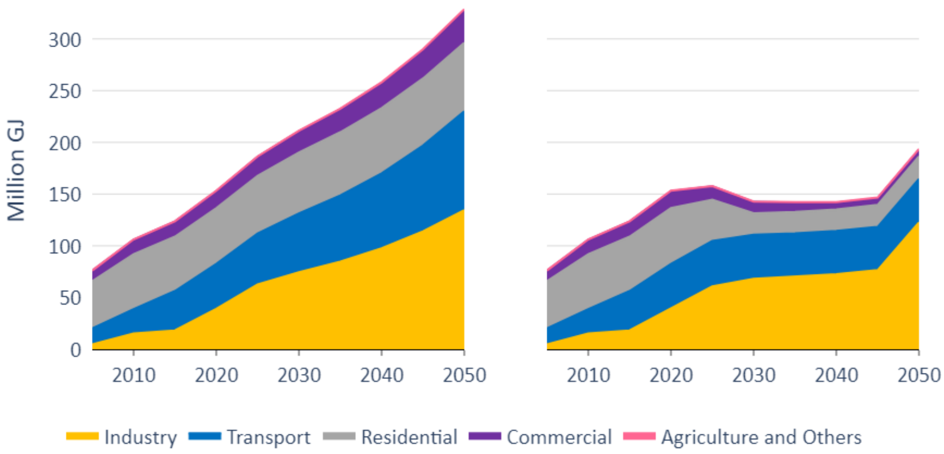
Results are calculated every five years, beginning in 2025 and extending through 2050.[9] Historical years extending back to 2005 are included in most calculated results where possible, or where the historical record helps to place forecasted scenario results in context.

The model used LEAP version 2020.1.0.114 and NEMO version 2.1.0 to do its calculations. The model version 6.08.3 used in this report is an evolution of the AEO8 model, a multi-region model that contains one region for each AMS. However, since only the Lao PDR region is calculated, the results calculated for this study may differ compared to the results for Lao PDR when all of the AMS are calculated for the AEO8 scenarios, which also simulate electricity transmission among the AMS.

3.1. Energy Demand

Final energy demand, or final energy consumption, represents the consumption of energy in its final form where it is transformed into useful work or heat. Results for the Baseline Scenario and Net-zero Scenario are presented adjacent to one another, below, first for overall consumption by fuel and second for consumption by sector. Additional sector-specific results follow.

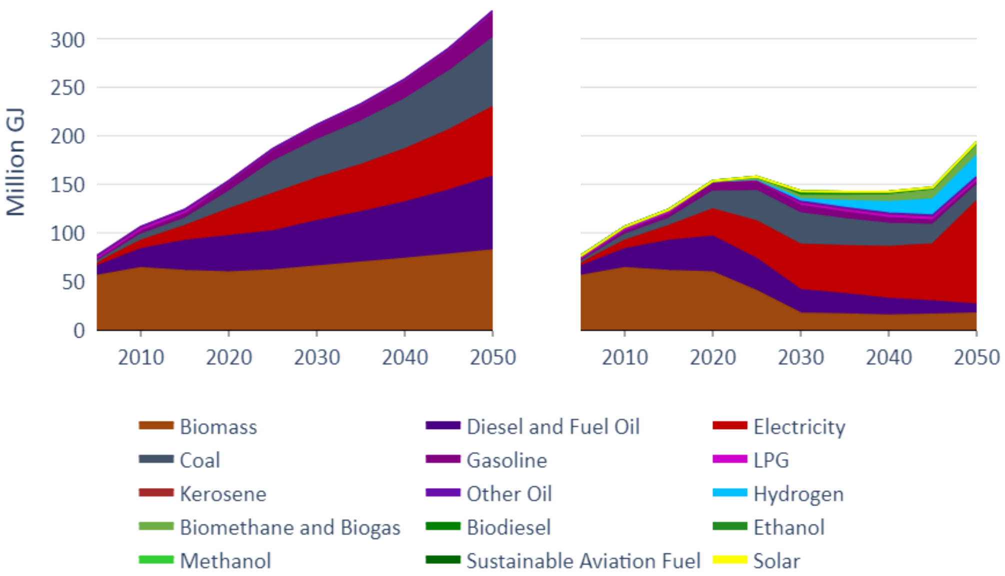
Figure 5 Final energy demand by sector, Baseline Scenario (Left) and Net-zero Scenario (Right)



Source: ACE and SEI. All rights reserved.

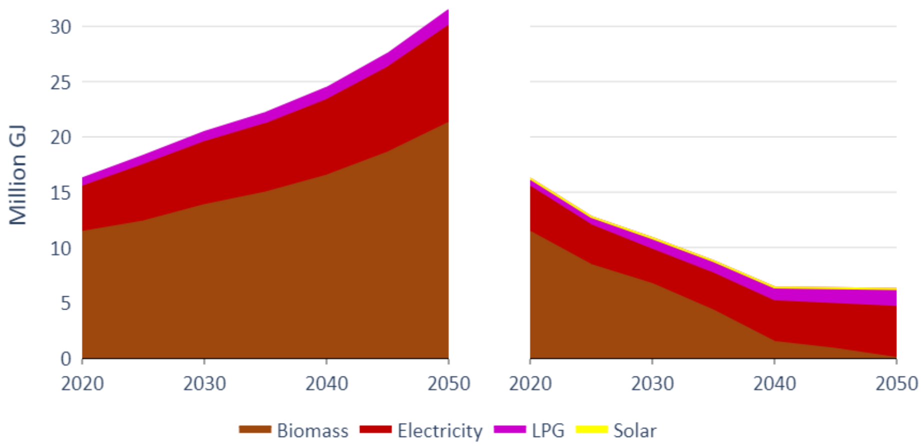
[9] In the AEO model, scenarios begin in the year 2023. However, year 2023 and 2024 are not calculated and are not shown in Chapter 3.

Figure 6 Final energy demand by fuel, Baseline Scenario (Left) and Net Zero Scenario (Right)



In each scenario, industry becomes the largest energy consumer by 2050, overtaking transportation, and overtaking all building (including both residential and commercial) energy use. Total energy demand in the Net-zero Scenario is lower than in the Baseline Scenario in all projected years, which is a broad result of the increases to efficiency or switching to more efficient fuels that occurs in the Net-zero Scenario. In both residential and commercial buildings, the reduction in energy use is primarily due to shifts away from traditional wood and charcoal. In the commercial sector (highlighted in Figure 7), wood

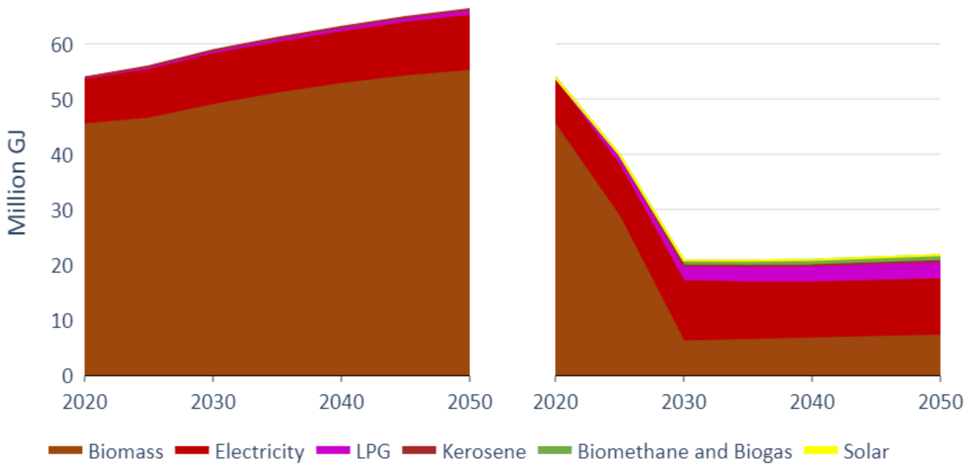
Figure 7 Final energy demand in the commercial sector, Baseline Scenario (Left) and Net Zero Scenario (Right)



consumption for food processing and preparation is eliminated by 2040, followed in 2050 by charcoal. In place of these traditional fuels a modest amount of electricity is added by electric appliances, but overall electricity consumption is offset by efficiency improvements primarily in lighting and space cooling.

In the residential sector, the shift away from wood fuel is especially dramatic. For example, following the SDG 7[10] Roadmap for Lao PDR, households in the Net-zero Scenario are expected to have universal access to clean cooking technologies by 2030 [35].[35]. Historically and continuing throughout the Baseline Scenario, traditional biomass has dominated residential energy use. Hence, its near removal on such a short time scale (shown in Figure 8) is one of the defining features of the Net-zero Scenario's energy consumption picture.

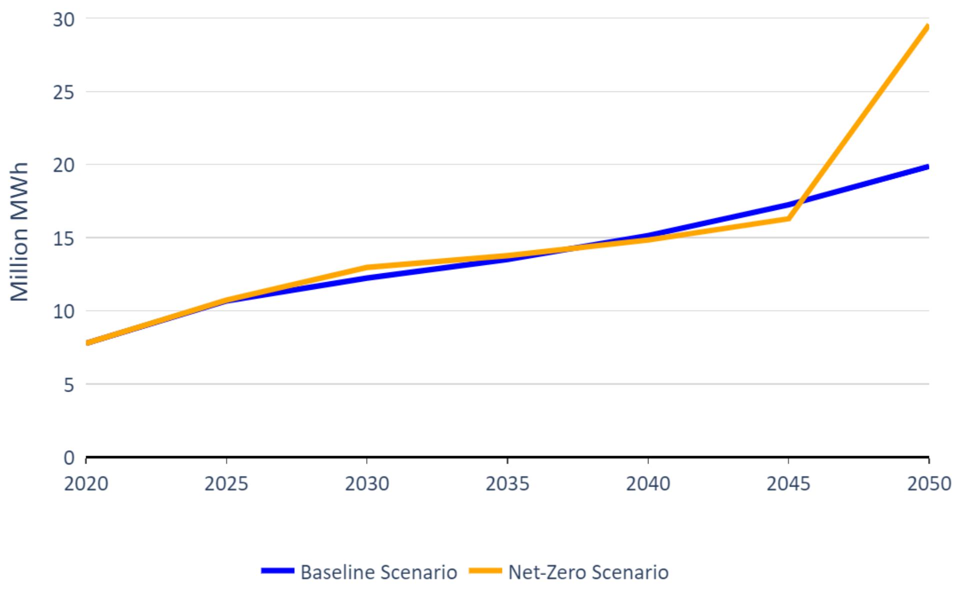
Figure 8 Final energy demand in the residential sector, Baseline Scenario (Left) and Net-zero Scenario (Right)



Electrification of key end-uses occurs across all sectors in the Net-zero Scenario, most significantly for on-road transportation due to the introduction of EVs. However, improvements in electrical efficiency for commercial lighting and cooling, and across the industrial sector (even despite modest electrification of process heat), nearly cancel this growth. As a result, annual electricity demand is nearly the same in both scenarios until the final few years of the scenario (shown in Figure 9), when electricity use for direct air capture (DAC) becomes pronounced. In these results, these are classified as industrial electricity use, and they are significant: alone, DAC makes up more than half of industrial electricity consumption in 2050 and is responsible for almost 40% of final electricity demands among all sectors.

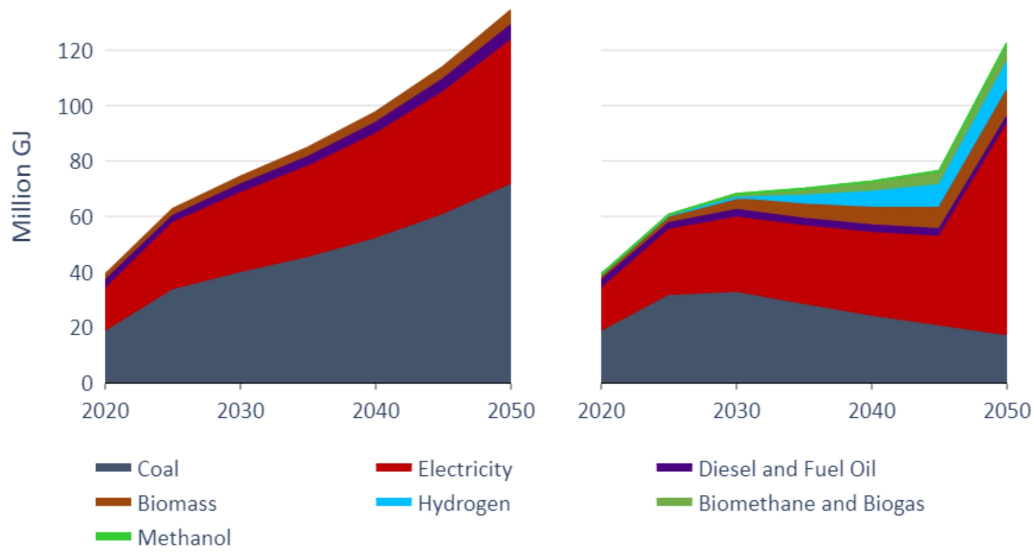
[10] SDG 7 (Sustainable Development Goal 7) is one of the 17 United Nations Sustainable Development Goals, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. It emphasizes increasing the share of renewable energy, improving energy efficiency, and expanding infrastructure and technology to support sustainable energy systems, particularly in developing regions.

Figure 9 Electricity consumption for projected years in both scenarios.



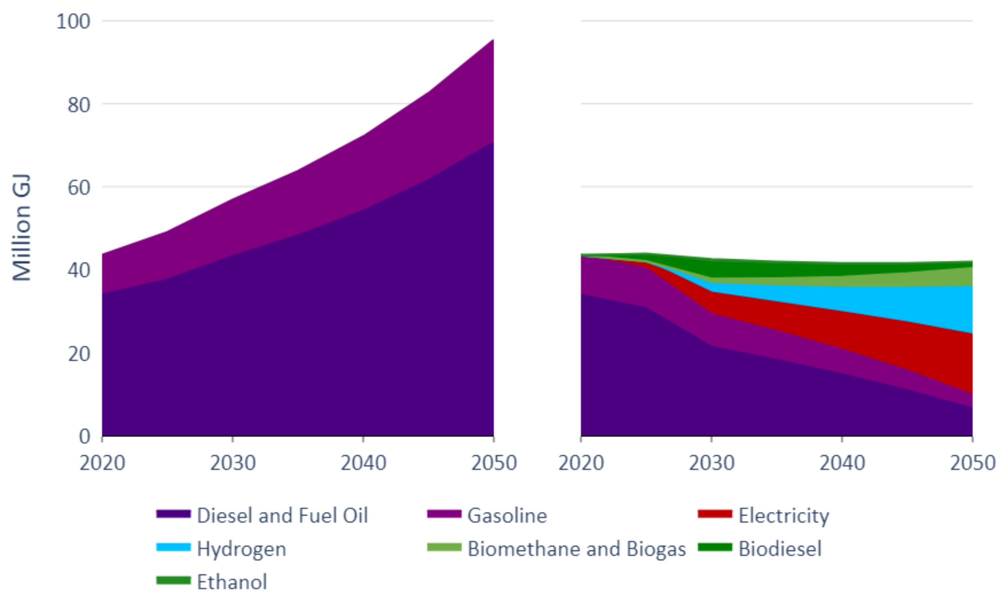
Looking deeper into the industrial sector, changes in the energy demand in the Net-zero Scenario can be characterised as a shift away from coal towards biofuels (biomethane and biomass) and hydrogen, as shown in Figure 10. Industrial efficiency – primarily from the ATS and RAS Scenarios and not specifically implemented as part of the Net-zero Scenario assumptions – reduces electricity consumption for industry until the final critical years of the scenario when DAC is needed to reach the net-zero GHG target. High-efficiency heat pumps used to provide low-temperature heat in the Net-zero Scenario add only modest amounts of electricity demand.

Figure 10 Final energy demand in the industrial sector, Baseline Scenario (Left) and Net Zero Scenario (Right)



Measured in energy consumption, on-road transport becomes the second-largest sector in Lao PDR over the forecasted time period, in both scenarios. Under the Baseline Scenario, growth in passenger demand (passenger-kilometres) and freight demand (tonne-kilometres) translates directly into growth in energy demand, since the mixture of technologies and their efficiencies remains unchanged from current levels. However, under the Net-zero Scenario, final demand for all fuels declines slightly compared to current levels, despite this continued growth in passenger-kilometres and tonne-kilometres. Figure 11 compares the resulting final energy consumption for road transport.

Figure 11 Final energy demand for on-road transport, Baseline Scenario (Left) and Net-zero Scenario (Right)



Source: ACE and SEI. All rights reserved.

Increases to energy demand in the Net-zero scenario are suppressed by technology change in all modes, but most importantly in buses and motorcycles, which provide most of the passenger transport in Lao PDR. In motorcycles, gasoline consumption is reduced in favour of electric motorbikes, while diesel buses are displaced by a mix of electricity, biodiesel, biomethane and a small amount of hydrogen consumed in fuel cell vehicles. Private vehicles and taxicabs also migrate from gasoline and diesel vehicles towards electricity, with smaller amounts of ethanol, biodiesel and hydrogen.

3.2. Energy Supply

As described in Section 2.1.2, energy supply modelling is conducted using a series of modules representing the transformation of one or more fuels into other energy products. These modules represent different energy supply sectors and production processes taking place in Lao PDR, and collectively they show a picture of how fuels are produced or imported to satisfy domestic demands or export requirements. This section begins with a discussion of electricity supply results, concluding with a simplified energy balance table for key years of the Net-zero Scenario.

3.2.1. Electricity

Capacity expansion, electricity dispatch and storage are all simulated within the AEO model. Capacity results shown in the following figures include both existing and planned (exogenous) capacity, and other (endogenous) capacity that may be selected by the model following each scenario's capacity expansion rules. Annual energy production is shown only for electricity generation technologies, while dispatch results on a sub-annual basis include energy stored or released from energy storage technologies like batteries and pumped hydropower. Annual electricity requirements (from final demand as well as intermediate electricity requirements for other energy supply processes) and peak system load are displayed first in Figure 12, since these two results fundamentally drive capacity expansion and dispatch.

Figure 12 Annual electricity requirements (left) and annual peak load for each scenario.

Source: ACE and SEI. All rights reserved.

Annual electricity requirements follow a similar upward trajectory established in Figure 9, but the two scenarios are more differentiated with the Net-zero Scenario requiring higher levels of electricity generation. The reason is that Figure 12 includes intermediate consumption of electricity for energy supply processes that were inactive under the Baseline Scenario – notably, hydrogen production via electrolysis. Peak load also increases in 2050, by 22% and 35% relative to 2025 levels, in the Baseline and Net-zero Scenarios, respectively. An interesting feature of peak load in the Net-zero Scenario is that its rate of increase does not change substantially after 2045 as the annual electricity requirements do. Despite the large electricity demands brought by DAC in 2050, these requirements can be satisfied during off-peak periods, which reduces stress on the electrical grid.

Generation and storage capacity are shown in Figure 13 Capacity expansion occurs much more rapidly in the Net-zero Scenario, reaching nearly 30 GW by 2030, compared to just over 18 GW in the Baseline Scenario. While this rapid buildout is partially to meet the growing electricity needs of the Net-zero Scenario, the primary reason for the difference is the inclusion of national capacity targets for coal, hydro, solar, wind and pumped hydro in the ATS Scenario, which is an element of the Net-zero Scenario. These exogenous capacity additions account for nearly 9 GW of the capacity difference between the two scenarios in 2030. Since these capacity targets occur in the model regardless of the electricity requirements in the Net-zero Scenario, the results reveal that they are more than enough to satisfy the country's electricity requirements for decades to come. In fact, the model does not select any new endogenous capacity after 2030 until 2045, and even then, only a small amount (only 92.8 MW) of bioenergy with CCS is added, primarily for its carbon dioxide removal ability.

Figure 13 Electricity generation and storage capacity, Baseline Scenario (Left) and Net-zero Scenario (Right)

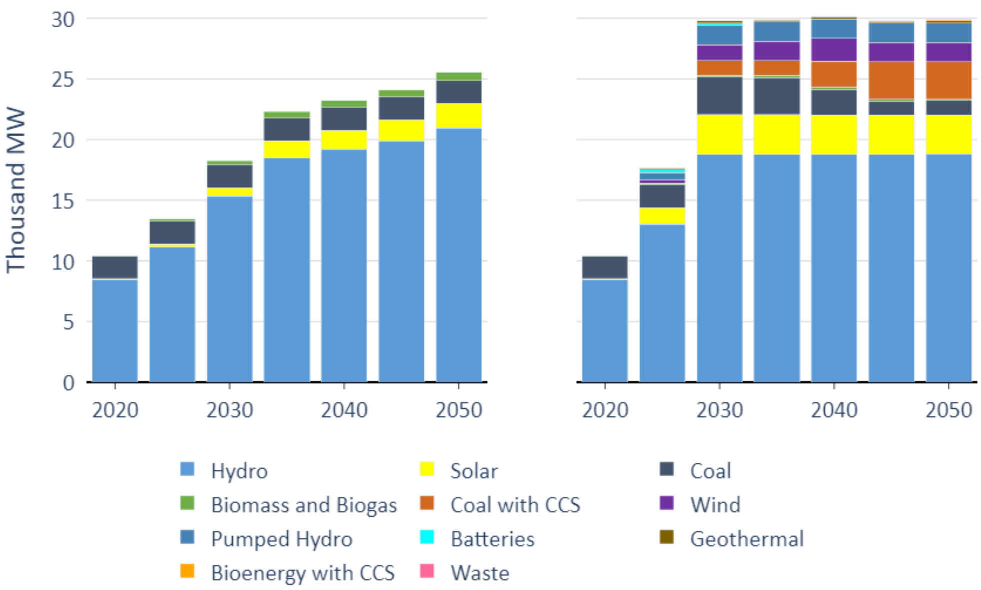
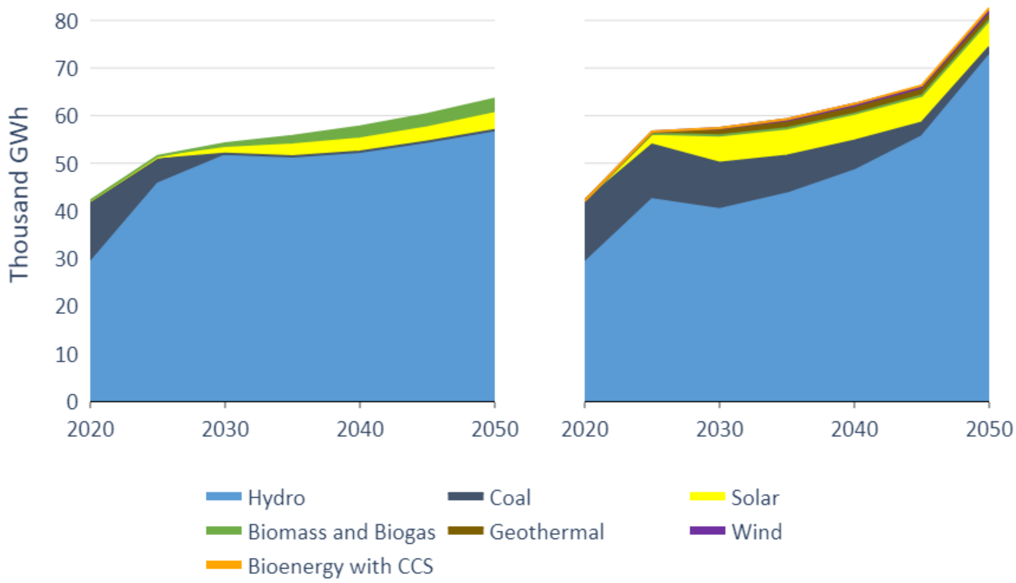


Figure 14 Electricity generation, Baseline Scenario (Left) and Net-zero Scenario (Right)

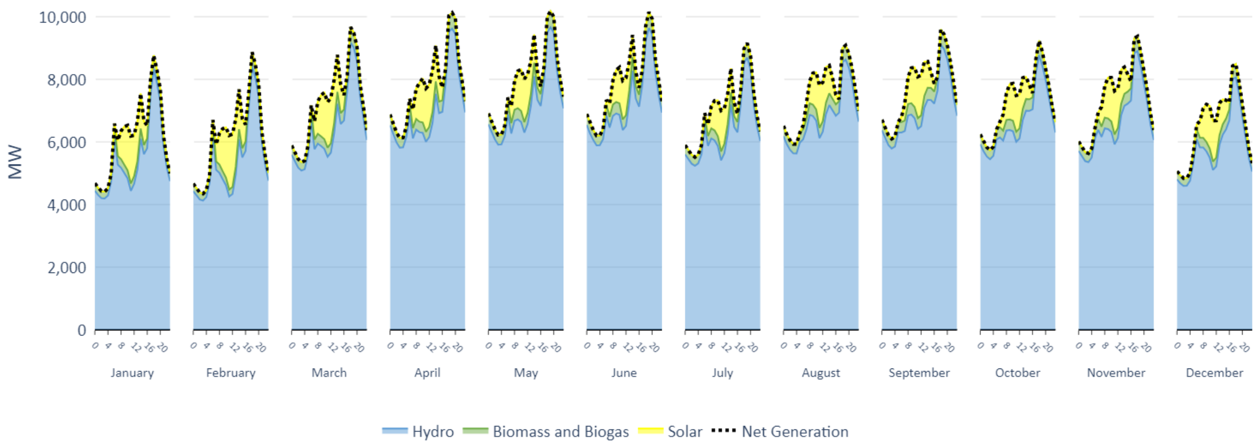


Source: ACE and SEI. All rights reserved.

From Figure 14 it can be seen that energy generation rises in step with electricity requirements (see Figure 12). Both scenarios remain dominated by electricity from hydro, with solar occupying the second-place spot in 2050. Together with solar, geothermal and wind resources in the Net-zero Scenario help displace biomass and biogas electricity in the Baseline Scenario, which are relatively high-cost and therefore outcompeted by other renewables using the Net-zero Scenario's least-cost methods. Coal-fired electricity, which is produced exclusively from subcritical coal plants operating inefficiently, but still very cost-effectively, declines more slowly in the Net-zero Scenario. Even though the Net-zero Scenario assumes that over 3 GW of CCS-equipped supercritical coal capacity will be added by 2050, the model does not dispatch this capacity due to its high cost and availability of cheaper alternatives. This counterintuitive result sharpens the need for power purchase agreements (PPAs) to accompany any coal-fired capacity equipped with CCS, or other market conditions that allow them to produce relatively high-cost electricity. But this result also clarifies the limited role for CCS-equipped fossil fuels in a net-zero future. Even if these plants captured 100% of their CO_2 emissions at the point of combustion – an ideal capture rate that has not been demonstrated – upstream emissions (for example, methane emissions from coal beds) mean that the technology still emits GHGs.

Looking deeper into the electricity results for the year 2050, contributions from each resource in each representative hour of each month (the model's *time slices*) can be shown. The results for the Baseline Scenario (Figure 15) reveal relatively little about the intra-year generation trends, with wind and solar producing electricity only when available, and dispatchable resources like hydropower and biomass filling the remainder of the country's

Figure 15 Power generated by each resource within each representative hour of each month in the year 2050, under the Baseline Scenario.



needs[11].

Note: Axis labels below the chart refer to the hour of a day (following 24-hour format) within each month.
Source: ACE and SEI. All rights reserved.

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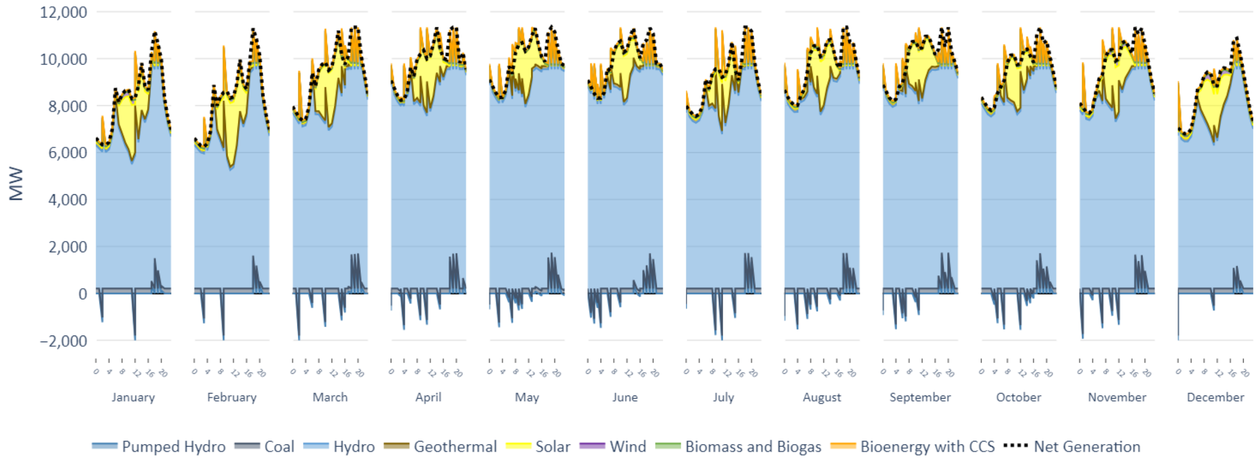
[11] The Baseline Scenario, which is derived from the Baseline Scenario of the AEO8, does not use least-cost optimisation for performing capacity expansion and dispatch calculations. Instead, it relies on a rule-based method for simulating electricity dispatch, under which wind and solar produce energy at their full capacity when the resource is available, and all other resources are assigned a fixed dispatch order to fulfil the remainder of the electricity needs in each time slice.

Figure 16 Power Generation by each resource within each representative hour of each month in the year 2050, under the Net Zero Scenario.



Note: Axis labels below the chart refer to the hour of a day (following 24-hour format) within each month.
Source: ACE and SEI. All rights reserved.

Figure 16 describes a more nuanced story, with electricity stored and released from pumped hydropower resources. In each month, electricity from hydropower is typically stored during the very early hours of the morning. Later in the morning as solar begins to produce electricity, even more energy is stored, generally only before mid-day. This energy is then released during the evening hours typically between 17:00 and 20:00, as solar electricity generation wanes. Though energy may be stored seasonally, absorbed in one month and released during another, there is no strong evidence that this is occurring in the model. While energy storage from pumped hydro helps to smooth periods of supply and demand mismatch, dispatchable hydropower still provides the majority of the grid's flexibility through 2050 in the Net-zero Scenario.

3.2.2. Other Energy Supply

Projected energy balance tables from the Net-zero Scenario for 2030 and 2050 are shown in Tables 6 and 7, respectively. An energy balance is an established way to represent all flows or all fuels (or "energy carriers") in an economy, in which the extraction or import of each fuel can be traced through the energy system: from extraction, through fuel transformation processes, to final demand or export. These tables are a convenient way to capture the overall production and consumption of all fuels in an economy.

Table 6 Projected energy balance table for the year 2030, under the Net Zero Scenario.[12]

Units: Million GJ	Electricity	Natural Gas	Petroleum	Coal	Biomass	Biofuels	Synthetic Fuel	Wind	Solar	Hydro	Geothermal	Hydrogen	Total
Production	-	-	-	166.87	33.76	-	-	2.12	20.73	145.07	25.39	-	393.94
Imports	3.14	0.10	36.26	0.05	4.39	0.00	-	-	-	-	-	-	43.95
Exports	-147.08	-	-	-18.21	-	-	-	-	-	-	-	-	-165.29
Total Primary Supply	-143.94	0.10	36.26	148.72	38.15	0.00	-	2.12	20.73	145.07	25.39	-	272.60
Fossil Fuel Production and Processing	-	1.00	-	0.00	-	-	-	-	-	-	-	-	1.00
Charcoal Production	-	-	-	-	-6.96	-	-	-	-	-	-	-	-6.96
Electricity Generation	206.61	-	-	-115.32	-0.31	-	-	-2.12	-20.72	-145.07	-25.39	-	-102.32
Alternative Fuel Production	-4.46	-0.10	-	-1.09	-14.12	8.32	0.03	-	-	-	-	2.48	-8.93
Losses and Own Use	-10.67	-	-	-	-	-	-	-	-	-	-	-	-10.67
Total Transformation	191.48	-0.10	-	-116.41	-21.39	8.32	0.03	-2.12	-20.72	-145.07	-25.39	2.48	-128.89
Industry	27.21	-	2.72	32.31	4.02	1.39	0.03	-	-	-	-	0.40	68.08
Transport	5.15	-	29.42	-	-	6.03	-	-	-	-	-	2.08	42.68
Residential	10.96	-	2.88	-	6.06	0.90	-	-	0.01	-	-	-	20.81
Commercial	3.10	-	1.06	-	6.68	-	-	-	0.00	-	-	-	10.84
Agriculture and Others	0.30	-	0.19	-	-	-	-	-	-	-	-	-	0.49
Total Demand	46.71	-	36.26	32.31	16.76	8.32	0.03	-	0.01	-	-	2.48	142.89

[12] For legibility, energy products (columns) and flows (rows) shown in the table are aggregated from the more detailed information available in the model. “Biofuels” includes biodiesel, biomethane, biogas, ethanol and sustainable aviation fuel, while “synthetic fuels” includes methanol and ammonia. “Biomass” includes all solid biomass and municipal solid waste. Values may not sum due to rounding.

Table 7 Projected energy balance table for the year 2050, under the Net Zero Scenario.[13]

Units: Million GJ	Electricity	Natural Gas	Petroleum	Coal	Biomass	Biofuels	Synthetic Fuel	Wind	Solar	Hydro	Geothermal	Hydrogen	Total
Production	-	-	-	63.97	33.13	-	-	2.61	20.20	261.48	29.10	-	410.49
Imports	3.14	0.03	17.94	0.34	20.94	0.00	-	-	-	-	-	-	42.38
Exports	-144.26	-	-	-18.21	-	0.00	-	-	-	-	-	-	-162.46
Total Primary Supply	-141.11	0.03	17.94	46.10	54.07	0.00	-	2.61	20.20	261.48	29.10	-	290.41
Fossil Fuel Production and Processing	-	-	0.00	0.00	-	-	-	-	-	-	-	-	0.00
Charcoal Production	-	-	-	-	-4.66	-	-	-	-	-	-	-	-4.66
Electricity Generation	297.34	-	-	-21.05	-7.44	-	-	-2.61	-20.15	-261.48	-29.10	-	-44.49
Alternative Fuel Production	-33.54	-0.03	-	-8.47	-25.32	13.94	0.20	-	-	-	-	21.80	-31.43
Losses and Own Use	-14.88	-	-	-	-	-	-	-	-	-	-	-	-14.88
Total Transformation	248.92	-0.03	0.00	-29.53	-37.42	13.94	0.20	-2.61	-20.15	-261.48	-29.10	21.80	-95.46
Industry	76.48	-	2.87	16.58	9.53	6.68	0.20	-	-	-	-	10.26	122.59
Transport	14.60	-	9.74	-	-	6.20	-	-	-	-	-	11.54	42.08
Residential	10.20	-	3.35	-	7.11	1.06	-	-	0.05	-	-	-	21.77
Commercial	4.62	-	1.63	-	-	-	-	-	0.00	-	-	-	6.25
Agriculture and Others	0.53	-	0.35	-	-	-	-	-	-	-	-	-	0.88
Total Demand	106.43	-	17.94	16.58	16.64	13.94	0.20	-	0.05	-	-	21.80	193.57

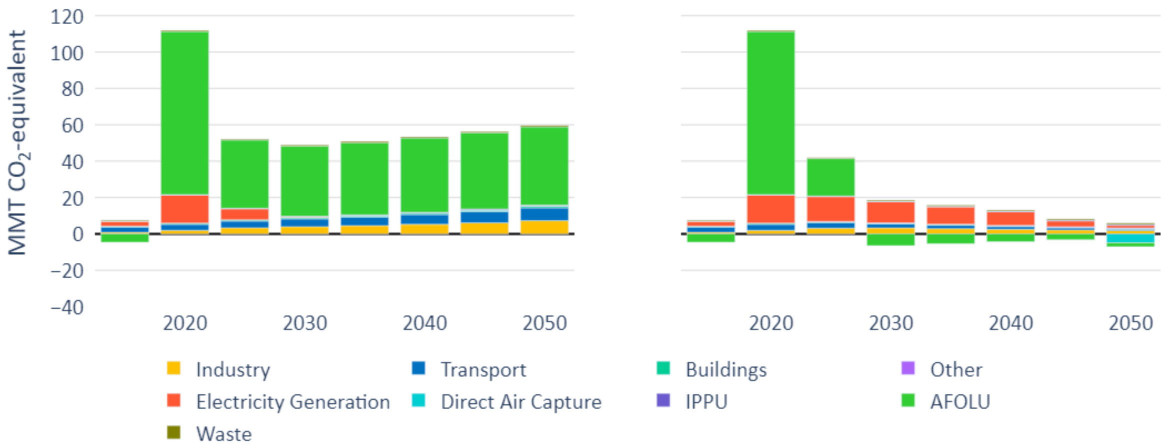
[13] For legibility, energy products (columns) and flows (rows) shown in the table are aggregated from the more detailed information available in the model. “Biofuels” includes biodiesel, biomethane, biogas, ethanol and sustainable aviation fuel, while “synthetic fuels” includes methanol and ammonia. “Biomass” includes all solid biomass and municipal solid waste. Although electricity requirements from direct air capture appear are classified as industrial, electricity provided for direct air capture is not subject to losses as it is for other final demands. Values may not sum due to rounding.

With its significant hydropower potential, Lao PDR is a major source of electricity exports for neighbouring countries, and this is reflected in the energy balance. Coal production continues even in 2050, meeting export demand as well as domestic requirements from power and industry. As demand for biofuels grow, imports of biomass, once relatively small in 2030, grow to become nearly 40% of primary biomass supply in 2050. Petroleum product imports are reduced by half from 2030 to 2050 in the Net-zero Scenario, the majority of which are consumed by the transportation sector. Note that total primary supply for most renewables assumes that the energy content of these resources is equal to the electricity that can be produced. This is equivalent to assuming that wind, solar and hydro can operate with perfect efficiency. However, electricity production from biomass and geothermal resources is assigned a lower efficiency, which magnifies their total primary requirements relative to other renewables.

3.3. Greenhouse Gas Emissions

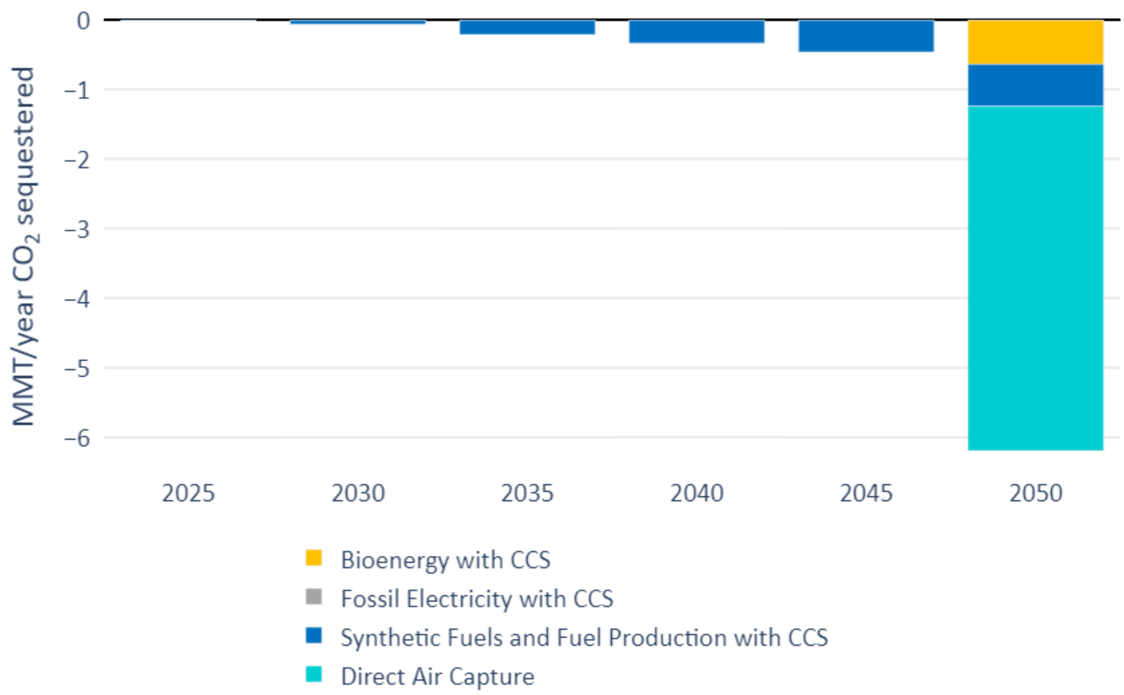
Completing the results from this modelling study are the GHG emissions associated with each scenario. Total GHG emissions are presented in Figure 17 for all sectors.

Figure 17 Greenhouse gas emissions from all sources in Baseline Scenario (Left) and Net-zero Scenario (Right), using 100-year GWP



Emissions in the Baseline Scenario are dominated by AFOLU and IPPU, most of which arise from cement production, both of which are classified as non-energy sources. This illustrates the challenge in meeting net-zero targets using only mitigation measures affecting energy-related sectors, and the necessity of taking action across all sectors of the Lao PDR economy. In the Net-zero Scenario, Lao PDR's conditional NDC targets (including, most significantly, targets for the forestry sector) are assumed to be achieved by 2030 and persist thereafter. This is the single largest source of emission reductions between the Baseline and Net-zero Scenarios, as well as the source of the steep decline in emissions between 2020 and 2030. Assumptions made about the forestry carbon sink (detailed in Section 2.2.3.a) mean that forestry can be counted on to provide some negative emissions, providing a "cushion" that allows the remaining sectors to retain some positive emissions while still reaching net-zero. However, the size of this forestry sink is not enough; even in the Net-zero Scenario, residual GHG emissions are found in many sectors, most prominently IPPU, waste, coal consumed for industry and power (and associated methane released from its production), and remaining transport diesel and gasoline. These emissions must then be offset by carbon dioxide removal, which in the model is offered primarily through DAC.

Figure 18 Total sequestered carbon dioxide by technology in the energy sector, for the Net-zero Scenario.



Source: ACE and SEI. All rights reserved.

Figure 18 shows the total amount of CO_2 sequestered in the Net-zero Scenario, whether from energy-sector carbon dioxide removal or CCS (not shown: CDR from forestry assumed in the NDC). Regardless of its origin, the implications are that by 2050, Lao PDR must be able to securely store over 6 million tonnes of CO_2 per year, unless additional actions are taken to reduce GHG emissions from the remaining sectors.

Patuxay in Vientiane, Lao PDR

Chapter 4

Cross-cutting issues achieving Lao Net Zero by 2050

Chapter 4: Cross-cutting issues achieving Lao Net-zero by 2050

The road towards Lao PDR's net-zero ambitions by 2050 is a multifaceted challenge that requires dealing with a wide range of cross-cutting issues, including energy infrastructure, economic sustainability and regional cooperation. In terms of energy infrastructure, the country's heavy reliance on hydropower has also caused some complexities: balancing hydropower's dominance with the diversification of RE sources, mitigating environmental and social impacts, and navigating the complexities of public-private partnerships which can impact the roadmap towards Lao PDR's net-zero targets. Economic constraints, including rising debt, inflation and labour shortages, further complicate the transition. Additionally, regional electricity trade offers revenue opportunities but increases financial dependencies. To ensure long-term sustainability of its net-zero roadmap, Laos must address these challenges while encouraging innovation and increasing regional energy integration. This chapter investigates these interconnected issues, providing insights into the critical paths to achieving a net-zero future.

4.1. Laos PDR's Economic Challenges

The Lao economy still faces considerable challenges, including elevated public debt in 2024, currency depreciation and inflationary pressures, even as robust growth persists across developing Asia and the Pacific [36]. Despite some progress in recovery, the country has struggled to regain its pre-pandemic growth trajectory. Laos's external debt has risen significantly in recent years, driven primarily by large-scale in vestments in infrastructure projects, particularly hydropower. While public and publicly guaranteed debt saw a modest decline from USD13.9 billion in 2022 to USD13.8 billion in 2023, the burden of servicing this debt has surged, creating mounting fiscal pressures [36]. The ratio of external debt service to government revenue increased sharply from 27% to 43%, underscoring the growing strain on public finances. In response, the government sought debt deferrals totalling USD1.9 billion between 2020 and 2023 to alleviate liquidity constraints [36], [37]. However, these measures provided only temporary relief, as the country continues to grapple with a fragile economic foundation.

The debt struggles have contributed to the depreciation of the Lao kip. The currency experienced a sharp devaluation in 2024, largely driven by the country's substantial external debt obligations, including payments by EDL Generation Public Company. The currency lost 7.5% of its value against the US dollar, despite interventions by the Bank of Lao PDR, such as raising interest rates and tightening foreign exchange regulations [36]. This depreciation compounded existing economic vulnerabilities, especially as inflation soared to an average of 25.3% in 2024, further straining households and businesses [36].

The inflationary pressures have been exacerbated by labour shortages stemming from out-migration, which have driven up domestic wages and production costs. Businesses, in turn, have passed these costs onto consumers, fuelling inflationary expectations and contributing to price instability. Compounding this issue, structural challenges such as low labour force participation, a lack of skilled workers and an unfavourable business environment have hindered economic growth, as highlighted by the World Bank [38].

Lao PDR's over-reliance on FDI, also poses risks to Laos's financial stability, despite its economic opportunities. A growing influence from China, primarily through trade, investment and infrastructure development, has deepened the country's dependence. Chinese FDI in Laos has surged significantly since 2014 and reached an all-time high of approximately USD 2.76 billion in 2016 [39]. This influx of capital has bolstered infrastructure development, including roads, railways and hydropower projects, and played a vital role in poverty reduction efforts [40]. However, while these investments offer economic opportunities, they also pose financial risks, particularly due to the concentration of capital in specific sectors such as mining and energy. This sectoral imbalance may create vulnerabilities in economic sustainability, making diversification essential to reduce exposure to external shocks [41].

China is also Lao PDR's largest trading partner, dominating both exports and imports. In 2022, Laos exported USD2.73 billion in raw materials like copper, tin and timber to China, while importing USD 2.1 billion in machinery, electronics and consumer goods [42]. The reliance on resource-based exports ties the economy to the volatile global commodity prices, which can lead to significant fluctuations in revenue [43]. Additionally, the high import costs for machinery and consumer goods further strain the country's financial stability [44]. As this trade imbalance contributes to Laos's economic vulnerability, it is imperative for Lao PDR to reduce its economic dependence on one particular country.

As achieving net-zero targets requires more finance, ensuring economic sustainability through managing debt, inflation and currency exchange, stability is more crucial than ever [45]. Like many developing countries, Lao PDR must expand trade ties beyond the current partners while developing value-added industries through strengthening manufacturing and agricultural processing in order to gradually reduce the dependency on raw material exports [46].

4.2. Navigating the energy market complexities

Central to the energy ecosystem, the state-owned company EDL controls national electricity generation, transmission and distribution. With operations mostly focused on hydropower, EDL manages a mix of smaller local generating plants and larger scale power plants. This all-encompassing plan not only meets Laos PDR's internal energy needs but also strengthens its cross-border electricity trading programmes, thereby confirming its position as a regional RE centre.

The majority of hydropower projects in Lao PDR is developed through public-private partnerships, often under build-operate-transfer (BOT) concession agreements for a project with an installed capacity more than 5 MW and build-own-operate (BOO) for small-scale RE projects required by the government [47], [48]. Although public-private partnership is necessary for the implementation of net-zero targets, it is also important to carefully design its mechanism and framework to minimise its complexity which might hinder the implementation of net-zero goals.

These agreements, particularly for large-scale hydropower projects, often involve fixed tariffs and guaranteed PPAs. As most of the hydropower is exported, these agreements prioritise financial returns over sustainability and can hinder the diversification of the energy mix. They may actually discourage the development of other forms of RE such as solar, wind or biomass geared towards domestic energy consumption [47], [49]. While financial policies supporting other forms of RE energy remain limited, integrating similar mechanisms, such as PPAs or incentive-based tariffs, into the existing framework could enhance RE diversification and promote a more balanced energy mix in Laos.

On the distribution side, EDL acts as the single buyer of electricity for domestic distribution. It centralises the purchase of electricity from various producers and distributes it to consumers across the country. However, this monopolistic procurement structure limits competition and innovation, making it difficult to implement flexible, market-driven mechanisms that could promote RE consumption [50]. The situation is further complicated by the fact that the domestic grid remains underdeveloped, with infrastructure gaps particularly in rural areas, hindering full integration [51].

Large industrial and commercial consumers, including mining operations and export-oriented manufacturing facilities, often procure electricity directly under special tariffs or agreements due to their larger and more consistent demand [52], which may not align with ensuring long-term sustainability objectives. This is because the focus on providing cheap, reliable electricity to businesses may not always support efforts to reduce carbon emissions or encourage the use of cleaner, RE sources. Moreover, the MEM is currently facing financial difficulties which arose partly due to special electricity tariffs applied to large industrial and commercial consumers. In September 2024, MEM proposed consideration of a progressive pricing structure for the 2024-2028 period, in which rates increase with higher consumption levels to encourage higher energy efficiency [53].

4.3. Power Trade: Lifeline or Trap for Laos?

Cross-border electricity trading is a central element of Lao PDR's' strategy to gain economic benefits. As energy demand continues to rise in each of the ten ASEAN countries, all of their governments are looking for ways to secure reliable and affordable electricity supplies.

EDL manages the export of hydropower to neighbouring countries while also overseeing the import of electricity when necessary. It operates and maintains high-voltage transmission lines that are used for cross border electricity transmission [47]. According to the Laos Electricity Development Strategy, 2021-2030, the government via EDL has agreed to export up to 9 GW to Thailand, 5 GW to Vietnam, 3 GW to Cambodia, 500 MW to Myanmar and 300 MW to Malaysia towards 2025 [17].

Laos' reliance on hydropower is well-founded, as electricity exports to Thailand, Cambodia, Vietnam, Singapore and China have become a major driver of the nation's trade surplus [42]. In 2022, the country exported 35.11 billion kilowatt-hours of electricity [54], which were valued at approximately USD 2.4 billion, accounting for 28.5% of Lao PDR's total exports, and contributing to a trade surplus exceeding USD 1 billion [55].

Beyond the bilateral electricity trading, Lao PDR also plays a crucial role in the ASEAN Power Grid (APG). As a key framework that supports regional electricity trading, promoting the integration of electricity markets across ASEAN countries, the APG could serve Lao PDR's economic interest in electricity exports to beyond the existing cross-border interconnections. In 2022, the Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP), was launched as a pioneer initiative that underscores the importance of regional cooperation in achieving energy security and sustainability.

The project enabled Laos to export up to 100 MW of renewable hydropower to Singapore, using the existing transmission infrastructure in Thailand and Malaysia [56]. In 2024, the

LTMS-PIP entered its second phase, which aims to double the capacity of electricity traded to 200 MW and introduce multidirectional power trade, allowing additional supply from Malaysia to be included [57]. The Energy Market Authority (EMA) of Singapore has extended Keppel's electricity importer license to support this expansion, highlighting the project's scalability and the growing momentum for multilateral electricity trading in the region [58].

While electricity trading generates substantial profits for Lao PDR, relying solely on this revenue stream is unwise. The country should diversify its economic strategy, especially since much of its hydropower development is financed with debt [59], [60]. Despite the increased revenue from electricity exports, it is insufficient to significantly reduce Lao PDR's mounting debt burden, as debt servicing obligations continue to outpace export earnings. This creates a cyclical "chicken-and-egg" dilemma in which relying on export revenues to repay debt is undermined by the financial pressures imposed by the debt itself. Furthermore, a drop in export revenues or increased competition from neighbouring countries could jeopardise the country's ability to meet its debt obligations, exacerbating its economic problems.

4.4. Double-Edged Sword of Laos Hydropower

The construction of large-scale hydropower projects often involves significant environmental and social trade-offs, including impacts on biodiversity [61], local communities [62], [63], and water resources [64]. Climate change is also likely to affect hydropower generation, as erratic weather patterns, including prolonged droughts [65], [66], can reduce water availability [67] and, consequently, the amount of electricity produced [68]. The construction of dams disrupts aquatic ecosystems, affecting fish migrations, river hydrology and sediment transfers, which in turn negatively impact biodiversity and local communities that rely on these resources. The impacts of these changes can be felt up to 1,000 km away from the dams [69].

One of the key impacts is the interruption of fish migration and changes in species distribution. Hydropower dams create barriers that prevent the seasonal migrations of fish species, leading to a reduction in fish populations. In the Sesan, Sre Pok and Sekong, usually called the 3S river system, connectivity has been drastically reduced, resulting in a predicted loss of 40-50% of fish species in areas above the dams [69], [70]. The Don Sahong Dam, in particular, has raised concerns about its effect on migratory fish and local fisheries [71].

The transformation of riverine ecosystems into lacustrine ones due to the creation of dam reservoirs also alters habitats, pushing away species that depend on flowing water [70]. This habitat loss is particularly detrimental to species found in the seasonally flooded forests of the Mekong, which affects fisheries and local livelihoods [72]. Additionally, the reduction in fish populations and changes in river hydrology negatively impact agriculture and food security. In the Lower Mekong Basin, the construction of dams has led to significant losses in fisheries and agricultural productivity, thus affecting the GDP of countries like Cambodia and Vietnam [73].

Additionally, the combination of anthropogenic influences like upstream dam development and climate change is expected to further exacerbate these issues. Climate change is likely to alter water inflows and increase water losses due to higher evaporation rates and more extreme flooding events. These changes will have serious implications for hydropower generation as well as water availability for agricultural and domestic use, particularly in the Nam Ngum River Basin [74], [75].

From the lens of local communities, hydropower development offers both positive and negative effects. On the positive side, hydropower projects contribute to economic growth by creating jobs and improving infrastructure, such as roads and social programmes, which can benefit local populations [76]. These projects often lead to the development of schools, healthcare facilities and tourism infrastructure, which can enhance human and social capital [76].

However, the negative impacts of hydropower development are considerable. Environmental disruptions occur as river flows are altered, ecosystems are degraded and fish populations decline, all of which affect communities that depend on these river resources for their livelihoods [69], [77]. Social and structural injustices are also prevalent, particularly when resettlement is involved, as projects often fail to compensate affected communities adequately, exacerbating poverty and inequity [62], [63], [78]. Furthermore, large hydropower projects can increase the risk of vector-borne diseases due to ecological changes, though some initiatives have implemented health measures to mitigate these risks [79].

4.5. Enhancing Regional Cooperation

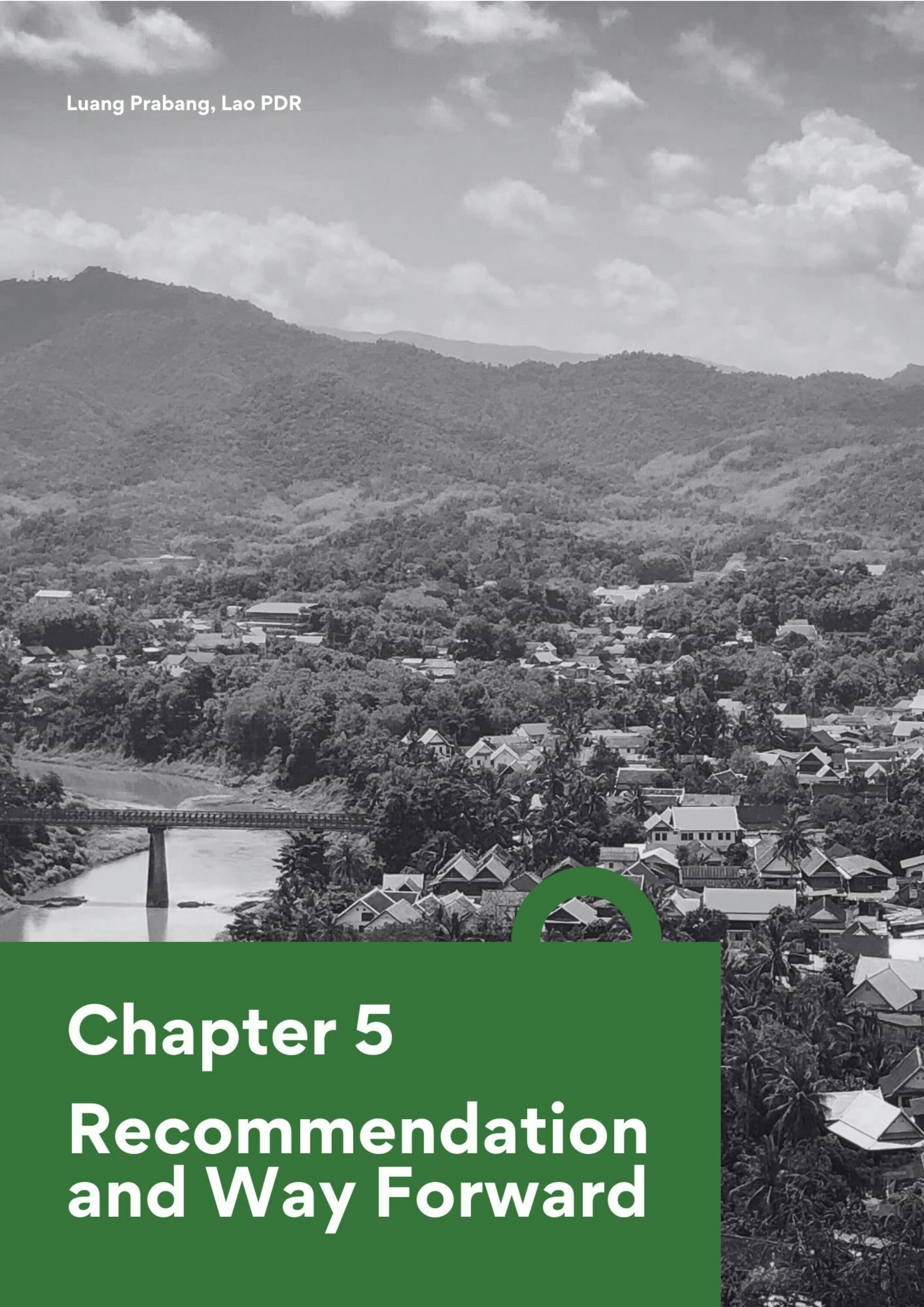
Achieving net-zero emissions is not solely a techno-economic challenge for Laos. It requires enhanced cooperation at the regional level, given the interconnectedness of energy systems, markets and policies across ASEAN. Laos, as a landlocked country with abundant hydropower resources, is strategically positioned to play a pivotal role in the regional energy landscape. However, realising this potential requires close collaboration among the AMS to address shared challenges, such as energy security, market integration and access to financing. Enhancing cooperation with ASEAN is vital for Laos to harness regional synergies, benefit from collective resources and align its national efforts with broader regional ambitions.

The current regional energy blueprint, ASEAN Plan of Action for Energy Cooperation (APAEC) Phase II: 2021-2025, has historically served as a cornerstone of regional energy collaboration [80]. Previous iterations of APAEC have facilitated progress in key areas that are closely related with individual country efforts, including RE deployment and cross-border energy trade. Hence it is important to understand that the upcoming iteration of the blueprint should embrace the past achievements.

For Lao PDR, the APAEC post-2025 is particularly critical. A future-focused APAEC can help Lao PDR leverage its RE potential, enhance regional energy security and access innovative financing mechanisms. Having alignment with the other AMS' national strategies and the broader regional framework, Lao PDR can ensure it remains an integral part of ASEAN's sustainable energy transition as well as the APG [81].

Moreover, the transition to net-zero requires substantial financial resources. The APAEC post-2025 can serve as a catalyst by facilitating access to various financial instruments, mechanisms and incentives. This includes expanding funding opportunities by collaborating with international financial institutions to create dedicated funds for RE and low-carbon infrastructure projects. It could offer incentive schemes by designing regional programmes to attract private sector investment in green technologies.

Through an enhanced APAEC post-2025, the region can unlock new opportunities for policy alignment, RE integration and financial support. For Lao PDR, this cooperative framework is essential not only for achieving its transition to net-zero, but also for contributing to the collective resilience and sustainability of ASEAN as a whole.



Luang Prabang, Lao PDR

Chapter 5

Recommendation and Way Forward

Chapter 5: Recommendation and Way Forward

5.1. Policy Recommendations

5.1.1. Demand-side intervention

In the residential sector, transitioning to clean cooking technologies must be prioritised, replacing traditional biomass with LPG, biogas and electric cooking solutions. Improving building energy efficiency through insulation, appliances standard and labelling, reflective coatings and smart cooling systems can significantly reduce electricity demand. Promoting sustainable building designs and encouraging behavioural incentives, such as gamified energy-saving initiatives, can further enhance efficiency.

The transition to cleaner technologies in commercial settings focuses on cooking, cooling, water heating, refrigeration and lighting. Commercial cooking will shift from biomass to LPG and electric induction technologies, with a gradual phase-out of wood and charcoal. Space cooling will adopt efficient heat pump systems, while water heating will rely on heat pump water heaters, some using secondary heat exchangers for better efficiency. Solar water heaters will also contribute to commercial hot water needs. Efficient refrigerators and LED lighting will be widely implemented, enhancing energy efficiency and sustainability across commercial sectors.

The transport sector must shift towards electrification, alternative fuels and greater efficiency. Expanding electric and hydrogen-powered vehicles, alongside biofuels and biomethane, will be essential for decarbonising road transport. Investment in charging and refuelling infrastructure will support adoption, while autonomous and connected transport systems can improve efficiency and reduce congestion. Aviation should integrate fuel-efficient technologies, electric taxiing systems and sustainable aviation fuels (SAF) to lower emissions.

For industry, decarbonisation requires a shift to low-carbon manufacturing and cleaner process heating. Electric heat pumps, hydrogen and biomass-based heating should replace fossil fuel boilers. High-emission materials like cement and steel must transition to lower-carbon alternatives, while carbon capture and storage (CCS) should be integrated to minimise industrial emissions.

Beyond direct energy consumption, industrial processes generate substantial emissions that require dedicated solutions. CCS should be deployed in key sectors such as cement, steel and chemicals, ensuring emissions are permanently stored or repurposed. DAC technologies offer long-term carbon removal, while expanding the production of hydrogen-based ammonia and methanol can reduce dependence on fossil-based industrial feedstocks. For a detailed roadmap on demand-side interventions, please refer to Annex C.

5.1.2. Supply-side intervention

Lao PDR must rapidly expand its clean energy infrastructure to decarbonise electricity generation. This requires scaling up renewables, investing in energy storage, phasing out fossil fuels and developing low-carbon fuels like hydrogen and biomethane.

Hydropower will remain central, but reliance on it alone poses risks due to seasonal variations and climate change impacts. Diversifying the energy mix with onshore wind, solar, geothermal and floating solar will strengthen energy resilience.

A robust energy storage system is essential for integrating variable renewables. Expanding lithium-ion batteries and, crucially, pumped hydro storage, will improve grid flexibility and reliability. Additionally, grid modernisation and digitalisation should be prioritised to optimise energy distribution.

To avoid greater reliance on direct air capture (DAC) technology, which is still in the early stages of deployment, existing fossil fuel generation should be retrofitted with CCS to minimise emissions, and no new fossil fuel power plants should be built without CCS. Bioenergy with CCS (BECCS) offers a promising solution for carbon-negative electricity generation, helping offset emissions from hard-to-abate sectors.

Low-carbon fuels will be crucial for sectors where direct electrification is not viable. Green hydrogen[14] production from electrolysis, powered by renewables, should be scaled up for transport, industry and power generation. Biomethane from anaerobic digestion can replace fossil gas in selected applications. Sustainable biofuels, including biodiesel and renewable diesel (HVO), should be expanded for use in aviation and heavy transport, while hydrogen-based methanol and ammonia can serve as low-carbon alternatives in the chemical and shipping industries. For a detailed roadmap on supply-side interventions, please refer to Appendix C.

5.1.3. Cross-cutting cutting issues

Transition to net-zero must balance energy security, economic sustainability and regional cooperation. While hydropower remains dominant, diversifying the energy mix, enhancing public-private partnerships and strengthening grid infrastructure will be critical for a resilient energy transition. Economic challenges such as rising debt, inflation and currency depreciation highlight the need for diversified trade, sustainable financing and industrial growth to reduce dependence on foreign investments and resource exports. In the energy sector, rigid PPAs and a monopolistic electricity market hinder renewable integration. Market reforms and policy incentives are needed to encourage competition and clean energy adoption.

Regional electricity trade has bolstered economic growth, but overreliance on hydropower exports creates financial vulnerabilities. Cross-border initiatives like the LTMS-PIP offer economic benefits, yet balancing domestic energy security and economic independence is crucial. Meanwhile, the expansion of hydropower brings environmental and social challenges, necessitating sustainable planning, climate resilience and community engagement. Stronger ASEAN cooperation will be essential for climate finance, RE integration and regional energy market expansion. Aligning with the APAEC post-2025 framework can support Lao PDRs' clean energy ambitions while ensuring broader economic and environmental sustainability.

5.2. Data and Model Improvement

Effective policymaking for Lao PDR's net-zero transition requires high-quality and robust modelling frameworks to ensure accurate energy forecasting, emissions tracking and policy impact assessments. Currently, Lao PDR's energy planning is hindered by the lack of detailed,

[14] Green hydrogen is produced through electrolysis using electricity from RE sources, resulting in zero direct emissions. It is a key vector for deep decarbonization, enabling emissions reduction in hard-to-abate sectors such as industry, transport, and energy storage while supporting the integration of variable RE.

sector-specific energy data, necessitating reliance on broad assumptions, which can introduce uncertainties in both planning and implementation. Gaps in the data lead to estimations that may not fully capture variations in energy use across sectors. Addressing these gaps is critical for improving energy demand forecasting, emissions accounting and sectoral policy design.

5.2.1. Improved granularity in energy data to reduce the reliance on assumptions for more accurate planning

Improving data granularity will be crucial for designing targeted, evidence-based interventions that align with sectoral realities. To improve data granularity, Lao PDR should expand energy surveys to gather detailed consumption data across key sectors like manufacturing and mining, standardise data collection frameworks with consistent reporting protocols, and utilise real-time energy monitoring technologies such as smart meters. Additionally, promoting data-sharing mechanisms between industries, business, government agencies and research institutions would help build a centralised energy database, improving transparency and policy alignment. With better energy data, policymakers can design more precise energy policy, refine emissions reduction strategies and reduce uncertainties linked to assumption-based modelling.

5.2.2. Developed the whole bottom-up approach in the sub sectoral-level energy consumption to accommodate specific intervention for various energy efficiency measures

Current modelling approaches in Lao PDR combine top-down and bottom-up methods, with the top-down approach aggregating energy consumption at the national level. This limits the ability to assess the effectiveness of sector-specific interventions. Transitioning to a fully bottom-up modelling framework—where energy use is estimated at the subsectoral and process-specific levels—can provide more accurate projections and support targeted policy development. This approach allows for detailed intervention design, as policymakers can tailor energy efficiency programmes to the specific needs of each industry. It also enhances the assessment of efficiency measures by offering a clearer understanding of how technologies like heat recovery systems, electrification and hydrogen adoption impact consumption and emissions. Additionally, it enables better alignment with international standards, allowing Lao PDR to harmonise its energy accounting methodologies and improve access to global climate finance.

To implement this approach effectively, Lao PDR should develop a comprehensive industrial energy dataset that tracks process-level energy use within key subsectors, engage industry stakeholders for insights on operational energy demand, and integrate advanced modelling tools such as machine learning-based energy forecasting and scenario analysis to enhance predictive accuracy.

References

Vang Vieng, Lao PDR

References

[1] Phaysone Phouthonesy, 'Lao PDR Country Report', in *Energy Outlook and Energy-Saving Potential in East Asia 2023*, Jakarta: ERIA, 2023, pp. 213–238. [Online]. Available: https://www.eria.org/uploads/media/Books/2023-Energy-Outlook/16_Ch.10-Lao-PDR.pdf

[2] World Bank, 'Population Estimates and Projections'. The World Bank, 2024. doi: 10.57966/GHB2-8V85.

[3] J. Menon and P. Warr, 'The L ao Economy: Capitalizing on Natural Resource Exports', *Asian Economic Policy Review*, vol. 8, no. 1, pp. 70–89, Jun. 2013, doi: 10.1111/aepr.12006.

[4] World Bank, 'Lao PDR Country Economic Memorandum Summary'. [Online]. Available: https://www.worldbank.org/en/country/lao/brief/lao-pdr-country-economic-memorandum-summary

[5] World Bank, 'Lao PDR Economic Monitor', World Bank Group, Apr. 2024. [Online]. Available: https://thedocs.worldbank.org/en/doc/5c2594a0cc6846465fe3bafda50ad993-0070062024/original/WB-LaoEconomicMonitorApril20-24web.pdf

[6] World Bank, 'Official exchange rate (LCU per US$, period average)'. WDI, 2025. [Online]. Available: https://data.worldbank.org/indicator/PA.NUS.FCRF

[7] F. Mieno and K. Demachi, 'Macroeconomic Imbalance, External Debt, and the Financial System in Laos', *Asian Economic Policy Review*, vol. 19, no. 2, pp. 295–318, Jul. 2024, doi: 10.1111/aepr.12469.

[8] Ministry of Planning and Investment of Lao PDR, '2030 Vision and 10-Year Socio-Economic Development Strategy (2016-2025)', Ministry of Planning and Investment of Lao PDR, Lao PDR, Jun. 2016. [Online]. Available: https://rtm.org.la/wp-content/uploads/2024/10/Vison-2030-and-10-Year-Socio-Economic.pdf

[9] World Bank and GFDRR, 'Climate Change Country Profile: Lao PDR', World Bank Group, Washington, D.C., 2018. [Online]. Available: https://climateknowledgeportal.worldbank.org/sites/default/files/2018-10/wb_gfdrr_climate_change_country_profile_for_LAO_0.pdf

[10] D. Boland, E. Allen, and F. Thomas, 'Strengthening Foundations to Unlock Green Finance in the Lao People's Democratic Republic', Asian Development Bank, Manila, Philippines, ADB Briefs, Dec. 2023. doi: 10.22617/BRF230574-2.

[11] OEC, 'Electricity exports and imports: Lao PDR'. [Online]. Available: https://oec.world/en/profile/bilateral-product/electricity/reporter/lao

[12] Asian Development Bank, 'Lao People's Democratic Republic Energy Sector Assessment, Strategy, and Road Map:', Asian Development Bank, Manila, Philippines, Dec. 2019. doi: 10.22617/TCS190567.

[13] UNESCAP, 'Energy Transition Pathways for the 2030 Agenda SDG 7 Roadmap for the Lao People's Democratic Republic', United Nations for Economic and Social Commission for Asia and Pacific, 2022. [Online]. Available: https://www.unescap.org/sites/default/d8files/knowledge-products/SDG7%20road%20map%20Lao%20PDR.pdf

[14] H. Sumad and E. Portale, 'Making a Difference in People's Lives: Rural Electification in the Lao People's Democratic Republic', World Bank Group, Washington, D.C., 2018. [Online]. Available: https://hdl.handle.net/10986/30390

[15] ERIA and MEM, ‘Lao PDR Energy Outlook 2020’, Economic Research Institute for ASEAN and East Asia, 2020. [Online]. Available: https://www.eria.org/uploads/media/Research-Project-Report/Lao-Energy-Outlook-2020/Lao-PDR-Energy-Outlook-2020.pdf

[16] Electricite Du Laos, ‘Electricite Du Laos - State Enterprise Moves Forward with New, Stable Steps’, Electricite Du Laos - State Enterprise Moves Forward with New, Stable Steps.

[17] Ministry of Energy and Mines Lao PDR, ‘Lao PDR’s Power Development Strategy (2021-2030)’, Ministry of Energy and Mines of Lao PDR, Vientiane, Dec. 2021. [Online]. Available: https://aseanenergy.sharepoint.com/:b:/s/ACCEPTPhase2/EaEkfXwQbclGgDAOOE6cDbcBlZ7jUIe4dLatB9nlL5QFRQ?e=7WcXpH

[18] Ministry of Energy and Mines Lao PDR, ‘Energy and Mining Statistics Report’, 2023.

[19] J. C. Teets, A. Byambasaikhan, Y. S. Kam, W. Liang, and L. Morrow, ‘The Battery of Southeast Asia: Challenges to Building a Regional Transmission Grid’. FPRI: Foreign Policy Research Institute., Apr. 09, 2024. [Online]. Available: https://coilink.org/20.500.12592/5qfv0qd

[20] Phongsavanh Phomkong, ‘Promoting Private Investments in Renewable Energy in Laos’, presented at the Regional Workshop and Policy Dialogue on Transitioning ASEAN Towards Low Carbon Economy, Vientiane, Lao PDR, Jul. 2024.

[21] Chitpanya Phamisith, ‘Lao’s Power and Electricity Update 2023’, presented at the Workshop on An Energy Sector Roadmap to Net-zero Emissions of Lao PDR, Vientiane, Lao PDR, Oct. 30, 2023.

[22] GoL, ‘Decree on Climate Change’. GoL, 2019. Accessed: Jan. 18, 2025. [Online]. Available: https://lpr.adb.org/sites/default/files/resource/%5Bnid%5D/lao-pdr-climate-change-decree-eo-321-21-oct-2019-eng.pdf

[23] World Bank, ‘Lao PDR Forest Note’, World Bank Group, 2020.

[24] UNFCCC, ‘Statement by the Lao People’s Democratic Republic at COP26’, 2021. [Online]. Available: https://unfccc.int/sites/default/files/resource/LAO_PEOPLEs_DEMOCRATIC_REPUBLIC_cop26cmp16cma3_HLS_EN.pdf

[25] World Bank, ‘Technical Recommendations for Lao PDR’s Long Term Low Emissions Development Strategy - Full Report (English)’, World Bank Group, Washington, D.C., 2024. [Online]. Available: http://documents.worldbank.org/curated/en/099061924060517291/P1775941f0b1690d4188dd1e9592c5b5d8c

[26] UNDP, ‘Lao PDR hosts major global funds in push for climate-resilient, sustainable future.’ [Online]. Available: https://www.undp.org/asia-pacific/press-releases/lao-pdr-hosts-major-global-funds-push-climate-resilient-sustainable-future

[27] Charlie Heaps, ‘LEAP: The Low emissions analysis platform’, Stockholm Environment Institute, Sommerville, MA, USA, 2022.

[28] ASEAN Centre for Energy, *Seventh ASEAN Energy Outlook LEAP Model (aeo7_v11.7_results85_updated.leap)*. (2022).

[29] ACE, ‘8th ASEAN Energy Outlook (AEO8)’, ASEAN Centre for Energy, Jakarta, 2024. [Online]. Available: https://aseanenergy.org/wp-content/uploads/2024/09/8th-ASEAN-Energy-Outlook.pdf

[30] S. Saatchi and Y. Yang, ‘Forest & Mangrove, Shrub & Grassland, and Wetland (Living Biomass) Emissions Emissions Methodology’. CTrees, Climate TRACE Emissions Inventory, 2023. [Online]. Available: climatetrace.org
[31] European Commission Joint Research Centre, ‘EDGAR (Emissions Database for Global Atmospheric Research) Community GHG database, comprising IEA-EDGAR CO2, EDGAR CH4, EDGAR N2O and EDGAR F-gases’. 2023.
[32] Ministry of Natural Resources and Environment, ‘The First Biennial Update Report’, Lao People’s Democratic Republic, Draft, Jul. 2020.
[33] Government of Lao PDR, ‘Nationally Determined Contribution (NDC)’, Mar. 2021.
[34] International Energy Agency, ‘ETP Clean Energy Technology Guide’, IEA, Paris, Sep. 2023. [Online]. Available: https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide
[35] United Nations Economic and Social Commission for Asia and the Pacific, ‘SDG 7 Roadmap for the Lao People’s Democratic Republic’, ST/ESCAP/3039, 2022. Accessed: Dec. 15, 2023. [Online]. Available: https://nexstepenergy.org/roadmap/Lao%20PDR
[36] Asian Development Bank, ‘Asian Development Outlook September 2024’, Asian Development Bank, Manila, Philippines, Sep. 2024. doi: 10.22617/FLS240452-3.
[37] K. Chanlivong, ‘Laos Seeks Debt Deferrals as External Payments Nearly Double to USD 950 Million’, *The Laotian Times*, Vientiane, Jul. 03, 2024. [Online]. Available: https://laotiantimes.com/2024/07/03/laos-seeks-debt-deferrals-as-external-payments-nearly-double-to-usd-950-million/
[38] World Bank, ‘Lao PDR Economic Growth : Accelerating Reforms for Growth - Thematic Section : Education for Growth and Development (English).’, World Bank Group, Washington, D.C., Report 189694, Apr. 2024. [Online]. Available: http://documents.worldbank.org/curated/en/099042724011042913/P1796281c1b7110881909c1e2a81cb81896
[39] CEIC, ‘Laos (FDI) Foreign Direct Investment: China’. [Online]. Available: https://www.ceicdata.com/en/laos/foreign-direct-investment-by-country/fdi-china
[40] P. Kyophilavong, M. C. S. Wong, S. Souksavath, and B. Xiong, ‘Impacts of trade liberalization with China and Chinese FDI on Laos: evidence from the CGE model’, *Journal of Chinese Economic and Business Studies*, vol. 15, no. 3, pp. 215–228, Jul. 2017, doi: 10.1080/14765284.2017.1346923.
[41] S. Candrawiranatakusuma and J. W. Bachtiar, ‘Lao People’s Democratic Republic’s Dependency on China’s Infrastructure Assistance’, *IJEAS*, vol. 9, no. 1, pp. 19–31, Dec. 2020, doi: 10.22452/IJEAS.vol9no1.2.
[42] The Observatory of Economic Complexity (OEC), ‘Laos-China Trade’, The Observatory of Economic Complexity (OEC). [Online]. Available: https://oec.world/en/profile/bilateral-country/lao/partner/chn
[43] Credendo, ‘Laos: Eroding liquidity and unsustainable debt service outlook could lead to debt relief agreement with China’. [Online]. Available: https://credendo.com/en/knowledge-hub/laos-eroding-liquidity-and-unsustainable-debt-service-outlook-could-lead-debt-relief
[44] Laos Post, ‘Economic Challenges in Laos: Inflation and Trade Deficit’, *Laos Post*, Vientiane, Jan. 02, 2025. [Online]. Available: https://laospost.com/economic-challenges-in-laos-inflation-and-trade-deficit

[45] J. Gu, ‘Building partnerships for sustainable development: case study of Laos, the BRI, and the SDGs’, *ARPE*, vol. 3, no. 1, p. 5, Apr. 2024, doi: 10.1007/s44216-024-00025-5.
[46] The Global Economy, ‘Laos: Industry value added’. [Online]. Available: https://www.theglobaleconomy.com/Laos/industry_value_added/
[47] Investment Promotion Department (IPD), ‘Investment Handbook for Lao PDR’. Ministry of Planning and Investment, 2022. [Online]. Available: https://investlaos.gov.la/wp-content/uploads/formidable/10/Investment_handbook_Eng.pdf
[48] Government of Lao PDR, ‘IPP Hydropower Procurement Manual for Lao PDR’. Government of Lao PDR, Jan. 2006. [Online]. Available: https://ppp.worldbank.org/public-private-partnership/sites/ppp.worldbank.org/files/2021-04/247_ipp_procurement_manual.pdf
[49] H. Phoumin and A. Phongsavath, ‘Energy Security White Paper: Policy Direction for Inclusive and Sustainable Development for Lao PDR’, Economic Research Institute for ASEAN and East Asia (ERIA, Jakarta, Sep. 2024. [Online]. Available: https://www.eria.org/research/energy-security-white-paper--policy-direction-for-inclusive-and-sustainable-development-for-lao-pdr
[50] J. D. Wilson, M. O’Boyle, and R. Lehr, ‘Monopsony behavior in the power generation market’, *The Electricity Journal*, vol. 33, no. 7, p. 106804, Aug. 2020, doi: 10.1016/j.tej.2020.106804.
[51] Japan International Cooperation Agency (JICA), ‘Data Collection Survey On Improvement Of Power System Operation In Laos’, Tokyo Electric Power Services Co. (TEPSCO), Final Report, Feb. 2024. [Online]. Available: https://openjicareport.jica.go.jp/pdf/12384376.pdf
[52] Laos Post, ‘Laos Explores New Electricity Pricing Model for 2024-2028 to Ensure Energy Sector Sustainability’, Vientiane, Dec. 27, 2024. [Online]. Available: https://laospost.com/laos-explores-new-electricity-pricing-model-for-2024-2028-to-ensure-energy-sector-sustainability
[53] K. Chanlivong, ‘Ministry of Energy and Mines Considers Electricity Price Adjustments for 2024-2028’, Vientiane, Sep. 02, 2024. [Online]. Available: https://laotiantimes.com/2024/09/02/ministry-of-energy-and-mines-considers-electricity-price-adjustments-for-2024-2028/
[54] The Global Economy, ‘Laos: Electricity Exports’, The Global Economy. [Online]. Available: https://www.theglobaleconomy.com/Laos/electricity_exports/
[55] C. Lapuekou, ‘Electricity Exports Propel Laos to Trade Surplus, Marking Record Growth’, *The Laotian Times*, Vientiane, Lao PDR, Mar. 06, 2024. [Online]. Available: https://laotiantimes.com/2024/03/06/electricity-exports-propel-laos-to-trade-surplus-marking-record-growth/
[56] Energy Market Authority (EMA), ‘Singapore commences first renewable energy electricity import via regional multilateral power trade’. Energy Market Authority (EMA), Jun. 23, 2022. [Online]. Available: https://www.ema.gov.sg/news-events/news/media-releases/2022/singapore-commences-first-renewable-energy-electricity-import-via-regional-multilateral-power-trade
[57] Energy Market Authority (EMA), ‘Singapore doubles power import capacity under LTMS-PIP Phase 2’. Energy Market Authority (EMA), Sep. 20, 2024. [Online]. Available: https://www.ema.gov.sg/news-events/news/media-releases/2024/singapore-doubles-power-import-capacity-under-ltms-pip-phase-2

[58] A. D. Wahyono, P. Wiratama, and B. Suryadi, ‘Growing Momentum of LTMS-PIP and Its Impact on Regional Integration’, ASEAN Centre for Energy. [Online]. Available: https://aseanenergy.org/post/growing-momentum-of-ltms-pip-and-its-impact-on-regional-integration/

[59] W. Jackson, ‘How Laos’ plans to fast-track development left it facing a debt and inflation crisis’, *ABC News*, Australia, Jul. 18, 2024. [Online]. Available: https://www.abc.net.au/news/2024-07-18/laos-debt-crisis-hydropower-infrastructure-loans/104080736

[60] N. C. Chin and L. L. Wan, ‘The cost of Laos’ quest to be Southeast Asia’s “battery”, and the World Heritage town at risk’, *Channel News Asia (CNA)*, Vientiane, Oct. 31, 2022. [Online]. Available: https://www.channelnewsasia.com/cna-insider/cost-laos-hydropower-quest-southeast-asia-battery-electricity-dams-risk-3029086

[61] C. Zhong and L. Hao, ‘Dilemmas of hydropower development in Laos’, *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 12, no. 6, pp. 570–575, Jun. 2017, doi: 10.1080/15567249.2016.1244579.

[62] D. J. H. Blake and K. Barney, ‘Structural Injustice, Slow Violence? The Political Ecology of a “Best Practice” Hydropower Dam in Lao PDR’, *Journal of Contemporary Asia*, vol. 48, no. 5, pp. 808–834, Oct. 2018, doi: 10.1080/00472336.2018.1482560.

[63] D. J. H. Blake and K. Barney, ‘Impounded rivers, compounded injustice: contesting the social impacts of hydraulic development in Laos’, *International Journal of Water Resources Development*, pp. 1–22, Jun. 2021, doi: 10.1080/07900627.2021.1920373.

[64] A. Soukhaphon, I. G. Baird, and Z. S. Hogan, ‘The Impacts of Hydropower Dams in the Mekong River Basin: A Review’, *Water*, vol. 13, no. 3, p. 265, Jan. 2021, doi: 10.3390/w13030265.

[65] M. Thilakarathne and V. Sridhar, ‘Characterization of future drought conditions in the Lower Mekong River Basin’, *Weather and Climate Extremes*, vol. 17, pp. 47–58, Sep. 2017, doi: 10.1016/j.wace.2017.07.004.

[66] K. Chann *et al.*, ‘Prolonged and Severe Drought in the Most Dammed Tributaries of the Lower Mekong Basin’, *Sustainability*, vol. 14, no. 23, p. 16254, Dec. 2022, doi: 10.3390/su142316254.

[67] L. A. Cuartas *et al.*, ‘Recent Hydrological Droughts in Brazil and Their Impact on Hydropower Generation’, *Water*, vol. 14, no. 4, p. 601, Feb. 2022, doi: 10.3390/w14040601.

[68] P. Moghaddasi, K. Gavahi, H. Moftakhari, and H. Moradkhani, ‘Unraveling the hydropower vulnerability to drought in the United States’, *Environ. Res. Lett.*, vol. 19, no. 8, p. 084038, Aug. 2024, doi: 10.1088/1748-9326/ad6200.

[69] A. Soukhaphon, I. G. Baird, and Z. S. Hogan, ‘The Impacts of Hydropower Dams in the Mekong River Basin: A Review’, *Water*, vol. 13, no. 3, p. 265, Jan. 2021, doi: 10.3390/w13030265.

[70] P.-J. Meynell, M. J. Metzger, and N. Stuart, ‘Assessing the Impacts of Changing Connectivity of Hydropower Dams on the Distribution of Fish Species in the 3S Rivers, a Tributary of the Lower Mekong’, *Water*, vol. 16, no. 11, p. 1505, May 2024, doi: 10.3390/w16111505.

[71] I. G. Baird, ‘The Don Sahong Dam in Laos: Political Ecology, Infrastructure, and the Changing Spatialities of Impacts on Fish and People’, *pac aff*, vol. 97, no. 2, pp. 365–390, Jun. 2024, doi: 10.5509/2024972-art1.

[72] I. G. Baird and M. A. S. Thorne, ‘The downstream impacts of dams on the seasonally flooded riverine forests of the Mekong River in northeastern Cambodia’, *South East*

Asia Research, vol. 31, no. 4, pp. 377–399, Oct. 2023, doi: 10.1080/0967828X.2023.2243584.
[73] Y. Yoshida *et al.*, 'Impacts of Mainstream Hydropower Dams on Fisheries and Agriculture in Lower Mekong Basin', *Sustainability*, vol. 12, no. 6, p. 2408, Mar. 2020, doi: 10.3390/su12062408.
[74] D. Jayasekera and J. J. Kaluarachchi, 'Climate change impacts on water sustainability in the Nam Ngum River Basin of Laos', presented at the WATER RESOURCES MANAGEMENT 2015, A Coruña, Spain, Jun. 2015, pp. 279–287. doi: 10.2495/WRM150241.
[75] T. Meema, Y. Tachikawa, Y. Ichikawa, and K. Yorozu, 'Uncertainty assessment of water resources and long-term hydropower generation using a large ensemble of future climate projections for the Nam Ngum River in the Mekong Basin', *Journal of Hydrology: Regional Studies*, vol. 36, p. 100856, Aug. 2021, doi: 10.1016/j.ejrh.2021.100856.
[76] A. Sivongxay, R. Greiner, and S. T. Garnett, 'Livelihood impacts of hydropower projects on downstream communities in central Laos and mitigation measures', *Water Resources and Rural Development*, vol. 9, pp. 46–55, Jun. 2017, doi: 10.1016/j.wrr.2017.03.001.
[77] K. Nhiakao, H. Yabar, and T. Mizunoya, 'Cost-Benefit Analysis of the Nam Che 1 Hydropower Plant, Thathom District, Laos: An Ex-Post Analysis', *Sustainability*, vol. 14, no. 6, p. 3178, Mar. 2022, doi: 10.3390/su14063178.
[78] K. Manorom, I. G. Baird, and B. Shoemaker, 'The World Bank, Hydropower-based Poverty Alleviation and Indigenous Peoples: On-the-Ground Realities in the Xe Bang Fai River Basin of Laos', *Forum for Development Studies*, vol. 44, no. 2, pp. 275–300, May 2017, doi: 10.1080/08039410.2016.1273850.
[79] G. Guerrier *et al.*, 'Strategic Success for Hydropower in Laos', *Science*, vol. 334, no. 6052, pp. 38–38, Oct. 2011, doi: 10.1126/science.334.6052.38-a.
[80] ASEAN Centre for Energy, 'ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025 Phase II'. ASEAN Centre for Energy, Nov. 2020. [Online]. Available: https://aseanenergy.org/asean-plan-of-action-for-energy-cooperation-apaec-phase-ii-2021-2025/
[81] IEA, 'Establishing Multilateral Power Trade in ASEAN', International Energy Agency, Paris, Aug. 2019. [Online]. Available: https://doi.org/10.1787/0c4a10e5-en
[82] ASEAN Centre for Energy, *Eighth ASEAN Energy Outlook LEAP Model (aeo8_model_bas_nz_6.08.03.leap)*. (Jan. 23, 2025).
[83] V. Gupta and C. Deb, 'Envelope design for low-energy buildings in the tropics: A review', *Renewable and Sustainable Energy Reviews*, vol. 186, p. 113650, Oct. 2023, doi: 10.1016/j.rser.2023.113650.
[84] M. Rawat and R. N. Singh, 'A study on the comparative review of cool roof thermal performance in various regions', *Energy and Built Environment*, vol. 3, no. 3, pp. 327–347, Jul. 2022, doi: 10.1016/j.enbenv.2021.03.001.
[85] Cool Coalition, 'A Cool Calculator to Support Net-zero Planning'. [Online]. Available: https://coolcoalition.org/the-cool-toolbox/cool-calculator/
[86] ENERGY STAR, 'Energy Efficiency Program Sponsor Frequently Asked Questions About ENERGY STAR Smart Thermostats | ENERGY STAR'. Accessed: Dec. 14, 2023. [Online]. Available: https://www.energystar.gov/products/heating_cooling/smart_thermostats/smart_thermostat_faq

[87] Parks Associates, ‘Parks Associates: 16% of US Internet Households Have a Smart Thermostat’. Accessed: May 17, 2024. [Online]. Available: https://www.prnewswire.com/news-releases/parks-associates-16-of-us-internet-households-have-a-smart-thermostat-301735558.html

[88] L. G. Valladares-Rendón, G. Schmid, and S.-L. Lo, ‘Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems’, *Energy and Buildings*, vol. 140, pp. 458–479, Apr. 2017, doi: 10.1016/j.enbuild.2016.12.073.

[89] J. W. Lee, H. J. Jung, J. Y. Park, J. B. Lee, and Y. Yoon, ‘Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements’, *Renewable Energy*, vol. 50, pp. 522–531, Feb. 2013, doi: 10.1016/j.renene.2012.07.029.

[90] L. G. Valladares-Rendón, G. Schmid, and S.-L. Lo, ‘Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems’, *Energy and Buildings*, vol. 140, pp. 458–479, Apr. 2017, doi: 10.1016/j.enbuild.2016.12.073.

[91] M. Yulianto *et al.*, ‘Performance assessment of an R32 commercial heat pump water heater in different climates’, *Sustainable Energy Technologies and Assessments*, vol. 49, p. 101679, Feb. 2022, doi: 10.1016/j.seta.2021.101679.

[92] ACCEPT II, ‘RE and EE Targets - ASEAN Climate Change and Energy Project’, ASEAN Climate Change and Energy Project (ACCEPT). Accessed: May 17, 2024. [Online]. Available: https://accept.aseanenergy.org/re-ee-targets/

[93] M. Wolfson, S. Mazur-Stommen, K. Farley, and S. Nadel, ‘Gamified Energy Efficiency Programs’, American Council for an Energy-Efficient Economy (ACEEE), Washington, D.C., Research Report, Feb. 2015. [Online]. Available: https://www.aceee.org/research-report/b1501

[94] Aviation Benefits Beyond Borders, ‘Efficient technology’. Accessed: Nov. 13, 2023. [Online]. Available: https://aviationbenefits.org/environmental-efficiency/climate-action/efficient-technology/

[95] International Energy Agency, ‘Aviation’, IEA. Accessed: Nov. 13, 2023. [Online]. Available: https://www.iea.org/energy-system/transport/aviation

[96] B. Graver, ‘Airline fuel efficiency: “If you can’t measure it, you can’t improve it.”’, International Council on Clean Transportation. Accessed: Nov. 14, 2023. [Online]. Available: https://theicct.org/aviation-fuel-efficiency-jan22/

[97] B. Graver, X. S. Zheng, D. Rutherford, J. Mukhopadhaya, and E. Pronk, ‘Vision 2050: Aligning Aviation with the Paris Agreement’, International Council on Clean Transportation, Washington, DC, Jun. 2022. [Online]. Available: https://theicct.org/wp-content/uploads/2022/06/Aviation-2050_report_final_v2.pdf

[98] IEA, ‘Aviation’, IEA, Paris. [Online]. Available: https://www.iea.org/energy-system/transport/aviation

[99] B. Graver, X. S. Zheng, D. Rutherford, J. Mukhopadhaya, and E. Pronk, ‘Vision 2050: Aligning Aviation with the Paris Agreement.’, International Council on Clean Transportation, Washington, D.C. [Online]. Available: https://theicct.org/wp-content/uploads/2022/06/Aviation-2050_report_final_v2.pdf

[100] J. Mukhopadhaya and D. Rutherford, ‘Performance Analysis of Evolutionary Hydrogen-Powered Aircraft’, International Council on Clean Transportation, 2022. [Online]. Available: https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf

[101] U.S. Department of Energy, ‘Alternative Fuels Data Center: Biodiesel Blends’. Accessed: Dec. 15, 2023. [Online]. Available: https://afdc.energy.gov/fuels/biodiesel_blends.html
[102] U.S. Department of Energy, ‘Alternative Fuels Data Center: Ethanol Blends’. Accessed: Dec. 15, 2023. [Online]. Available: https://afdc.energy.gov/fuels/ethanol_blends.html
[103] K. A. Subramanian, V. C. Mathad, V. K. Vijay, and P. M. V. Subbarao, ‘Comparative evaluation of emission and fuel economy of an automotive spark ignition vehicle fuelled with methane enriched biogas and CNG using chassis dynamometer’, *Applied Energy*, vol. 105, pp. 17–29, May 2013, doi: 10.1016/j.apenergy.2012.12.011.
[104] U.S. Department of Energy, ‘Alternative Fuels Data Center: Fuel Cell Electric Vehicles’. Accessed: Dec. 11, 2023. [Online]. Available: https://afdc.energy.gov/vehicles/fuel_cell.html
[105] L. Eudy and M. Post, ‘Fuel Cell Buses in U.S. Transit Fleets: Current Status 2020’, National Renewable Energy Laboratory, NREL/TP-540075583, 2021. [Online]. Available: https://www.nrel.gov/docs/fy21osti/75583.pdf
[106] Argonne National Laboratory, *Autonomie Suite*. (2023). [Online]. Available: https://vms.taps.anl.gov/tools/autonomie/
[107] National Renewable Energy Laboratory, ‘Transportation Annual Technology Baseline (ATB) Data’. 2022. [Online]. Available: https://atb.nrel.gov/transportation/2022/data
[108] National Renewable Energy Laboratory, ‘Transportation Annual Technology Baseline (ATB) Data’. 2022. [Online]. Available: https://atb.nrel.gov/transportation/2022/data
[109] C. Acar and I. Dincer, ‘The potential role of hydrogen as a sustainable transportation fuel to combat global warming’, *International Journal of Hydrogen Energy*, vol. 45, no. 5, pp. 3396–3406, Jan. 2020, doi: 10.1016/j.ijhydene.2018.10.149.
[110] WestPort Fuel Systems, ‘Hydrogen Mobility: Fully Integrated H2 HPDI Fuel System Truck Solution.’ [Online]. Available: https://www.westport-hpdi.com/wp-content/uploads/2023/05/westport-h2-hpdi-technical-specs-brochure.pdf
[111] M. Wang *et al.*, *Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2022 Excel)*. (2022). Argonne National Laboratory (ANL), Argonne, IL (United States). doi: 10.11578/GREET-EXCEL-2022/DC.20220908.1.
[112] Center for Sustainable Systems, University of Michigan, ‘Autonomous Vehicles Factsheet’. [Online]. Available: https://css.umich.edu/publications/factsheets/mobility/autonomous-vehicles-factsheet
[113] Argonne National Laboratory, ‘Energy Efficient Connected and Automated Vehicle Control’, Vehicle & Mobility Systems Department - Argonne National Laboratory, 2021. [Online]. Available: https://vms.taps.anl.gov/research-highlights/energy-efficient-connected-and-automated-vehicle-control/
[114] Center for Sustainable Systems, University of Michigan, ‘Autonomous Vehicles Factsheet’, 2023. [Online]. Available: https://css.umich.edu/publications/factsheets/mobility/autonomous-vehicles-factsheet
[115] USGS, ‘Metals and Minerals Report, Early Release of the 2021 Annual Tables’, Jul. 2023. Accessed: Nov. 23, 2023. [Online]. Available: https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/myb1-2021-cemen-ert.xlsx
[116] USGS, ‘Metals and Minerals Report’, Aug. 2020. Accessed: Nov. 23, 2023. [Online]. Available: https://d9-wret.s3.us-west-

2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/myb1-2021-cemen-ert.xlsx
[117] Lao Statistics Bureau, 'Statistical Yearbook 2022', Lao PDR Ministry of Planning and Investment, Jun. 2023.
[118] UN Climate Technology Centre & Network, 'Clinker replacement'. Accessed: Dec. 21, 2023. [Online]. Available: https://www.ctc-n.org/technologies/clinker-replacement
[119] I. Malico, R. Nepomuceno Pereira, A. C. Gonçalves, and A. M. O. Sousa, 'Current status and future perspectives for energy production from solid biomass in the European industry', *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 960–977, Sep. 2019, doi: 10.1016/j.rser.2019.06.022.
[120] G. Moral, R. Ortiz-Imedio, A. Ortiz, D. Gorri, and I. Ortiz, 'Hydrogen Recovery from Coke Oven Gas. Comparative Analysis of Technical Alternatives', *Ind. Eng. Chem. Res.*, vol. 61, no. 18, pp. 6106–6124, May 2022, doi: 10.1021/acs.iecr.1c04668.
[121] L. Deng and T. A. Adams Ii, 'Techno-economic analysis of coke oven gas and blast furnace gas to methanol process with carbon dioxide capture and utilization', *Energy Conversion and Management*, vol. 204, p. 112315, Jan. 2020, doi: 10.1016/j.enconman.2019.112315.
[122] IEA, 'Direct Air Capture 2022', Paris, 2022. [Online]. Available: https://www.iea.org/reports/direct-air-capture-2022
[123] National Renewable Energy Laboratory, 'Electricity Annual Technology Baseline (ATB)'. 2023. [Online]. Available: https://atb.nrel.gov/electricity/2023/about
[124] Government of Lao PDR, 'Renewable Energy Development Strategy in Lao PDR', 2011. [Online]. Available: https://policy.asiapacificenergy.org/sites/default/files/LIRE-Renewable_Energy_Development_Strategy_in_Lao_PDR.pdf
[125] M. Wang *et al.*, *Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2022 Excel)*. (2022). Argonne National Laboratory (ANL), Argonne, IL (United States). doi: 10.11578/GREET-EXCEL-2022/DC.20220908.1.
[126] IEA, 'Outlook for biogas and biomethane: Prospects for organic growth', Mar. 2020. [Online]. Available: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth
[127] United Nations Framework Convention on Climate Change, 'Methodological tool: Project and leakage emissions from anaerobic digesters, version 2.0'. 2017. Accessed: Dec. 12, 2023. [Online]. Available: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-14-v2.pdf
[128] IRENA, *Biogas for Domestic Cooking: Technology Brief*. Abu Dhabi: International Renewable Energy Agency, 2017. Accessed: Dec. 11, 2023. [Online]. Available: https://www.irena.org/Publications/2017/Dec/Biogas-for-domestic-cooking-Technology-brief
[129] Anuraag Nallapaneni and S. Sood, 'Emission Reduction Potential of Green Hydrogen in Ammonia Synthesis for Fertilizer Industry', WRI India, Oct. 2022. [Online]. Available: https://wri-india.org/blog/emission-reduction-potential-green-hydrogen-ammonia-synthesis-fertilizer-industry
[130] S. Sollai, A. Porcu, V. Tola, F. Ferrara, and A. Pettinau, 'Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment', *Journal of CO2 Utilization*, vol. 68, p. 102345, Feb. 2023, doi: 10.1016/j.jcou.2022.102345.

Appendices

Cu Lao Cham, Lao PDR

Appendices

Appendix A: Abbreviations

ACE	ASEAN Centre for Energy
ADB	Asian Development Bank
AEO	ASEAN Energy Outlook
AEO7	Seventh ASEAN Energy Outlook
AEO8	Eighth ASEAN Energy Outlook
AFOLU	Agriculture, Forestry and Other Land Uses
AMS	ASEAN Member States
APAEC	ASEAN Plan of Action for Energy Cooperation
APERC	Asia-Pacific Energy Research Centre
ATS	ASEAN Member States Target Scenario
BECCS	Bioenergy with Carbon Capture and Storage
BOT	Build-Operate-Transfer
BOO	Build-Own-Operate
BRT	Bus Rapid Transit
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CSP	Concentrated Solar Power
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalent
DAC	Direct Air Capture
EDGAR	Emissions Database for Global Atmospheric Research
EDL	Électricité du Laos
EE	Energy Efficiency
EMA	Energy Market Authority
ETP	Energy Technology Perspectives
EV	Electric Vehicle
FAME	Fatty Acid Methyl Esters
FDI	Foreign Direct Investment
GoL	Government of Lao People's Democratic Republic
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
GJ	Gigajoule
GMS	Greater Mekong Sub-region
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GW	Gigawatt
HVO	Hydrotreated Vegetable Oil
IMF	International Monetary Fund
IPD	Investment Promotion Department
IPPU	Industrial Processes and Product Use
JICA	Japan International Cooperation Agency
$KtCO_2e$	Kilotonne CO_2-equivalent
L-DAC	Liquid Direct Air Capture
Lao PDR	Lao People's Democratic Republic
LMB	Lower Mekong River Basin

LED	Light-emitting Diode
LEAP	Low Emissions Analysis Platform
LT-LEDS	Long-Term Low Emission Development Strategy
LTMS	Lao PDR-Thailand-Malaysia-Singapore
LTMS-PIP	Lao PDR-Thailand-Malaysia-Singapore Power Integration Project
LPG	Liquified Petroleum Gas
MEM	Ministry of Energy and Mines of Lao PDR
MJ	Megajoule
MONRE	Ministry of Natural Resources and Environment of Lao PDR
MW	Megawatts
NDC	Nationally Determined Contribution
NEM	New Economic Mechanism
NEMO	Next Energy Modelling System for Optimisation
OEC	Observatory of Economic Complexity
ORC	Organic Rankine Cycle
PDP	Power Development Plan
PPAs	Power Purchase Agreements
RE	Renewable Energy
RAS	Regional Aspiration Scenarios
RPA	Revenue Passenger-Kilometre
S-DAC	Solid Direct Air Capture
SDG	Sustainable Development Goals
SAF	Sustainable Aviation Fuels
SEI	Stockholm Environment Institute
SSP	Shared Socioeconomic Pathways
TFEC	Total Final Energy Consumption
TRL	Technological Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
WDI	World Development Indicator

Appendix B: Detailed assumptions for measures modelled in the Net-zero Scenario

1. Residential sector (R)

R1. Improved and clean cooking	**Sector:** Residential
Description: This measure tracks households' transition from primarily traditional biomass cooking to more efficient and less polluting technologies, such as improved biomass stoves, LPG, biogas and electric induction stoves. **Modelling approach:** On the demand side of the model, cooking energy requirements were assessed using an activity analysis with useful energy intensities, in which final energy requirements are calculated by specifying the useful quantity of cooking energy required, and the efficiency of devices that meet that requirement. The adoption of alternative technologies was represented by modifying the share of households using clean cooking methods (anything but traditional biomass or kerosene), and of those households using clean cooking methods, the share of each type of clean cookstove. Conversion efficiencies and emission factors for each technology were sourced from the AEO model	

[82]. Clean cooking technologies include improved wood/biomass stoves (which use wood biomass like traditional woodstoves but feature enhancements such as better ventilation and secondary combustion mechanisms for improved performance), biogas stoves, liquefied petroleum gas (LPG) stoves, and electric induction.

Implementation level in the Lao PDR Net-Zero Scenario: Shares of traditional versus clean cooking technologies in the Net-zero Scenario were initially based on the United Nations Economic and Social Commission for Asia and the Pacific [35] *SDG 7 Roadmap* and adjusted with stakeholder feedback from the In-Country Workshops. The goal was to maintain the 2020 level of charcoal usage (5.7% of households) while increasing the adoption of efficient wood stoves, LPG, biogas and electric induction stoves.

Specific assumptions for 2030 are as follows: 94.3% of households in Laos will have access to improved or clean cooking technologies. This includes 10% of households cooking with efficient wood stoves, 20% with LPG, 10% with domestic biogas and 54.3% using electric induction stoves. The remaining 5.7% of households will continue using traditional fuels, primarily charcoal, maintaining the same usage level as in 2020.

R2. Heat pump space cooling — **Sector:** Residential

Description: This measure considers the transition from average-efficiency, currently available air conditioning technology to the best-available heat pump technology for space cooling.

Modelling approach: Energy requirements for air conditioning were modelled using an activity analysis with useful energy intensities. The adoption of different air conditioning technologies (including the current stock average, the current sales average, efficient air conditioners and best practice heat pump technology) was represented by determining a share of households using each technology. The Energy Efficiency Ratio (EER) for each technology ranged from 26.9 Btu/Wh for the best available technology to 10 Btu/Wh for the current sales average. These were sourced from the AEO model [82].

Implementation level in the Lao PDR Net-Zero Scenario: By 2045, 28% of homes are assumed to use an air-conditioning technology, with all units employing the best-available heat pump technology. This assumption is based on current sales practices continuing through 2030, followed by a complete shift to the best-available technology thereafter (based on assumptions by the modelling team).

R3. Reflective coatings and cool roof technologies — **Sector:** Residential

Description: Reduction in the need for space cooling in homes outfitted with high reflectivity exterior coatings and cool roofs.

Modelling approach: This measure is modelled as tracking a reduction in the useful energy intensity of space cooling activities for households equipped with cool roofs or reflective exterior coatings. The reduction is measured in comparison to the model's Baseline Scenario energy intensity for space cooling. It effectively measures the average reduction that could be achieved by implementing this measure in all households. Gupta and Deb [83] show a range of cooling reductions between 2% and 42%, with a mean of 22% and a median of 23%. Rawat and Singh [84] report a mean value of 35.7% for tropical climates.

Implementation level in the Lao PDR Net-Zero Scenario: By 2050, reflective coatings and cool roof technologies are used by 40% of households [85] and stakeholder feedback during the Second In-Country Workshop), each requiring 22% less cooling [83].

R4. Programmable thermostats	**Sector:** Residential

Description: Increased uptake of programmable thermostats in households, which reduce demand for space cooling.

Modelling approach: This measure considers the reduction in the useful energy intensity of space cooling activities for households equipped with programmable thermostats. The reduction is measured in comparison to the model's Baseline Scenario energy intensity for space cooling. It effectively measures the average reduction that could be achieved by implementing this measure in all households. Homes with smart thermostats reduce cooling requirements by 8% [86].

Implementation level in the Lao PDR Net-Zero Scenario: By 2050, programmable thermostats are used by 16% of households, the current penetration of smart thermostats in the United States [87], each reducing cooling requirements by 8%.

R5. Optimal building orientation	**Sector:** Residential

Description: More homes are constructed according to their optimal building orientation and with improved design (e.g. window placement) to maximise daylight and natural ventilation, resulting in reduced demands for both space cooling and lighting.

Modelling approach: This measure gauges the reduction in space cooling energy intensity and lighting final energy intensity for optimally oriented residential buildings. The reduction is measured in comparison to the model's Baseline Scenario energy intensity for space cooling and lighting. It effectively measures the average reduction that could be achieved by implementing this measure in all homes. Considering space cooling and lighting together, Valladares-Rendón et al. [88] find optimal orientation can reduce demand by 5%-16%, while Lee et al. [89] report it can reduce demand by 23%, with both sources presenting results for buildings in tropical climates. Lee et al. [89] show that 97% of the reduction in total cooling and lighting demand is for cooling, and 3% is for lighting.

Implementation level in the Lao PDR Net-Zero Scenario: By 2050, 6% of households use optimal building orientation (25% of newly built households, an assumption made by the modelling team). Relative to the model’s Baseline Scenario, a 0.2% reduction lighting and 7.8% reduction in cooling demand is assumed, which is a conservative estimate based on Valladares-Rendón et al. [88].

R6. Heat pump water heaters	**Sector:** Residential

R7. Solar water heaters
Description: These measures gauge the increased uptake of more sustainable and efficient water heating technologies, including solar water heaters and heat pump water heaters, some of which are equipped with secondary exchangers to capture heat (and transfer it to a hot water tank) dissipated by a household's space cooling equipment. **Modelling approach:** Energy requirements for water heating were modelled using an activity analysis. The adoption of different technologies, including heat pumps and solar water heaters, was evaluated by assigning a share of households using each technology. The measure of energy intensity of the heat pump drawing heat from the outside air or the air conditioning exhaust is based on the difference between heat pump water heater performance in a tropical climate and an "interim" or temperate climate (from Table 9 [91]). Energy intensities for other water heating technologies were sourced from the AEO model [82]. **Implementation level in the Lao PDR Net-Zero Scenario:** By 2050, 15.6% of homes use water heating, of which 65% use heat pumps and 10% use heat pumps with waste heat recovery Another 25% of homes use solar thermal water heating, based on achievement of 50% of Vietnam's solar heating target [92].

R8. Gamifying electricity use	**Sector:** Residential
Description: Households opt to participate in a "gamified" energy efficiency programme, which uses behavioural incentives, rewards and competition to induce electricity consumers to reduce their energy use, either annually or during specific time periods. **Modelling approach:** This measure considers a reduction in the energy intensity of electricity technologies used for space cooling, water heating and lighting. The reduction is in comparison to the model's Baseline Scenario energy intensity for these end uses. It effectively measures the average reduction that could be achieved by implementing this measure in all households. Based on pilot programmes in the United States, Wolfson et al. [93] find that nearly two in five participating households reduced their electricity consumption by at least 3%, with many households achieving deeper reductions. **Implementation level in the Lao PDR Net-Zero Scenario:** The modelling team assumes that a participating household would be able to reduce lighting, water heating and cooling electricity use by 3%, and that by 2030, 20% of households could participate in a gamified energy efficiency programme.	

2. Commercial sector (C)

C1. Improved and clean cooking	**Sector:** Commercial
Description: This measure assesses the transition of commercial kitchens and food processing facilities away from biomass and towards LPG, conventional electric resistance and electric induction technologies.	

Modelling approach: On the demand side of the model, commercial cooking and food processing energy requirements were assessed using an activity analysis approach, in which shares of commercial floorspace are allocated to a number of cooking technologies, each of which is assigned a final energy usage per square metre of floorspace. The adoption of alternative technologies was represented by modifying the share of floorspace using LPG and electric cooking methods. Conversion efficiencies and emission factors for each technology were sourced from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: Shares of cooking technologies are characterised by several overlapping implementation assumptions describing gradual technological change, each beginning in the first scenario year with currently existing technologies. By 2030, 20% of commercial cooking switches over to LPG. By 2040, all wood consumption for cooking is phased out, followed in 2050 by all charcoal consumption. Also in 2050, shares of electric induction technologies reach 50% of cooking needs. Conventional (resistance-based) electric cooking technologies make up the remainder, reaching a peak of 41% of cooking in 2040 before declining to 30% by 2050.

C2. Heat pump space cooling	**Sector:** Commercial

Description: This measure tracks the transition from an average-efficiency, currently available air conditioning technology to the best available heat pump technology for space cooling.

Modelling approach: Energy requirements for commercial air conditioning were modelled using an activity analysis approach. Across the commercial floorspace that is cooled, the representation of different air conditioning technologies closely follows those established in the residential sector, including technologies representing the current stock average (which, by definition, provides 100% of cooling requirements in the model's historical period), and alternatives representing the current sales average, efficient air conditioners, and best practice heat pumps. Efficiencies for each of the commercial alternatives were estimated using the same percentage improvement from the current stock average as was assumed for the residential sector. These are described elsewhere in this Appendix.

Implementation level in the Lao PDR Net-zero Scenario: The modelling team assumed that 90% of cooled commercial floorspace uses the best available heat pump technology by 2050, while the remainder of cooling is provided by the efficient (though not best practice) technology.

C3. Heat pump water heaters	**Sector:** Commercial
C4. Solar water heaters	

Description: Similar to the water heating technologies deployed in the residential sector, these measures gauge the increased uptake of efficient water heating technologies in the commercial sector. Measures include solar and heat pump water heaters, some of which are equipped with secondary exchangers to capture heat dissipated by space cooling equipment, and to transfer it to a hot water tank.

Modelling approach: Energy requirements for water heating were modelled using an activity analysis. The adoption of different technologies, including heat pumps and solar water heaters, was represented by assigning a share for each technology among the commercial floorspace that uses water heating. Like the residential sector, energy intensity for the heat pump drawing heat from the outside air or an air conditioning exhaust is based on the difference between heat pump water heater performance in a tropical climate and an "interim" or temperate climate (from Table 9 [91]). Energy intensities for other water heating technologies were sourced from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2035, the modelling team assumed that of the mere 3% of commercial floorspace that uses water heating, 45% is met using heat pumps and 50% is met using heat pumps coupled to secondary heat exchangers. Solar water heating meets 2% of water heating needs, and the remainder is provided by electrical resistance. Implementation levels after this year remain stationary at 2035 levels.

C5. Efficient refrigeration — **Sector:** Commercial

Description: This measure assesses the transition from an average-efficiency, currently available refrigerator to a more efficient variant.

Modelling approach: Energy requirements for commercial refrigeration were modelled using an activity analysis approach. Within the commercial floorspace that uses refrigeration, two basic technologies describe the available refrigeration technologies – existing (meaning the currently available average technology) and efficient, which uses only 70% of the energy. All technical assumptions are drawn from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2040, the modelling team assumed that 90% of commercial floorspace with any type of refrigerator uses the more efficient variant of the technology.

C6. Light-emitting diode (**LED) lighting** — **Sector:** Commercial

Description: This measure assesses a transition away from all other electric lighting technologies towards LEDs.

Modelling approach: Energy requirements for commercial lighting were modelled using an activity analysis approach. Across the commercial floorspace that is lit, five different electric technologies are available: incandescent, compact fluorescent lighting (CFL), linear fluorescent, halogen and LED. Energy use per square metre for each technology was taken from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2030, the modelling team assumed that all lit commercial floorspace would use LED lighting.

3. Transport sector (T)

3.1. Aviation

T1. Improved aviation efficiency **Sector:** Transport

Description: This measure considers a range of actions that can result in improved fuel efficiency and reduced energy intensity for aviation. Technical efficiency improvements in aircraft in general, and their engines in particular, can either improve fuel burn through aerodynamic efficiency or reduce actual combustion use [94]. These actions include installing wingtip devices on aircraft to increase aerodynamic efficiency, and the use of light-weight materials like carbon composites to fabricate aircraft components. In addition to technical improvements, increasing payload and traffic efficiency (i.e. the weight of cargo and number of passengers carried per aircraft) contribute to reducing the energy intensity of aircraft operations [95]. Between 2005-2019, fuel efficiency of US commercial airlines improved 1.5% per year, with payload efficiency accounting for two thirds of those gains [96].

Modelling approach: Efficiency gains are modelled through a reduction in the energy intensity of both domestic and international aviation. These are based on reductions in energy intensity from technical, payload and traffic efficiency improvements [97], and are described in the following table for three possible scenarios: the "Action", "Transformation" and "Breakthrough" Scenarios. The percentage reductions in energy per revenue passenger-kilometre (RPK) found in this analysis were applied to the energy intensities in the AEO model, which are expressed as tonnes of oil equivalent per dollar of GDP.

Period	Category	Reduction in energy intensity (annual % change in energy use/RPK) (based on Tables 2-4 [97])		
		"Action" Scenario	"Transformation" Scenario	"Breakthrough" Scenario
2019-2034	Technical	-1.08	-1.08	-1.08
	Payload	-0.2	-0.35	-0.5
	Traffic	-0.1	-0.1	-0.1
	Total	**-1.38**	**-1.53**	**-1.68**
2035-2050	Technical	-1.15	-1.83	-2.16
	Payload	-0.2	-0.35	-0.5
	Traffic	-0.1	-0.1	-0.1
	Total	**-1.45**	**-2.28**	**-2.76**

Implementation level in the Lao PDR Net-zero Scenario: For Lao PDR, the mid-scenario assumptions ("Transformation" Scenario) from Graver et al. [97] were applied, reducing fuel use per passenger-kilometre for all domestic and international aviation by 1.53%/year initially, reaching 2.28%/year by 2035 and continuing to improve annually at that rate.

T2. Electric taxiing and ground operations at airports **Sector:** Transport

Description: An electric taxiing system is a system in which an electric motor, mounted to the landing gear, is used instead of an aircraft's engine during ground operations to reduce fuel use. This is more energy efficient than using the aircraft's main engines and makes the aircraft autonomous from towing trucks, also reducing delays at airports. Estimated fuel savings of 4% per flight can be achieved for short-haul aircraft that perform six to seven flights per day [34].

Modelling approach: This technology is modelled as the displacement of a very small quantity of fossil fuels used during taxiing. The measure is considered only for domestic aviation since the additional weight of taxiing equipment makes electric taxiing mainly attractive for short-haul aircraft with long taxiing times at airports [34].

Implementation level in the Lao PDR Net-zero Scenario: Beginning in 2035, electric airplane taxiing displaces 2% of jet kerosene with electricity (an assumption by the modelling team based on).

T3. Sustainable Aviation Fuel (SAF)	**Sector:** Transport

Description: Sustainable aviation fuels (SAFs) are compatible with existing airframes and engines up to 50% blends, with efforts underway to certify the use of 100% SAFs [97]. Uptake has been limited so far: according to the [98], SAF currently account for less than 0.1% of all aviation fuels consumed. By 2027, planned production capacities of SAF will provide 1-2% of jet fuel demand, though increasing the fuel share to 10% by 2030 will require significant investment in production capacity and supportive policies such as fuel taxes and low-carbon fuels standards.

Fuel share assumptions are based on Table 6 [97], which considers 3%, 8% and 17% SAF blends by 2030 in the “Action”, “Transformation”, and “Breakthrough” scenarios, respectively, reaching 50%, 80% and 100% by 2050.

Modelling approach: This technology is modelled as a shift away from jet kerosene to SAF in both domestic and international aviation. Fuel share assumptions are based on Table 6 [97], which considers 3%, 8% and 17% SAF blends by 2030 in the “Action”, “Transformation”, and “Breakthrough” scenarios, respectively, reaching 50%, 80% and 100% by 2050.

The modelling team calculated the ratio of the carbon intensity of SAF to traditional jet kerosene, which use a lifecycle assessment approach [97]. For SAF, a GHG intensity of 18.3 g CO_2e/MJ was used (which represents the average GHG emissions from biofuel produced through a Fischer-Tropsch process from agricultural residues, forest residues and municipal solid waste). For jet kerosene, a GHG intensity of 88.5 g CO_2e/MJ was used, resulting in a GHG intensity ratio with SAF of 0.207. This calculated ratio, based on CO_2-equivalence, was then applied to each individual GHG emission factor associated with jet kerosene in the AEO model, yielding an estimate of the GHG emission factors for SAF. For other non-GHG air pollutants, the modelling team assumed that emission factors are the same as for jet kerosene.

Implementation level in the Lao PDR Net-Zero Scenario: For Lao PDR, assumptions are based on the “Transformation” Scenario from [99],with SAF displacing 2% of jet kerosene by 2027, 8% by 2030, and 50% by 2050.

T4. Hydrogen fuel cell aviation	**Sector:** Transport

Description: Hydrogen, consumed in a fuel cell, is a net-zero enabling technology for aviation and an alternative to battery-powered aircraft. Such designs incorporate a hydrogen fuel cell used to generate electricity, as well as a smaller battery used to regulate power output or as back-up fuel source (but not as the aircraft's primary energy storage). The reduced battery capacity requirements compared to electric aircraft, together with the high energy density of hydrogen per unit mass, alleviate a major constraint of electric aviation that has generally restricted battery-power aircraft to short-haul flights only. Hydrogen fuel cell aircraft are at an early development stage and commercial application in small regional jets is only expected in the 2030s at the earliest [34]. By 2040, hydrogen aircraft may reach a maximum range of up to 3,500 km, which could serve approximately half of current commercial aviation needs [95].

Modelling approach: This technology is modelled as a shift away from jet kerosene to hydrogen in both domestic and international aviation. Based on [100], hydrogen fuel cell aircraft could service 31% to 38% of all passenger aviation traffic, as measured by revenue passenger-kilometre.

Implementation level in the Lao PDR Net-zero Scenario: Beginning in 2035, the modelling team assumes that hydrogen fuel cells would provide 30% of all energy needs for domestic and international aviation by 2050.

3.2. Road

T5. Biodiesel and bioethanol blending	**Sector:** Transport

Description: Blending biofuels into regular gasoline or diesel can reduce vehicles' carbon intensity. Biodiesel can be blended with ordinary diesel fuel using several common ratios: most commonly B5 (up to 5% biodiesel by volume) and B20 (6% to 20% biodiesel by volume), up to B100 (pure biodiesel) which can be used as a transport fuel but is typically used as a blendstock to produce lower percentage blends [101]. Ethanol is available in several different blends with motor gasoline, for use in conventional and flexible fuel vehicles. The most common are E10 (composed of 10% ethanol and 90% gasoline by volume), E15 (10.5% to 15% ethanol) and E85 (also known as flex fuel, composed of an ethanol-gasoline blend containing 51% to 83% ethanol) [102].

Modelling approach: Using volumetric and energetic fuel densities, volumetric blend ratios of either ethanol or biodiesel are converted into the share of energy that each blended fuel provides, and this is applied to the conventional diesel or gasoline that would be consumed in the model without fuel blending. Emission factors for biodiesel and ethanol are borrowed from diesel and gasoline respectively. However, their CO_2 emissions are assumed to be biogenic, and are not counted towards overall CO_2e.

Implementation level in the Lao PDR Net-zero Scenario: Beginning in 2024, the modelling team assumes that volumetric diesel and gasoline blends reach 20% biodiesel (B20) and 15% bioethanol (E15) by 2030.

T6. Biomethane vehicles	**Sector:** Transport

Description: Liquified biomethane can be used in vehicles powered by an internal combustion engine. For long-haul trucks in particular, the higher energy density of biomethane stored in cryogenic tanks can be a cost-efficient solution compared to using compressed methane. This technology still faces some technological challenges, including insulation of on-board liquified biomethane, the risk of methane leakage and incomplete methane combustion. Additionally, for this technology to deliver the full emissions reductions relative to diesel powertrains, the methane should be produced from renewable sources. Promising application opportunities are municipal fleets supplied by biomethane from municipal or agricultural waste. This technology could be applied on a wider scale in regions where existing natural gas distribution pipeline networks can be paired with the production of synthetic methane, via electrolysis of carbon-free electricity and a carbon source [34].

Modelling approach: This technology is modelled by shifting passenger-kilometres and tonne-kilometres away from fossil fuels to biomethane, in passenger buses and freight trucks. [103]found there is no significant change in fuel economy of vehicles fuelled with enriched biogas as compared to natural gas, and that both fuels result in comparable performance and emissions. Therefore, the same fuel economy and tailpipe emission factor assumptions for natural gas trucks and buses from the AEO model [82] are used for biomethane trucks and buses, with the exception that CO_2 emissions are assumed to be biogenic, and are not counted towards overall CO_2e.

Implementation level in the Lao PDR Net-zero Scenario: Biomethane passenger buses are gradually introduced, beginning in 2030 and finally reaching 10% of passenger-kilometres by 2050. Starting in 2025, biomethane is introduced in freight trucks, reaching 5% of tonne-kilometres in 2030 and 10% in 2050. In both cases, the modelling team assumes that these alternative technologies displace fossil fuels in proportion to their historical shares within passenger buses and freight trucks.

T7. Battery electric cars	**Sector:** Transport

Description: Electric vehicles use batteries (today, almost exclusively lithium-ion batteries) arranged in a battery pack array. The battery pack is combined with inverters and an electric motor to convert electrical energy provided by the batteries into mechanical energy [34].

Modelling approach: This technology is modelled as a shift away from fossil fuels to electric vehicles in private cars, buses, motorcycles, taxis and trucks. The modelling team assumes that the introduction of electric vehicles displaces fossil-fuelled technologies in proportion to the shares of those technologies in the vehicle fleet. Energy intensities per passenger-kilometer are taken from pre-existing assumptions in the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: Electric private passenger cars, motorcycles and taxis grow to represent 30% of passenger-km by 2030 and 80% by 2050. Electric trucks and buses reach 30% of tonne-km by 2030 and 60% by 2050. Assumptions for 2030 are based on the Lao PDR NDC [33], while adoption levels in 2050 are assumptions made by the modelling team based on a more aggressive trajectory.

T8. Hydrogen fuel cell electric vehicles **Sector:** Transport

Description: Fuel cell electric vehicles (FCEVs) are powered by hydrogen. Fuel cells convert energy stored as hydrogen, together with oxygen, into electricity that powers an electric motor. Hydrogen FCEVs are more efficient than conventional internal combustion engine vehicles and produce no harmful tailpipe emissions—only water vapour and warm air. Similar to conventional internal combustion engine vehicles, they can refuel in minutes and have a driving range of more than 480 km [104].

Modelling approach: This technology is modelled as a shift away from fossil fuels to hydrogen FCEVs in freight trucks, passenger buses, private passenger cars and taxis. The modelling team assumes that the introduction of FCEVs displaces fossil-fuelled technologies in proportion to the shares of those technologies in the vehicle fleet. Assumptions for fuel economy of the fuel cell vehicles are based on the following sources:

- *Buses:* average among second generation fuel cell electric buses, based on [105],
- *Trucks:* average for a Class 6 Medium Box truck and a Class 8 Long-haul Sleeper, based on [106] with data accessed through [107],
- *Taxis:* assuming a mid-sized passenger car in the mid-scenario from [106] with data accessed through [107],
- *Private passenger vehicles:* average for a mid-sized passenger car and a mid-sized passenger SUV in the mid-scenario from [106] with data accessed through [108].

Implementation level in the Lao PDR Net-Zero Scenario: The following adoption rates were assumed by the modelling team, expressed as shares of passenger-kilometres required within each vehicle category:

- *Private passenger vehicles and taxis:* beginning in 2030 and reaching 5% by 2050.
- *Buses:* beginning in 2030 and reaching 10% by 2050.
- *Trucks:* beginning in 2025 and reaching 5% by 2030, and 20% by 2050.

T9. Hydrogen combustion for trucking **Sector:** Transport

Description: Combusting hydrogen directly in an internal combustion engine (ICE) is an alternative use of hydrogen in transport, which does not rely on a fuel cell. While hydrogen-powered fuel cells have higher efficiencies and lower emissions than internal combustion engines, they require additional space and weight and are generally more expensive [109]. Compared to fossil fuel combustion engines, hydrogen can enhance system efficiencies, offer higher power outputs per vehicle and emit lower amounts of greenhouse gases.

Modelling approach: This technology is modelled as a shift away from fossil fuels to hydrogen ICEs in trucks used to transport freight. The modelling team assumes that the introduction of hydrogen ICE vehicles displaces other technologies in proportion to the shares of those technologies in the vehicle fleet. The fuel economy for hydrogen ICE vehicles is based on information from [110], for a WestPort H_2 high-pressure direct injection fuel system technology, which considers up to a 5% efficiency improvement over the conventional diesel ICE. Even though the main product of hydrogen combustion is water and no GHGs are produced, combusting hydrogen in the presence of air can lead to the formation of nitrogen oxides (NO_x). NO_x emission factors for a spark-ignition ICE vehicle running on liquid H_2 were obtained from [111].

Implementation level in the Lao PDR Net-zero Scenario: Beginning in 2025, the modelling team assumes that hydrogen-based ICE trucks provide 3% of tonne-kilometres for on-road freight transport by 2030, reaching 5% by 2050.

T10. Autonomous electric taxis	Sector: Transport

Description: Autonomous vehicles (AVs) replace a human driver partially or entirely in navigating a vehicle from an origin to a destination, while avoiding road hazards and responding to traffic conditions. They use combinations of technologies and sensors to sense the roadway, and other vehicles or obstructions. AVs are more likely to be electrified, and can achieve improved energy efficiency through eco-driving, platooning, decreasing congestion, emphasising vehicle performance over comfort, avoiding crashes, vehicle right-sizing and potentially increasing occupancy levels for ride-sharing. However, they could also lead to higher highway speeds, or increased travel due to lower costs, resulting in higher energy consumption. The interconnected impacts of these effects are difficult to measure, but one study has reported savings of up to 40% in total road transport energy in an optimistic scenario, compared with a 105% increase in energy requirements in a pessimistic scenario [112].

Modelling approach: This technology is applied to a portion of electrified taxis that would be introduced through a different scenario assumption describing the implementation of electric vehicles. Based on data from[113], [114], the modelling team assumes that autonomous and connected vehicles result in 20% energy savings compared to fully human-driven electric vehicles.

Implementation level in the Lao PDR Net-zero Scenario: Starting in 2030, the share of autonomous electric taxis increases to 25% of all electric taxis by 2050, based on [113], [114], and stakeholder feedback from the Second In-Country Workshop.

T11. Fuel economy improvements	Sector: Transport

Description: This measure reproduces autonomous fuel economy improvements across all road transport technologies that are deployed in the AEO8 model. No specific technology is represented, but the trend is reflective of historical improvements in fuel efficiency foreseen by ACE.

Modelling approach: An annual growth rate is applied to the fuel economy (distance per unit of energy consumed) of most vehicle technologies.

.**Implementation level in the Lao PDR Net-zero Scenario:** Fleet-wide average fuel economy for gasoline and diesel vehicles improves by 1.0%/year, based on the AEO8 AMS Targets Scenario [29].

4. Industrial sector (I)

I1. Reduced clinker in cement	Sector: Industry

Description: Clinker is an intermediate product required to manufacture cement. It is produced in a cement kiln, where carbon dioxide is emitted from both fuel combustion to supply the kiln with heat (classified as energy-related emissions), and from the sintering of limestone (classified as industrial process emissions). Alternative cement formulations with reduced clinker requirements can reduce greenhouse gas emissions from both of these sources.

Modelling approach: Energy requirements per unit of clinker production for bituminous coal, petroleum coke, diesel, LPG and residual fuel oil are derived from energy used for US clinker production [115], while the current share of clinker in cement is estimated by dividing clinker output by total US cement production in the same year (ibid.). Reductions in this ratio generate negative energy consumption that is subtracted from total industrial energy consumption. Emission reductions are based on energy consumption reductions and emission factors for each fuel, from the AEO model [82]. Reductions to industrial process emissions from cement manufacture are calculated by multiplying clinker production by process emissions per unit of clinker. The potential of the measure is limited by total national cement production [115], [116], [117], which is assumed to escalate over time at the same rate as other industrial activity.

Implementation level in the Lao PDR Net-Zero Scenario: Clinker content of cement is reduced by 30% by 2050, reaching 0.62 tonnes of clinker per tonne of cement [118].

I2. Electric heat pumps for low-temperature heat I3. Biomass circulating fluidized bed boilers for low- and high-temperature heat I4. Biomethane boilers for low- and high-temperature heat I5. Hydrogen boilers for high-temperature heat	Sector: Industry

Description: These measures consider the substitution of fossil fuels combusted for industrial process heat with alternative, clean fuel technologies. These include electric heat pumps for low-temperature heat, biomethane boilers and biomass combusted in a fluidised circulating bed boiler for both low- and high-temperature heat, and hydrogen boilers for high-temperature heat.

Modelling approach: These technologies are modelled as a shift away from fossil fuels that are assumed to be used for process heat (designated in the model as all varieties of coal, coke, natural gas, diesel and residual fuel oil) to biomass, biomethane, electricity and hydrogen. In each industrial subsector, the share of total final energy consumption used for process heat is estimated from [119], which is then applied to the designated process heat fuels to approximate the amount of these fuels used for process heating. The remainder is assumed to be used for other non-heat purposes. To implement the displacement, the final energy intensity of designated process heat fuels is reduced linearly until the year 2050. This may continue all the way to the share of its Baseline Scenario value estimated as non-heating use, in the case of maximum deployment (up to the full amount of estimated heat-related fuel use may be displaced). In its place, a mixture of electricity, biomass, biomethane and hydrogen is introduced in a specified ratio, by increasing the final energy intensity of these fuels in each industrial subsector. The amount of each alternative fuel introduced for each unit of fossil fuel displaced is modulated by the ratio of efficiencies: that of either a hydrogen boiler, biomethane boiler, biomass circulating fluidised bed boiler, or electric heat pump, to the efficiencies of a natural gas, coal, diesel or residual fuel oil boiler.

Implementation level in the Lao PDR Net-zero Scenario: Based on the modelling team's assumptions and stakeholder feedback, it is assumed that by 2050, 30% of all industrial process heat requirements are met by electricity, 30% by biomass, 30% by biomethane and 10% by hydrogen. Until 2050, any remaining process heat requirements would continue to be supplied by traditional fossil fuels.

I6. CO_2 capture and utilization in iron and steel production **Sector:** Industry

Description: Coke oven gas, created during iron and steel production, is rich in CO_2 that may be captured and sequestered or used. This measure refers to the capture and utilisation of CO_2 from iron and steel production as feedstock for methanol production. Any methanol that is produced in this way is assumed to be consumed in the same industrial subsector as a supplier of industrial heat, reducing the use of coal. This measure reduces energy-related emissions based on the differential combustion emissions of coal and methanol, as well as industrial process emissions, based on the avoidance of flared gases from coke ovens.

Modelling approach: This measure assumes that 50 cubic metres of coke oven gas is emitted per tonne of iron and steel production [120]. Together with a small quantity of blast furnace gas, this is used to meet both the process heat and CO_2 feedstock requirements for methanol production. Using process energy inflows and outflows from [121], the modelling team calculates an energetic methanol yield of 515.19 MJ per tonne of iron and steel production, and a utilisation potential of 1.66 kilogrammes of CO_2 per kilogramme of methanol produced (ibid.). Total methanol yield is estimated using projected total national iron and steel production [115], which is assumed to escalate over time at the same rate as other industrial activity.

Implementation level in the Lao PDR Net-zero Scenario: By 2050, the modelling team assumes that 100% of iron and steel production would be equipped with technology to capture CO_2 from coke ovens and blast furnaces, producing methanol for use within that sector. All methanol produced in this way is assumed to be consumed.

I7. Solid direct air capture (S-DAC) and sequestration **Sector:** Industry

Description: Alongside nature- and land-based mitigation strategies like afforestation, direct air capture (DAC) is an important technology-based CO_2 removal option for net-zero pathways. However, it is among the most (if not the most) expensive options for mitigating CO_2 emissions, in part because CO_2 concentrations in the air are orders of magnitude lower than in concentrated streams such as flue gases from combustion processes [122], where CO_2 might ordinarily be captured. Solid and liquid DAC (S-DAC and L-DAC respectively) are two leading technologies that rely on using heat to drive off concentrated

CO_2 from a capture medium. However S-DAC, relying on a solid adsorbent, relies on lower-temperature heat than L-DAC and can therefore more easily be fully powered using zero-carbon electricity (using electric heat pumps) or other renewable thermal energy.

Modelling approach: While the captured CO_2 can be used as a feedstock to produce synthetic fuels (recycling it), the measure considers only CO_2 sequestration, which creates a permanent reduction in atmospheric levels. In the AEO model, DAC is deployed endogenously as a technology that competes with electricity generation-related CO_2 capture and sequestration (fossil fuel plants equipped with CCS) and removal (bioenergy with CCS) in order to achieve an overall emissions limit applied to the energy sector. DAC is an energy-intensive process, and since S-DAC relies on low-temperature heat, this is assumed to be provided entirely by electricity using heat pumps. Overall energy requirements are 8.4 GJ per tonne of CO_2 are assumed [122], while costs of 300 USD per tonne of CO_2 sequestered are assigned as variable running costs, representative of a wide range of S-DAC costs in the literature (ibid.). The capacity of DAC facilities is not modelled.

Implementation level in the Load PDR Net-zero Scenario: No minimum level of DAC is specified in the scenario. Instead, S-DAC is included in the electricity sector optimisation calculations, where it may be deployed to meet the maximum economy-wide GHG emissions limit that is imposed for the scenario. Due to the relatively high costs of deploying DAC relative to other CO_2-neutral or -negative technologies, it is expected to be deployed as a last resort.

I8. Hydrogen displacement of coal and gas	**Sector:** Industry

Description: Hydrogen consumed for high-temperature industrial process heating may play an important role in decarbonising industrial energy use, and this is explored in a dedicated mitigation measure. However, depending on the manufacturing subsector, process heat comprises only 40% to 85% of industrial energy use [119], leaving coal consumption (or other thermal fuels) intact. To reduce emissions further, a top-down option is introduced in the model to displace a fraction of any remaining coal (or natural gas, if appropriate) consumed for industrial manufacturing.

Modelling approach: In the AEO model, industrial manufacturing includes all industrial subsectors except mining and construction. This measure is implemented by subtracting a portion of final consumption of coal (all varieties) and natural gas from these subsectors, and in its place, adding consumption of hydrogen, assuming an equivalent displacement of final energy use.

Implementation level in the Load PDR Net-zero Scenario: Beginning in 2030, the modelling team assumes that 33% (one third) of remaining coal and gas consumption is displaced by hydrogen by the year 2050.

5. Electricity generation and storage (E)

5.1. Renewables

E1. Large hydro	**Sector:** Electricity Generation

E2. Small hydro

Description: Hydropower is a mature and cost-competitive technology, today providing 16% of global electricity generation. Hydropower plants can be classified in three functional categories: run-of-river, reservoir (or storage) and pumped storage plants [34].

Modelling approach: Both large and small hydro were included as electricity production options within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) are taken from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2030, 8,435 MW of additional planned large hydro capacity is to be connected to the grid, alongside 2,000 MW of small hydro by 2040. Up to an additional 17,828 MW of capacity may also be added to supplement existing and planned capacity, 97% of which may be large hydro and the remainder may be small hydro, based on the AEO model and feedback received by the modelling team during the Second In-Country Workshop.

E3. Onshore wind **Sector:** Electricity Generation

Description: Wind turbines harness the kinetic energy of wind to produce electricity. The rotor converts the wind energy into rotational energy, which is then used in a generator to produce electricity. Onshore wind turbines are located on land in almost all kinds of locations and regions at the coast, in flat and complex terrain, in hot and cold climates, forests and deserts and are an established innovative technology, still growing in size, performance and ancillary services capabilities [34].

Modelling approach: An onshore wind technology was included as an electricity production option within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) are taken from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2030, 600 MW of additional planned wind capacity is to be connected to the grid, with an additional 1,000 MW added by 2040. Up to an additional 13,000 MW of capacity may also be added [82].

E4. Ground mount solar PV **Sector:** Electricity Generation

E5. Rooftop solar PV

Description: Photovoltaic (PV) devices convert sunlight into electrical energy. Today, the vast majority of PV modules are based on wafer-based crystalline silicon (c-Si). Solar PV technologies are already cost-competitive in regions with good resource conditions [34].

Modelling approach: Ground-mounted and rooftop-mounted solar PV technologies were included as electricity production options within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the

AEO model [82].maximum capacity and capacity additions) were derived from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2040, 2,000 MW of planned ground-mounted solar photovoltaic capacity is to be connected to the grid, and there are no specific plans to add rooftop solar capacity. Additional ground-mounted and rooftop solar may be added, but the maximum potential of these resources is sufficiently large (hundreds of gigawatts, based on [28]) that it provides no practical limit.

E6. Floating solar	**Sector:** Electricity Generation

Description: Floating PV systems are mounted on a structure that floats on the surface of a body of water – often a hydro reservoir – and can therefore benefit from the existing connection to the transmission grid. Floating PV systems benefit from an unobstructed view of the sky, and do not suffer the same sensitivities around land use and siting that ground-mounted PV projects often must negotiate [34].

Modelling approach: Floating solar PV technology was included as an electricity production option within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the AEO model [82].maximum capacity and capacity additions) were derived from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: The resource potential for Lao PDR is limited to 20% (an assumption by the modelling team) of the total solar potential, which is allocated among multiple technologies (ground-mount PV, rooftop-mount PV, CSP and floating PV). However, this means there is effectively no limit on the capacity that can be installed, based on estimated solar resource potential in the AEO model [82].However, this means there is effectively no limit on the capacity that can be installed, based on estimated solar resource potential in the AEO model [82].

E7. Concentrating solar power (CSP)	**Sector:** Electricity Generation

Description: CSP technologies use mirrors to reflect and concentrate sunlight onto a receiver. The energy from the concentrated sunlight heats a high-temperature fluid in the receiver, which can be used to drive a turbine or power an engine to generate electricity : CSP power systems can be configured in several different ways [34]:

- Solar towers use hundreds or thousands of small reflectors (called heliostats) to concentrate the sun rays on a central receiver placed atop a fixed tower. The concentrating power of the tower concept achieves very high temperatures, thereby increasing the efficiency at which heat is converted into electricity and reducing the cost of thermal storage.
- Parabolic trough systems consist of parallel rows of mirrors (reflectors) curved in one dimension to focus the sun rays. Stainless steel pipes (absorber tubes) with a selective coating serve as the heat collectors. A synthetic oil transfers the heat from the collector pipes to heat exchangers, producing superheated steam to run a steam turbine and produce electricity.

- Linear Fresnel reflectors (LFRs) approximate the parabolic shape of trough systems. They use long rows of flat or slightly curved mirrors to reflect the sun rays onto a downward-facing linear, fixed receiver.

Modelling approach: A solar CSP technology was included as an electricity production option within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the AEO model [82]. maximum capacity and capacity additions) were derived from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: The resource potential for Lao PDR is limited to 10% (an assumption by the modelling team) of the total solar potential, which is allocated among multiple technologies (ground-mount PV, rooftop-mount PV, CSP and floating PV). However, this means there is effectively no limit on the capacity that can be installed, based on estimated solar resource potential in the AEO model [82].However, this means there is effectively no limit on the capacity that can be installed, based on estimated solar resource potential in the AEO model [82].

E8. Geothermal	**Sector:** Electricity Generation

Description: Organic Rankine Cycle (ORC) geothermal power plants use a heat exchanger and secondary working fluid with a boiling point below that of water to transfer geothermal energy through. This technology generally applies to lower-temperature systems, from as low as 73-180 °C, due to the current maximum operating temperature of pumping technology. Flash steam geothermal plants (more common than ORC, comprising about two thirds of currently installed geothermal capacity worldwide) are used for higher-temperature geothermal resources in which water reservoirs have temperatures at or above 200°C. In these high-temperature reservoirs, the liquid water component boils, or flashes, as pressure drops. Separated steam is piped to a turbine to generate electricity, and remaining hot water may be flashed again at progressively lower pressures and temperatures to obtain more steam.

Modelling approach: The core AEO model included a single geothermal power generation process, which the modelling team interprets to represent geothermal flash technology. A separate geothermal ORC technology was then included as an additional electricity production option, with technical and cost assumptions derived from the [123]

Implementation level in the Lao PDR Net-zero Scenario: By 2050, up to 59 MW of geothermal capacity is connected to the grid, based on Lao PDR's 2011 Renewable Energy Development Strategy [124]). Optionally, the model may construct additional geothermal flash capacity endogenously.

E9. Biomass combustion	**Sector:** Electricity Generation
E10. Biomass gasification	
E11. Biogas digestion	
E12. Waste	

Description: These measures relate to the use of bioenergy for electricity generation, including direct combustion of biomass, gasification of biomass to produce syngas (which is then combusted to generate electricity), combustion of biogas produced from organic materials, and combustion of waste for electricity generation in waste management facilities.

Modelling approach: Biomass combustion, biomass gasification, biogas and waste technologies were all included within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the AEO model [82].maximum capacity and capacity additions) were derived from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2026, 112 MW of planned biomass combustion capacity is to be added to the grid's pre-existing 43 MW, based on feedback from the Second In-Country Workshop and assumptions in the AEO model [82]. By 2050, an additional 650 MW of biomass combustion capacity, 93 MW of biomass gasification capacity and 93 MW of biogas digestion capacity can be connected to the grid, corresponding to 70%, 10% and 10% of the total estimated biomass potential, respectively.

5.2. Generation technologies equipped with carbon capture, utilization and storage

E13. Supercritical coal with CCS	**Sector:** Electricity Generation
E14. Ultrasupercritical coal with CCS	
E15. Bioenergy with CCS	

Description: Power generation with carbon capture, utilisation and storage (CCUS, though often shortened to simply CCS) refers to a suite of technologies that involve the capture of CO_2 from power generation facilities that use either fossil fuels or biomass for fuel. If not being used on-site, the captured CO_2 is compressed and transported to be used in a range of applications, or injected into deep geological formations, including depleted oil and gas reservoirs or saline formations, which trap the CO_2 for permanent storage. Although there are a variety of CO_2 capture technologies, the most advanced and widely adopted are chemical absorption and physical separation. CCS technologies can play an important role in the transition to net-zero. Through CCS retrofits, existing fossil-fuel based power plants can continue to operate while substantially reducing their carbon footprint. Additionally, bioenergy with carbon capture and storage (BECCS) power plants can generate net removals of CO_2 from the atmosphere. By capturing CO_2 from biomass combustion after the biomass has naturally sequestered atmospheric CO_2 during its growth, BECCS can help offset emissions from the power generation or other sectors.

Modelling approach: Multiple CCS processes were modelled within the model's electricity generation module, including Bioenergy with CCS, Coal Supercritical with CCS and Coal Ultrasupercritical with CCS. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the AEO model [82]. For all CCS-equipped processes, a new pollutant called "sequestered carbon dioxide" was introduced to track the total quantity of captured CO_2. The emission factor for this pollutant represents the CO_2 capture rate, which assumes a capture efficiency in the range of 90-95%.

Implementation level in the Lao PDR Net-zero Scenario:

- Between 2035 and 2045, 1,878 MW of existing subcritical coal capacity is replaced (retrofitted) by supercritical coal with CCS (based on an assumption by the modelling team).
- Using assumptions from the AEO model, there is effectively no limit to the maximum capacity for ultrasupercritical coal with CCS that the model may add endogenously [82].
- By 2050, up to 93 MW of BECCS capacity can be connected to the grid (10% of the estimated biomass potential, based on feedback from the First In-Country Workshop, with overall biomass resource potential from the AEO model).
- Maximum capacity additions were restricted based on lead times for each technology in the AEO model [82].

5.3. Storage

E16. Lithium-ion batteries	**Sector:** Electricity Generation

Description: Integration of growing amounts of variable renewable energy will increase the need for flexibility and energy storage. Lithium-ion batteries, due to their high performance and rapidly dropping costs, are already used for many stationary applications. In the power sector, their modularity allows them to provide a range of services, from frequency regulation and ancillary services to transmission and distribution investment deferral. Key advantages compared to other technologies are high energy densities, long cycle life, and an effective and scalable manufacturing process [34].Key advantages compared to other technologies are high energy densities, long cycle life, and an effective and scalable manufacturing process [34].

Modelling approach: Lithium-ion batteries were modeled within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the AEO model [82]. maximum capacity and capacity additions) were derived from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2050, up to 1,000 MW of lithium-ion battery storage may be connected to the grid, based on feedback provided during the Second In-Country Workshop.

E17. Pumped storage hydro	**Sector:** Electricity Generation

Description: Pumped hydro storage plants store energy using two water reservoirs, one at a higher altitude than the other. Water is pumped up from the lower reservoir to the higher reservoir using electricity, converting the electrical energy into gravitational potential energy. The stored energy can be converted back into electricity by allowing the water to move from the higher to the lower reservoir, driving a turbine like a conventional hydropower station.

Pumped hydro is now a mature technology that is widely used on a commercial scale [34].Pumped hydro is now a mature technology that is widely used on a commercial scale [34].

Modelling approach: Pumped hydro was modelled within the model's electricity generation module. All technical and cost assumptions, as well as existing and planned capacities, and other capacity constraints (e.g. maximum capacity and capacity additions) were derived from the AEO model [82]. maximum capacity and capacity additions) were derived from the AEO model [82].

Implementation level in the Lao PDR Net-zero Scenario: By 2030, 1,000 MW of pumped storage is to be connected to the grid, based on feedback provided during the Second In-Country Workshop. By 2050, the modelling team assumes that up 17,471 MW of pumped storage hydro capacity can be connected to the grid (i.e., up to the maximum capacity of large hydro).

6. Other supply (S)

S1. Hydrogen production from electrolysis **Sector:** Other energy supply

Description: Hydrogen may be produced through the electrolysis of water, which uses electricity to separate the hydrogen molecule from oxygen. Electrolysis is promoted as a net-zero emissions technology because it enables the production of hydrogen from clean electricity, or may function as an energy storage medium for excess renewable electricity.

Modelling approach: The model simulates the production of gaseous hydrogen for energy purposes, which may include hydrogen from polymer electrode membrane (PEM) electrolysis as well as a number of other production pathways. Due to technical challenges, the model does not currently enforce the use of only excess renewable electricity in the PEM electrolysis process – any electricity may be used. However, in the Net-zero Scenario, the electricity grid will be sufficiently emissions-free that the modelling team does not view this as a significant methodological compromise. Transformation efficiencies for feedstocks and auxiliary energy inputs for hydrogen production are calculated from GREET's hydrogen production module [125]. Auxiliary requirements of electricity are also included, for pre-cooling and compressing the final product. Emission factors for GHGs, and CO_2 sequestration rates, are taken from GREET's Scope 1 combustion and non-combustion emission rates (ibid.). Hydrogen that is produced for non-energetic purposes, such as feedstock for fertiliser production, is not explicitly represented.

Implementation level in the Lao PDR Net-zero Scenario: The modelling team assumes that 80% of all hydrogen requirements would be met using electrolysis.

S2. Conventional hydrogen production with CCS **Sector:** Other energy supply

Description: Conventional hydrogen production processes include steam methane reforming (SMR) of natural gas, the dominant hydrogen pathway today, as well as gasification of either coal or biomass. Each of these technologies may be coupled with CCS, significantly reducing carbon dioxide emissions, or in the case of biomass gasification with CCS, potentially resulting in negative emissions.

Modelling approach: The model simulates the production of gaseous hydrogen for energy purposes, which may include hydrogen from CCS-equipped pathways. Transformation efficiencies for feedstocks and energy inputs into gaseous hydrogen are calculated from GREET's hydrogen production module [125]. Auxiliary requirements of electricity are also included, for pre-cooling and compressing the final product. Emission factors for GHGs, and CO_2 sequestration rates, are taken from GREET's Scope 1 combustion and non-combustion emission rates (ibid.). Hydrogen produced for non-energy purposes, such as feedstock for fertiliser production, is not explicitly represented.

Implementation level in the Lao PDR Net-zero Scenario: The modelling team assumes that 20% of all hydrogen requirements are met using coal gasification, which transitions to coal gasification with CCS by 2035.

S3. Biomethane production from anaerobic digestion	**Sector:** Other energy supply

Description: Biomethane is a gas generated from biomass, waste or other feedstocks, consisting of nearly pure methane (typically over 98% by volume). It is produced by upgrading biogas which is typically only 45%-75% methane [126], the remainder consisting of CO_2 and other impurities. Biomethane use can be an important net-zero technology because of its ability to substitute directly for natural gas in applications for which ordinary biogas is not appropriate. Modelling the production of biomethane is important for scenarios that include end-use consumption of biomethane.

Modelling approach: Biogas may be produced through anaerobic digestion or biomass gasification, though only anaerobic digestion of biomass is represented in the model. This is coupled with two upgrading technologies: water scrubbing (a common method of biogas upgrading requiring additional electricity inputs, represented as "Anaerobic Digestion with Upgrading" in the model) and methanation (a more efficient method of biogas upgrading requiring hydrogen, represented as "Anaerobic Digestion with Methanation" in the model). Transformation efficiencies for both processes account for the production of biogas under elevated temperature conditions (where the heat supplied is assumed to be from the combustion of the biomass feedstock, thus affecting the overall process efficiency). Emission factors for the transformation of biomass into biomethane are taken from the AEO model's representation of biogas production [82]

Implementation level in the Lao PDR Net-zero Scenario: 80% of all biomethane requirements are produced by using water scrubbing technologies to upgrade biogas produced from anaerobic digesters. The remaining 20% is produced by upgrading the biogas through methanation. Assumptions were based on a proposal by the modelling team, validated by stakeholders during the Second In-Country Workshop.

S4. Biogas production from anaerobic digestion	Sector: Other energy supply

Description: This measure refers to the production of biogas from organic materials through the anaerobic digestion process. Biogas that is produced is mainly used for cooking in households.

Modelling approach: The production of domestic biogas was modelled in a dedicated transformation module on the supply side of the model. This module simulates small-scale anaerobic digestion of biomass to produce biogas, composed of 60% methane and 40% other gases. The methane fraction and GHG emission factors were sourced from a methodological tool produced by the UNFCCC [127]. The efficiency of converting biomass to biogas, primarily from animal waste, was based on IRENA [128].

Implementation level in the Lao PDR Net-zero Scenario: 100% of all domestic biogas requirements are met by anaerobic digesters based on a proposal by the modelling team and validated by stakeholders during the Second In-Country Workshop.

S5. Biodiesel production from FAME	Sector: Other energy supply

Description: Production of biodiesel from fatty acid methyl esters (FAME), which can be blended with fossil diesel at rates of up to 20% by volume.

Modelling approach: The model considers the blending of biodiesel from FAME with ordinary diesel up to 20% by volume. Biodiesel production process efficiency was calculated from GREET1 [125], accounting for the production of oil from palm fresh fruit bunches (3.4 dry lb/lb palm oil), as well as methanol inputs required for transesterification (945 BTU/lb finished biodiesel). The modelling team assumes that 1 GJ of energy contained in palm oil energy can be used to produce 1 GJ of finished renewable diesel. Any energy to mass conversions are performed offline, using fuel densities of 15.5 GJ/tonne biomass and 43.33 GJ/tonne biodiesel taken from the AEO model.

Auxiliary energy use for the following fuels was calculated from GREET1 (ibid.), and includes fuels used for palm oil production and biodiesel production through transesterification:

- Natural Gas: 460 BTU/lb biodiesel produced
- Electricity: 43 BTU/lb palm oil produced, plus 55 BTU/lb biodiesel produced
- Biodiesel: 37 BTU/lb palm oil produced. Note GREET1 specifies diesel (not biodiesel), but the modelling team assumes this fuel requirement could be met from the process' output fuel.

The emission factors for each fuel (feedstock or auxiliary) were derived from the AEO model [82] with the following assumptions:

- Natural Gas: Combusted in a boiler, and assumed to produce the same emissions as would be found for industrial consumption of natural gas.
- Biodiesel: Combusted in a boiler, and assumed to produce the same emissions as would be found for industrial consumption of biodiesel.

Implementation level in the Lao PDR Net-zero Scenario: The modelling team assumes that 100% of B20 biodiesel requirements are met using FAME biodiesel.

S6. Biodiesel production from HVO **Sector:** Other energy supply

Description: Production of renewable diesel from hydrotreated vegetable oil (HVO), which can be blended with fossil diesel at rates of up to 100% by volume without modification to equipment. HVO renewable diesel is a sustainable aviation fuel, which can be blended up to 50% with jet kerosene.

Modelling approach: The model considers the blending of biodiesel from HVO with ordinary diesel to up to 100% by volume. Production process efficiency was calculated from GREET1 [125]. It accounts for the production of oil from palm fresh fruit bunches (3.4 dry lb/lb palm oil), as well as hydrogen inputs required for hydrotreating (1550 BTU/ lb finished renewable diesel). The modelling team assumes 1.51 GJ of energy contained in palm oil energy can be used to produce 1 GJ of finished renewable diesel. Any energy to mass conversions are performed offline, using fuel densities of 15.5 GJ/tonne biomass and 43.33 GJ/tonne biodiesel taken from the AEO model.

Auxiliary energy use for the following fuels was calculated from GREET1 (ibid.) and includes fuels used for palm oil production and biodiesel production through transesterification:

- Electricity: 43 BTU/lb palm oil produced, plus 133 BTU/lb renewable diesel produced
- Biodiesel: 37 BTU/lb palm oil produced. Note GREET1 specifies diesel (not biodiesel), but SEI assumes this fuel requirement could be met from the process' output fuel.

The emission factors for each fuel (feedstock or auxiliary) were derived from the AEO model [82], assuming biodiesel combusted in a boiler, and assumed to produce the same emissions as would be found for industrial consumption of biodiesel.

Implementation level in the Lao PDR Net-zero Scenario: For the Lao PDR Net-Zero Scenario, the modelling team assumes all biodiesel requirements beyond those needed to meet B20 demands, as well as all sustainable aviation fuel requirements, would be met using renewable diesel production from HVO.

S7. Ammonia and methanol production from hydrogen **Sector:** Other energy supply

Description: Ammonia (NH_3) and methanol (often abbreviated MeOH) are commonly produced chemicals that are used as feedstocks for other chemical industries. Ammonia is a key ingredient in the production of fertiliser, making it one of the most commonly produced industrial chemicals in the world. However, both NH_3 and MeOH can be used as an energy carrier, and have been consumed as fuels typically for heavy-duty transport and maritime shipping.

Modelling approach: As industrially-produced chemicals, it is possible that the energetic inputs needed to produce both NH_3 and MeOH may already be represented within the AEO model's industrial demand sector. However, the output of these chemical products is not modelled explicitly, if they are not later consumed for energy purposes. Therefore, the modelling team creates a distinction between NH_3 and MeOH produced explicitly for energy-related purposes and models these production pathways using dedicated energy supply modules. These modules produce NH_3 from hydrogen using an energy efficiency of 87.2%, based on [129], with auxiliary electricity consumption (for separating N_2 from the ambient air) of 0.15 GJ/GJ of NH_3 produced (ibid.). MeOH is produced from hydrogen using an energy efficiency of 80.0%, based on [130], with auxiliary electricity use of 0.04 GJ/GJ of hydrogen consumed (ibid.). In both cases, the additional hydrogen and electricity requirements are met using the model's upstream hydrogen and electricity production modules.

Implementation level in the Lao PDR Net-zero Scenario: All (100%) of the ammonia and methanol requirements, which arise from the consumption of these fuels in key demand sectors, are satisfied using a single production pathway transforming hydrogen into the desired output.

Appendix C: Net Zero Implementation Roadmap for Lao PDR

Demand-Side Intervention Roadmap

Short-term (2025-2030)

- Residential
  - 94.3% of households have clean cooking access.
  - 3% energy intensity reduction of cooling, water heating and lighting.
- Commercial
  - 20% of commercial cooking transitions to LPG.
  - 100% of lit commercial floorspace uses LED lighting.
- Transport
  - Introduce SAF to reach 8%.
  - Introduce biodiesel (B20) and bioethanol (E15) blends.
  - EVs contribute 30% of passenger-km and 30% of freight-km.
  - Fuel economy improvement for ICE vehicles by 1%/year.
- Industry
  - Increase technology capacity to introduce electrification, hydrogen and biomethane boilers.

Medium-term (2030-2040)

- Residential
  - •Transition from the current average air conditioning technology to a more efficient heat pump cooling.
- Commercial
  - 95% of total water heating needs made up by solar water heaters.
  - Phase-out wood consumption for cooking.
  - 90% of commercial floor space uses more efficient refrigerators.
- Transport
  - Improved aviation energy intensity reaching 2.28%/year.
- Industry
  - Introducing hydrogen displacement of coal and gas

Long-term (2040-2050)

- Residential
  - 28% of homes will use air-conditioning with the best-available energy efficient heat pump appliances.
  - Use of reflective coatings, programmable thermostat and optimal building orientation.
  - 15.6% of homes are equipped with domestic solar/heat pump water heating.
- Commercial
  - 90% of cooled commercial floor space uses the best available heat pump technology, while the remainder of cooling is provided by efficient technology.
  - 50% of all commercial floorspace uses electric induction technologies. Conventional electric cooking technologies make up the remainder of cooking needs, reaching a peak of 41% of cooking in 2040 before declining to 30% by 2050.
- Transport
  - 50% SAF by 2050
  - 30% of energy needs for domestic and international aviation met by hydrogen fuel cells.
  - Biomethane accounts for 10% of bus passenger-kilometres and 10% of freight truck tonne-kilometres.
  - 80% of passenger vehicles are EVs
  - 20% of private passenger-km FCEV by 2050.
  - 5% of tonne-kilometres on road freight transport made up by hydrogen-based ICE trucks
- Industry
  - CO2 capture and utilisation (100% in iron and steel production).
  - 90% of all industrial process heat requirements are proportionally met by electricity, biomass, biomethane, while remainder made up by hydrogen.
  - Remaining coal and gas consumptions is displaced by hydrogen.
  - DACs for helping to reduce non-energy sector emission.

Supply-Side Intervention Roadmap

Short-term (2025-2030)

- **Electricity Generation & Storage**
  - 19 GW of electricity generation from hydropower.
  - Installed capacity to have 50% share from renewable energy (solar, wind, geothermal and biomass)
  - Introduce and develop 1600 MW pumped hydro storage.
- **Other Energy Supply**
  - Introduce hydrogen production using electrolysis from hydropower.
  - Develop biodiesel production from FAME

Medium-term (2030-2040)

- **Electricity Generation & Storage**
  - CCS in coal power generation reaches 50% of the total coal power plant installed capacity.
- **Other Energy Supply**
  - 20% of all hydrogen requirements are met using coal gasification
  - Expand production of renewable diesel from HVO

Long-term (2040-2050)

- **Electricity Generation & Storage**
  - Deployment of bioenergy with CCS (BECCS) projects.
  - Increase uptake of CCS for coal/phase down coal.
- **Other Energy Supply**
  - 80% of all hydrogen requirements are met using electrolysis from renewable energy
  - All energy-related ammonia and methanol requirements are met using hydrogen as a feedstock.

In Memoriam: Taylor Binnington

It is with profound sorrow that we honour the memory of Taylor Binnington, who passed away in Vermont, US, on 8 March 2025. As a dedicated partner of the ASEAN Centre for Energy (ACE) through the Stockholm Environment Institute (SEI), Taylor made invaluable contributions to ASEAN's energy transition through his work across multiple editions of the ASEAN Energy Outlook.

Taylor played a key role in developing An Energy Sector Roadmap to Net-zero Emissions for Lao PDR working closely with ACE and the stakeholders in Lao PDR. More than a scientist, he was a mentor and a teacher, generously sharing his knowledge through workshops in Lao PDR and with the ACE team. His ability to explain complex modelling with clarity and patience left a deep impression on those who had the opportunity to learn from him.

Taylor was not only brilliant in his field, but also a person of great humility and kindness. He was a thoughtful collaborator who approached his work with sincerity, always willing to offer support. His presence brought a sense of camaraderie to every project, and his commitment to a sustainable energy future was evident in all that he did. Above all, he was a true friend.

His work will continue to inspire us as we move forward in advancing sustainable energy transitions in the ASEAN region. Our thoughts and deepest condolences go out to his family, colleagues and all who had the privilege of knowing him.

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This report is a product of the ASEAN Climate Change and Energy Project II (ACCEPT II)

ACCEPT II is a continuation of ACCEPT Phase 1 that was successfully accomplished on 31 March 2022. The commencement of the 48-month project officially began on 1 November 2022. This collaborative project between the ASEAN Centre for Energy (ACE) and the Norwegian Institute of International Affairs (NUPI) is funded by the Norwegian Government, under the Norwegian-ASEAN Regional Integration Programme (NARIP). The project aims to support ASEAN member states and ASEAN's capacity to transition to Low-Carbon Energy System and contribute to carbon neutrality or a net zero future.

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