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Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050

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HIGHLIGHTS

- The assessment of ASEAN power sector pathways to net-zero emissions by 2050.
- The NEMO optimization framework of LEAP is used to integrate variable renewable energy.
- Timely utilization of ASEAN's vast renewable energy resources is a key to achieving net-zero.
- GHG emissions of the ASEAN power sector peak in 2029 and reach zero by 2050.
- The net-zero power sector scenario involves an abatement cost of 12 USD/ton CO2e.

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ABSTRACT

The power sector is one of the major contributors to global greenhouse gas emissions while also being vulnerable to climate change in its own right. Accordingly, the global power sector needs to accelerate decarbonization. This paper assesses power sector pathways to net-zero emissions by 2050 for the Association of Southeast Asia Nations (ASEAN) using the Low Emissions Analysis Platform (LEAP). In addition to simulating a net-zero emissions scenario, the paper builds reference and renewable policy scenarios, enabling an analysis of additional measures required beyond the business as usual and current policy trajectories to achieve net-zero emissions. The LEAP simulation results indicate that under the net-zero emissions scenario, ASEAN member states need to swiftly capitalize on their currently underutilized renewable energy potential to reach net-zero emissions by 2050. By then, there will have to be a substantial transformation of the technological portfolio with variable renewable energy and energy storage coming to play central roles. The LEAP simulations also indicate that renewable and energy storage technologies are more cost-competitive than carbon capture and storage for achieving the long-term net-zero emissions goal. In the LEAP modeling, GHG emissions rise until they peak in 2029, then gradually decline until reaching zero by 2050. Meanwhile, the emission abatement cost is 16 USD/ton CO_2e in the renewable policy scenario and 12 USD/CO_2e in the net-zero emissions scenario.

1. Introduction

In 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report showing that the world needs to reach net-zero emissions by around 2050 if global warming is to be limited to 1.5 °C in accordance with the Paris Agreement [1]. As of September 2021, 55 countries had responded by pledging national net-zero emissions targets. Two of them, Bhutan and Suriname, have achieved their targets, 12 of them enshrined their commitments in national law, and the rest put their targets in policy documents [2]. In addition, 21% of the world's 2,000 largest public companies have committed to net-zero emissions

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Nomenclature

ASEAN	Association of Southeast Asia Nations
LEAP	Low Emissions Analysis Platform
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
NEMO	Next Energy Modelling System for Optimization
REF	Reference scenario
RET	Renewable energy target scenario
NZE	Net-zero emissions scenario
PDP	Power Development Plan
PV	Photovoltaic
USC	Ultra-Supercritical
NGCC	Natural Gas Combine Cycle
NGOC	Natural Gas Open Cycle
HPS	Hydro Pumped Storage
CCS	Carbon Capture and Storage
NGCCS	Natural Gas with CCS
BECCS	Bioenergy with CCS

[3].

This article analyzes the Association of Southeast Asia Nations (ASEAN) power sector pathway toward net-zero emissions in 2050. The ASEAN member states comprise Brunei, Cambodia, Indonesia, Lao People's Democratic Republic (PDR), Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. In 2018, the ASEAN energy sector contributed 1.4 gigatons (Gt) of carbon dioxide (CO_2) emissions [4], constituting 4% of the global energy-related CO_2 emissions in the same year. ASEAN is home to more than 661 million people [5] and is one of the fastest-growing economic regions in the world [4]. Yet, ASEAN average electricity consumption per capita is still only 1,560 kW-hours (kWh), less than half of the global average of 3,300 kWh in 2018 [6]. This implies that electricity demand in ASEAN will continue to increase in the next decade. Accordingly, the International Energy Agency (IEA) projected a rise in ASEAN energy-related CO_2 emissions to 2.4 Gt in 2040, 71% higher than the 2018-level. On the other hand, Southeast Asia is one of the most vulnerable regions to climate change [7,8]. Thus, it makes sense to see the ASEAN low-carbon pathway not only as a luxury imposed by the Paris Agreement but also as a necessity given the unprecedented impacts of climate change posed to the region itself.

We assess the ASEAN power sector net-zero pathway using the Low Emissions Analysis Platform (LEAP) software developed by the Stockholm Environment Institute. LEAP has been adopted by thousands of organizations in more than 190 countries worldwide [9], and has been used in 85 country reports under the United Nations Framework Convention on Climate Change (UNFCCC) and more than 70 peer-reviewed journals papers [10]. Despite its widespread use, there is still a scarcity of publications that use the most recent LEAP capability for simulating energy storage. In this study, we utilize the Next Energy Modelling System for Optimization (NEMO) framework, which allows for the analysis of the role of energy storage and the development of robust climate change planning responses. We developed two other scenarios besides the net-zero emissions scenario, namely the reference scenario and the renewable energy target scenario. Thus, the net-zero pathway analysis includes a comparison with the reference and existing policy trajectory pathways, revealing additional measures required beyond the reference and current policies for the ASEAN power sector to achieve net-zero emissions by 2050.

This article makes two main contributions to the literature. Firstly, to the best of our knowledge, this is the first time the ASEAN power sector pathway for net-zero emissions has been analyzed. We use country-specific data and model the net-zero pathway for each of the 10 ASEAN member states, zooming in on the level of individual technologies. Subsequently, we consolidate the results at the ASEAN level. Secondly, we include an analysis of grid integration of variable renewable energy and the role of energy storage using the NEMO optimization framework, which facilitates energy storage capacity addition endogenously. This adds to the current publications using the LEAP methodological framework, allowing more robust climate mitigation policy modeling. Moreover, the methodological approach and the incorporation of energy storage in the modeling can be replicated for similar assessments in other regions or countries. Furthermore, this study involves a unique dataset on each ASEAN country, enabling a bottom-up, technological level analysis of the ASEAN power sector. Thus, this article provides a detailed overview of the current state and outlook of the ASEAN power sector in terms of technology mix, electricity generation, GHG emissions, and cost implications of different power sector development pathways.

The remaining portions of this paper proceed as follows: Section 2 elaborates on the ASEAN power sector context and existing literature modeling the low-carbon pathways of the ASEAN power sector. Section 3 describes the simulation scenarios, LEAP modeling methodology, and input data. Section 4 discusses the LEAP modeling results and analyzes the significance of the findings. Finally, Section 5 summarizes the findings, discusses the study's limitations, and offers suggestions for future research.

2. Literature review

2.1. Overview of the ASEAN power sector

Driven by rapid economic growth and urbanization, ASEAN electricity demand grew at an average rate of 6.3% between 2008 and 2018 [11]. The region has relied on fossil fuels to meet the growing demand. In 2020, fossil fuels made up 78% of the ASEAN electricity mix, shared between coal (44%), natural gas (32%), and oil (2%) (Fig. 1a)[1]. Hydropower accounted for 16% of the electricity mix while other renewables supplied only 6% of the region's electricity.

The region's GHG emissions in 2020 reached 668 million tons CO_2e[2] (Fig. 1b). Coal contributed 72% of the carbon emissions, followed by natural gas (26%), and oil (2%). Comparing the ASEAN member states, the five largest contributors of GHG emissions were Indonesia (32.2%), Vietnam (18.8%), Malaysia (16.7%), Thailand (14%), and The Philippines (10.5%). The other five countries only accounted for less than 8% of the ASEAN power sector emissions in 2020, with Brunei being the smallest contributor.

The ASEAN member states have committed to reducing their GHG emissions under the Paris Agreement. Their Nationally Determined Contributions (NDCs) include strategies to increase renewable energy capacity. Table 1 summarizes the national renewable energy targets of each ASEAN country. Southeast Asia is blessed with vast renewable energy resources. Yet, they are currently underutilized. According to a study conducted by the National Renewable Energy Laboratory [12], the ASEAN countries have an abundant potential for utility-scale, land-based wind and solar photovoltaic (PV) power development. Southeast Asia's total solar PV and wind power technical potential is 29,967 GW-peak (GWp) and 1,383 GWp, respectively. Besides solar and wind potentials, all ASEAN member states except for Singapore have hydropower resources (Table 2). Biomass potential is also present in eight Southeast Asian countries, above all Indonesia.

Currently, most ASEAN power systems are managed under a single-buyer market structure. Only the Philippines and Singapore have competitive wholesale electricity markets [26]. In the single-buyer system, independent power producers were created to share the

[1] Consolidated from [11,45,46,61–63].

[2] Calculated using IPCC tier-1 emission factor embedded in LEAP

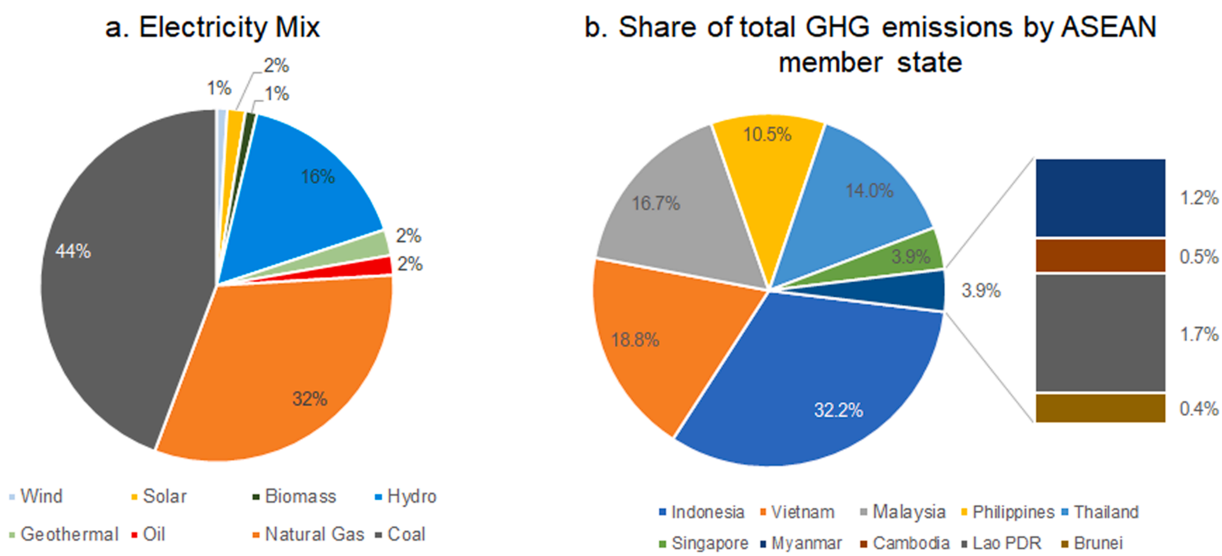

Fig. 1. ASEAN electricity generation mix and GHG emissions shares in 2020.

Table 1
Renewable energy targets by ASEAN country.

Country	Renewable energy target	Source
Brunei	10% renewable energy share in installed power generation capacity by 2035	6th ASEAN Energy Outlook [11]
Cambodia	3% of residential electricity demand from solar PV by 2035	6th ASEAN Energy Outlook [11]
Indonesia	23% renewable energy share by 2025	Government Regulation No 79/2014: National Energy Policy [13]
Lao PDR	30% renewable energy share of total energy consumption by 2025, including 20% of electricity from renewable energy that is not large-scale hydro	Vision 2030 and 5-year power development plan (2016–2020) [14,15]
Malaysia	31% by 2025, 40% in 2035, including large hydro	Report on Peninsular Malaysia Generation Development Plan 2020 (2021 – 2039) [16]
Myanmar	12% share of RE in national power generation mix by 2030 (excluding large-scale hydro)	National Energy Master Plan (2015) [17]
Philippines	Triple RE installed capacity by 2030 from 2010 level to 15.3 GW from 5.4 GW	National Renewable Energy Program (NREP) 2011: Sectoral Plans and Roadmap [18]
Singapore	350 MWp of solar capacity by 2020 and at least 2 GWp by 2030	Sustainable Singapore Blueprint 2015 Singapore's Energy Story [19]
Thailand	30% RE share in total final energy consumption (TFEC) by 2036, including 15–20% renewable electricity in total generation	Alternative Energy Development Plan (AEDP) 2015 [20]
Vietnam	32% RE share in power generation by 2030 and 43% by 2050	Vietnam's Renewable Energy Development Strategy up to 2030 with an outlook to 2050 (Decision 2068/QD) [21,22]

financial burden of the power sector and promote competition. The mechanism was intended to increase power sector efficiencies and reduce electricity prices. By contrast, the liberalization of markets in the Philippines and Singapore was meant to ensure transparency, fair grid access, and attract a sufficient number of market players to achieve efficiency. The ASEAN member states are also diverse in terms of size, population, and development levels [11]. Despite various national contexts, grid interconnections have been built between some ASEAN countries, including Cambodia, Indonesia, Lao PDR, Malaysia,

Table 2
Renewable energy resources of the ASEAN countries, GW.

ASEAN member states	Biomass [23,24]	Hydro [23]	Geothermal [23,25]	Wind [12]	Solar PV[12]
Brunei	–	0.07	–	0.02	16
Cambodia	–	10.00	–	69.00	3 198
Indonesia	32.60	75.00	29.50	50.00	1 052
Lao PDR	1.20	26.00	0.05	13.00	1 278
Malaysia	0.60	29.00	–	2.00	1 965
Myanmar	0.99	40.40	–	482.00	7 717
Philippines	0.24	10.50	4.00	217.00	1 910
Singapore	–	–	–	0.02	2
Thailand	2.50	15.00	–	239.00	10 538
Vietnam	0.56	35.00	0.34	311.00	2 847

Singapore, Thailand, and Vietnam with 35 terawatt-hours (TWh) of power exchanged in 2019 alone [11]. Most of the interconnectors are between Thailand and its neighbors.

2.2. Studies on modeling low-carbon ASEAN power sector

Energy and climate policy modeling is receiving increasing attention in the ASEAN region. Huber et al. [24] employ the URBS-ASEAN linear optimization model to simulate capacity and hourly dispatch of generation, transmission, and storage. The study involves a scenario for lowering the carbon intensity of the ASEAN power sector starting from a base level of 250 g/kwh to 0 g/kwh and indicates the technology mix and cost for each carbon intensity level. Despite its early consideration of zero-emission, even before the signing of the Paris Agreement, the study only simulates one year, i.e., 2050, and lacks analysis of the pathways towards 2050. Thus, the trajectory of technological change to achieve zero emissions by 2050 remains unexplored. The most recent modeling study is the 6th ASEAN Energy Outlook, which provides four scenarios for the ASEAN power sector until 2040 [11]. That study uses the LEAP accounting framework to analyze the four ASEAN pathways in terms of power capacity, electricity generation, and GHG emissions. The first scenario is a baseline scenario, and the three other scenarios are alternative scenarios, following national, regional, and global climate policy trajectories. However, a scenario for a net-zero emissions pathway of the ASEAN power sector was not included in the study. Moreover, the study lacks an analysis of the cost of capacity expansion, which is crucial for a comprehensive analysis of different capacity expansion pathways.

Other studies focus on one or a few ASEAN power systems. Handayani et al. [10] assess the plausible trade-offs between the objectives of electrification and climate change mitigation in the context of the Indonesian power sector. The study utilizes LEAP to investigate the implications of those objectives for costs, technology deployment, and GHG emissions across several scenarios. Misila et al. [27] also employ LEAP to examine the potential for reducing GHG emissions by utilizing renewable energy and increasing energy efficiency from 2015 to 2050. The findings include the potential for domestic renewable energy and energy efficiency measures to contribute to Thailand's NDC. Nong et al. [28] employ the GTAP-E-Power model to examine the impact on the Vietnamese economy of additional taxes on coal and petroleum which were proposed as a part of the Vietnamese climate policy strategy. The results indicate that a higher fossil fuel tax would foster the expansion of renewable energy. On the other hand, it would also cause a decline in Vietnam's GDP. Haiges et al [29] evaluate the Malaysian 2050 power sector pathway, following a set of three technology-based scenarios. The paper uses The Integrated Market Allocation-Energy Flow Optimisation Model System (TIMES) to analyze electricity demand, capacity, electricity generation, costs, and CO_2 emissions. Mondal et al. [30] also employ TIMES to assess low-carbon strategies for the Philippines' power sector from 2014 to 2040. The strategies are covered in four scenarios: carbon tax, renewable energy target, reduction of coal, and subsidy for renewables. Meanwhile, Maliq [31] investigates the potential of renewable energy sources to meet the power demand for water heating in Brunei using Hybrid Optimization of Multiple Energy Resources software.

All the studies mentioned above address energy and climate change policies in various contexts within ASEAN and assess their implications for the power sector using modeling software. While these studies show how climate policy drives the transition to a low-carbon power sector, none has included a long-term analysis of a net-zero pathway scenario. Moreover, the three studies that used LEAP have not utilized the Next Energy Modelling System for Optimization (NEMO), which was recently added to LEAP to enable simulations of storage capacity. Therefore, a study on the ASEAN pathway to net-zero emissions utilizing LEAP with the NEMO optimization framework can contribute to the development of modeling methodology, a better understanding of the innovations required to achieve the 1.5 °C Paris Agreement target as well as improved understanding of the outlook and exigencies of one of the world's fastest-growing power sectors.

3. Methodology and data

3.1. Scenario development

The main objective of this study is to analyze the pathways for the ASEAN power sector from 2021 to 2050, taking into consideration the Paris Agreement goal. We develop three scenarios: a reference scenario, a renewable energy scenario, and a net-zero emission scenario.

Reference scenario (REF): This scenario assumes the continuation of each ASEAN member state's current electricity generation technology portfolio in the expansion of the power sector during the period 2021–2050. This scenario serves as the reference when assessing the impacts of the two alternative scenarios on the technology mix, costs, and GHG emissions. This scenario involves the following assumptions:

- Deployment of technology is limited to conventional technologies that were already used on a large scale before 2020, mainly coal-fired power plants and natural gas combined cycle power plants.
- Renewable capacity expansion is limited to the currently employed technologies in each ASEAN country.
- There is no limitation in terms of domestic fossil fuel uses.
- No specific target is set for renewable energy deployment.

Renewable Energy Scenario (RET): This scenario follows the ASEAN member states' renewable energy targets and is in line with their respective NDCs and power development plans (PDPs). This scenario includes the following characteristics:

- The capacity expansion aims to achieve the renewable energy target of each ASEAN country (Table 1). Thus, the renewable energy targets function as constraints for the models.
- The types of technology considered for future capacity expansion include ultra-supercritical (USC) coal, natural gas combined cycle (NGCC), natural gas open cycle (NGOC), diesel, hydro, mini-hydro, geothermal, wind, biomass, solar PV, nuclear, hydro pumped storage (HPS) and Li-ion battery.
- Renewable capacity expansions are constrained by their availability in each ASEAN country (Table 2)
- LEAP chooses the types of technology to be deployed based on costs (least-cost optimization) and the set objectives.

Net Zero Emissions Scenario (NZE): In this scenario, the ASEAN power sector goes beyond the current NDC commitments, aiming at net-zero emissions by 2050. The main characteristics of this scenario include:

- GHG emissions must be net-zero by 2050.
- Types of technology considered for future capacity expansion include ultra-supercritical coal (USC coal), natural gas combined cycle (NGCC), natural gas open cycle (NGOC), diesel, hydro, mini-hydro, geothermal, wind, biomass, solar PV, nuclear, coal with carbon capture and storage (CCS), natural gas with CCS (NGCCS), bioenergy with CCS (BECCS), hydro pumped storage (HPS) and Li-ion battery.
- Renewable, BECCS, and HPS deployments are constrained by their technical potentials (Table 2)

3.2. Modeling with LEAP

LEAP is equipped with the essential features needed for this study. Firstly, LEAP's "scenario manager" permits simulations of several pathways for expanding the power system based on different assumptions. Secondly, LEAP can run both accounting and least-cost optimization modeling of power system expansion, giving the flexibility to use different approaches to model the set scenarios. Finally, LEAP modeling outputs include features required for this study, among others capacity mix, electricity generation mix, total costs, and GHG emissions.

One shortcoming of LEAP is that it does not account for transmission and distribution infrastructure expansion. As a result, the power system expansion simulation in this article assumes that electricity can be transmitted to any load station at any time and neglects transmission and distribution network constraints. Transmission capacity and spatial analysis of each power plant and substation would require additional modeling.

The LEAP methodology for the ASEAN power sector is illustrated in Fig. 2. Input Parameters include electricity demand, technical, economic, and environmental parameters, and a set of constraints. Electricity supply simulations are carried out for the three scenarios, utilizing the accounting framework for the REF scenario and the

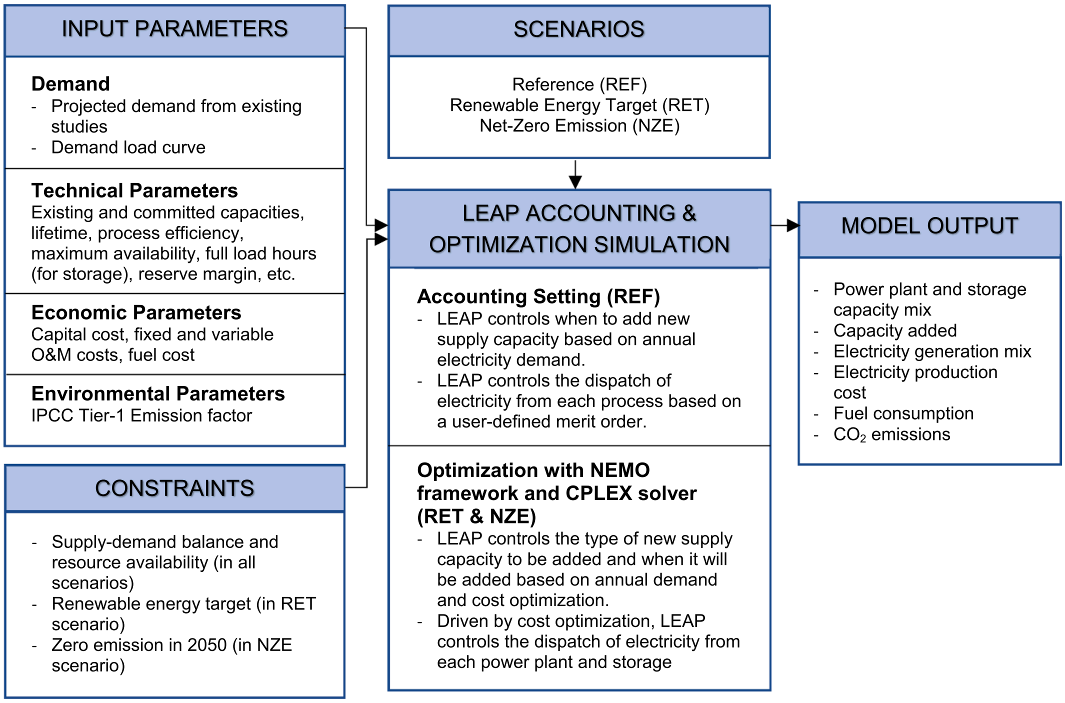

Fig. 2. LEAP methodology.

optimization framework for the RET and NZE scenarios. The electricity supply simulation should satisfy the projected electricity demand for each year, taking into account energy resource availability, especially for renewable energy. We run LEAP simulations for each ASEAN country and consolidate the results at the regional level. Due to data and methodological limitations for simulating the grid interconnection between countries, it is assumed that, aside from the existing and committed capacity for electricity import and export, there will be no additional power exchange between ASEAN countries.

3.2.1. Demand projection

The demand for electricity in this study is calculated using the demand growth projections stipulated in existing studies. Thus, the electricity demand in a given year is the sum of the previous year's demand plus the anticipated growth (Eq. (1)). Next, the total electricity demand in the power system of each ASEAN country for a specific year is calculated as the sum of electricity demanded and electricity losses during the transmission and distribution process in the same year (Eq. (2) and Eq. (3))

$$ED_t = (ED_{t-1} \times EDG_t) + ED_{t-1} \tag{1}$$

where ED_t is the electricity demand in year t, and EDG_t is the percentage of growth in the electricity demand in year t.

$$TED_t = ED_t + EL_t \tag{2}$$

where TED_t is the total electricity demand in year t, and EL_t is the electricity losses of transmission and distribution networks.

$$EL_t = ED_t \times TL_t \tag{3}$$

where TL_t is the percentage of transmission and distribution losses in year t.

3.2.2. Electricity supply simulation

LEAP simulates the three scenarios based on various input parameters. The accounting setting simulates the power system expansion needed to meet the future electricity demand, regardless of costs. We use this setting when modeling the reference scenario, which simulates the continuation of the base year's power generation mix without least-cost consideration. On the other hand, the optimization setting enables the construction of least-cost capacity expansion models and electricity dispatch in a power system under various constraints. We utilize this setting for simulating alternative scenarios, while constraining the simulation with, among others, a minimum share of renewable electricity being targeted by each ASEAN country.

When using the optimization setting in LEAP, the optimal solution is defined as the power system with the lowest total net present value of all costs over the whole computation period, from the base year to the end year (Eq. (4)). This setting operates through integration with an optimization framework, which relies on a solver software tool for developing decision optimization models. Handayani et al. [32] describe detailed descriptions of LEAP. This study extends the work of Handayani et al. [32] by incorporating NEMO, an open-source, high-performance energy system optimization program that was recently added to LEAP. NEMO simulates an energy system with perfect foresight using least-cost optimization. This essentially means that it strives to meet electricity demand over time at the lowest possible cost. Cost minimization is performed concurrently for all modeled time periods, and all costs are discounted to the start of the simulation [33]. Costs can include investment costs, fixed and variable operation and maintenance costs, and fuel costs (see Eq. (4)).

$$TC = \sum_{t}^{N_t} \sum_{p} \frac{1}{(1+d)^t} (Cc \times Ca_t + foc_t \times Ca_t + Voc_t \times P_t + Fc_t) \tag{4}$$

where TC is the total cost, N_t denotes the total years from 2021 through to 2050, p is the power generation technology, d is the discount rate, Cc is the initial capital cost, Ca_t is the capacity in year t, foc_t is the fixed operation and maintenance costs in year t, Voc_t is the variable operation and maintenance costs in year t, P_t is the output power in year t, and Fc_t is the fuel cost in year t.

NEMO is a high-performance, open-source modeling tool for energy system optimization developed in the Julia programming language. The key features of NEMO that are relevant for this study include the least-cost optimization of energy supply and demand; its ability to model renewable energy targets, and most importantly, its capability to simulate energy storage while taking variable renewable energy operation profiles into account. Thus, it enables robust climate change planning and an analysis of the role of energy storage [33].

The energy storage simulation is based upon the daily patterns of electricity demand in each country versus the maximum availability of each power generation technology. The maximum availability of a generation technology is the ratio of the maximum energy produced to what would have been produced if the process ran at full capacity for a given period (expressed as a percentage). Therefore, for a robust simulation of the needed storage capacity in our model, we use a demand load curve to represent the daily demand pattern, which was derived from the historical average daily load with monthly variations, consisting of 288-time slices of a year, as shown in Appendix A. On the supply side, the maximum availability of solar PV is represented by an availability curve that shows the daily variations of solar PV's availability per month, which was derived from historical data [34].

NEMO can use multiple solvers, including GLPK, Cbc, CPLEX, Gurobi, and Mosek [9]. Because of the complexities of the simulations in this study, we employ CPLEX optimizer, a high-performance mathematical programming solver software developed by IBM, to work with NEMO instead of using the LEAP built-in solver kit.

3.2.3. GHG emission calculation

GHG emissions from electricity production include carbon dioxide, nitrous oxide, and methane, which are calculated based on the IPCC Tier-1 emission factors embedded in LEAP.

$$CE = \sum_{p}\sum_{f} EF_{f,p} \times \frac{1}{E_p} \times P_p \tag{5}$$

where CE is the GHG emissions, $EF_{f,p}$ is the GHG emission factor from one unit of primary fuel type f consumed for producing electricity through technology p, E_p is the efficiency of technology p, and P_p is the output power from technology p.

Table 3
Summary of model input parameters.

Input Data	Value	Source
Annual demand growth	1% – 8%	Referred to PDPs [15,25] and 6th ASEAN Energy Outlook estimates [11]
Transm. and distrib. losses	2% – 20%	Referred to PDPs [35,36,37,38,39,40,41] and the World Bank [42]
Reserve margin	25% – 35%	Referred to PDPs [5,7–10,41] and ASEAN Interconnection Masterplan Study III [43]
Load curve	See Appendix A	[43,61]
Existing capacity and retirement	See Appendix B	Referred to ASEAN country statistics [44,45,46,47], PDPs [15,37,38,41], and 6th ASEAN Energy Outlook [11]
Environmental parameter	Per technology	IPCC tier-1 emission factor [9]
Discount rate	4.3% – 18.3 %	[48]
Inflation rate	0.6% – 9.2 %	[49]

3.3. Input data and assumption

We carried out LEAP simulations for each ASEAN country, treating a country as a power system with specific country-driven data and assumptions. We collected country-specific data from various resources, including ASEAN member states' PDPs and power statistics, and data from ASEAN Energy Outlook 6, as summarized in Table 3. Therefore, this study characterizes the actual situation of ASEAN member states rather than relying on the LEAP default data, enabling a robust policy projection. We relied on the literature and publicly available data banks to obtain statistics that are currently unavailable in the ASEAN member states, including the technological characteristics of new technology such as a Li-ion battery.

Electricity demand was calculated using the demand growth projections specified in the ASEAN member states' PDPs when available, complemented with the projection of the 6th ASEAN Energy Outlook [11]. The electricity demand growth projections in the mentioned studies have not yet included specific targets/assumptions of the electric vehicle penetration nor increased industrial electrification and their effect on future electricity demand. Additionally, we included the impact of Covid-19 on the electricity demand in the base year based on national data and assumptions.

Most of the power system data, i.e., transmission and distribution losses, reserve margin, and energy load curve were taken from ASEAN countries' PDPs, supplemented with the ASEAN Interconnection Masterplan Study III data and World Bank DataBank. The latter source also provided data on interest and inflation rates. The energy load curve for each country's power system was derived based on hourly load data, represented by 288 time-slices of a year. This level of detail enables the simulation of energy storage required to balance the variable renewable energy.

The technical data accuracy of existing power plants is essential for a reliable base year representation. To address this concern, we obtained the data from ASEAN member states' energy statistics and PDPs, complemented with data from the 6th ASEAN Energy Outlook, which include capacity, planned retirement, process efficiency, historical production, and capacity factor. We utilized the technology and environmental database embedded in LEAP for the environmental parameter, which provides the IPCC tier-1 emission factors for different fuels.

This study includes 16 technologies that are potentially added for the expansion of the ASEAN power system, namely: Ultra Super Critical Coal (USC coal), Natural Gas Combined Cycle (NGCC), Natural Gas Open Cycle (NGOC), diesel, geothermal, hydro, mini-hydro, biomass, wind, solar photovoltaic (solar PV), nuclear, coal with CCS (coal CCS), natural gas combined cycle with CCS (NGCCS), bioenergy with CCS (BECCS), Li-ion battery, and hydro pumped storage (HPS). New technologies, i.e., nuclear and CCS were included in the simulation starting from 2035. As shown in Table 4, the technological characteristics data represent specific country data where available, with additional regional and international level data when country-specific data is unavailable. The capital cost data considered the cost change over time due to technological learning and were inputted exogenously into the LEAP. We assume that the entire renewable energy potential (Table 2) can be utilized over the horizon of the study period with no constraints.

4. ASEAN decarbonization pathways: LEAP results

ASEAN electricity demand is projected to reach 3,323 TWh by 2050, more than threefold the electricity demand in 2020 (Fig. 3a). ASEAN electricity consumption goes 3,948 kWh/capita by 2050. Combined, Indonesia and Vietnam have 58% of the total ASEAN electricity demand in 2050 while Cambodia and the Philippines see the highest and second-highest electricity demand growth, respectively.

Accordingly, our simulation using LEAP estimates total electricity generation of 3,715 TWh across the ASEAN countries will be required to satisfy the demand in 2050 (Fig. 3b). Thus, ASEAN electricity generation

Table 4
Characteristics of technologies.

Technology	Lifetime (years)[a]	Efficiency (%)[b]	Maximum availability (%)[c]	Capacity credit (%)[**]	Capital cost (USD/MW)[d]	Fixed OM cost (USD/MW)[e]	Variable OM cost (USD/MWh)[f]	Fuel cost (USD)[g]
USC coal	30	42	80	100	1 520–1 900	56.6	0.11	2–4 per MMBTU
NGCC	30	56	85	100	690–1 200	23.5	2.30	7–11.7 per MMBTU
NGOC	30	33	92	100	770–1 100	23.2	1.00	7–11.7 per MMBTU
Diesel	30	45	95	100	800	8.0	6.40	0.6 per Liter
Hydro	50	100	36	51	1 450–2 080	37.7	0.65	–
Mini Hydro	50	100	76	58	2 400–2 700	53.0	0.50	–
HPS	50	80	90	25	860	8.0	1.30	–
Geothermal	30	15	90	100	2 497–4 000	50.0	0.25	–
Solar PV	25	100	17.7	22	1 190–2 000	14.4	0.00	–
Wind	27	100	28	35	1 500–2 550	60.0	0.00	–
Biomass	25	31	80	100	2 000–2 300	47.6	3.00	1.3–3.5 per MMBTU
Nuclear	40	33	85	100	6 000	164.0	8.60	9.3 per MWh
Coal CCS	30	34	80	100	3 470	98.4	3.21	2–4 per MMBTU
NGCCS	30	48	80	100	1 840	32.5	3.50	7–11.7 per MMBTU
BECCS	20	30	90	100	5 453	64.0	8.00	1.3–3.5 per MMBTU
Li-ion Battery	20	94	17	22	2 002	7.6	2.30	–

[**] Capacity credit in LEAP is defined as the fraction of the rated capacity being used in the calculation of the reserve margin. The values are calculated based on the ratio of availability of the intermittent plant to the availability of a standard thermal plant [9].
[a] [50,51].
[b] [50,64].
[c] [65,53,52].
[d,e,f] [50,64,53,43,66,54].
[g] [43,56,67].

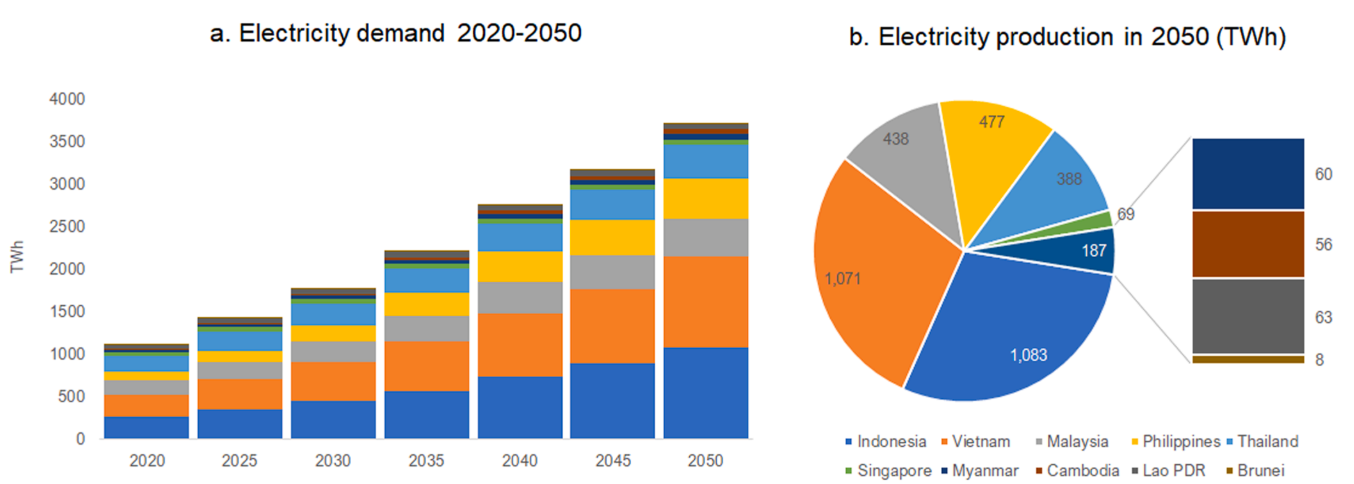

Fig. 3. Projected ASEAN electricity demand and supply.

represents 7% of the global electricity generation projected by the IEA [57]. The following sections discuss the outlook of future ASEAN power sector expansion based on the three scenarios. Meanwhile, a summary of results for each country is presented in Appendix C.

4.1. Reference scenario

Under the reference scenario, which assumes the continuation of the base year technology portfolio and ignores current ASEAN climate mitigation policy and the Paris Agreement 1.5 °C goal, fossil fuel-based power plants remain dominant throughout the study period. The total capacity in 2050 reaches 927 GW, dominated by coal and natural gas, which together with oil constitute 62% of the capacity mix, leaving a 38% share for renewables (Fig. 4a). Vietnam has the largest installed capacity in ASEAN, 306.3 GW, followed by Indonesia (243.6 GW), the Philippines (120.7 GW), Thailand (94.2 GW), Malaysia (94 GW), and the remaining 68.2 GW is shared between Myanmar, Cambodia, Singapore, Lao PDR, and Brunei.

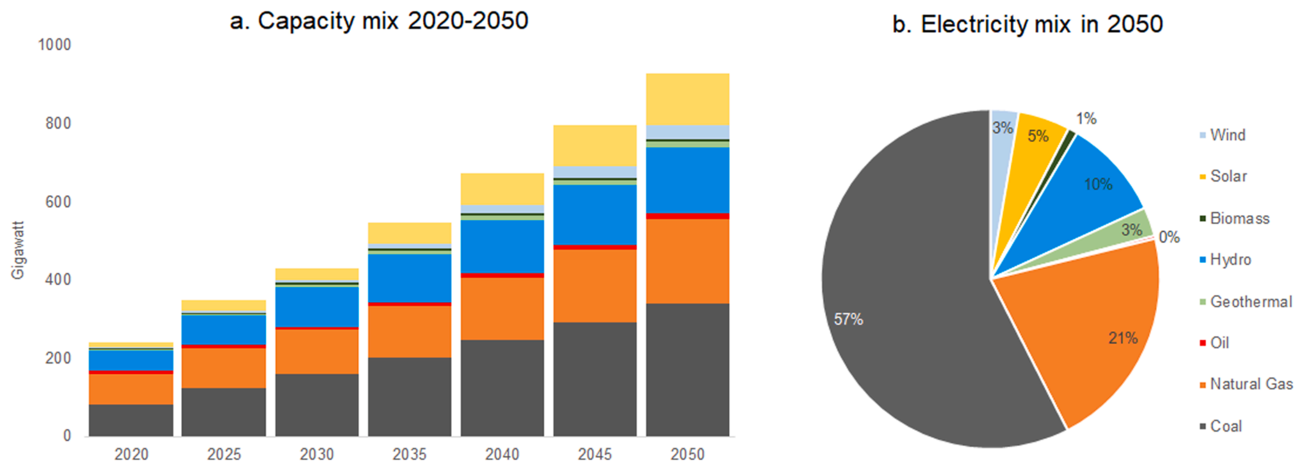

Fig. 4. Installed capacity and electricity generation mix in the REF scenario.

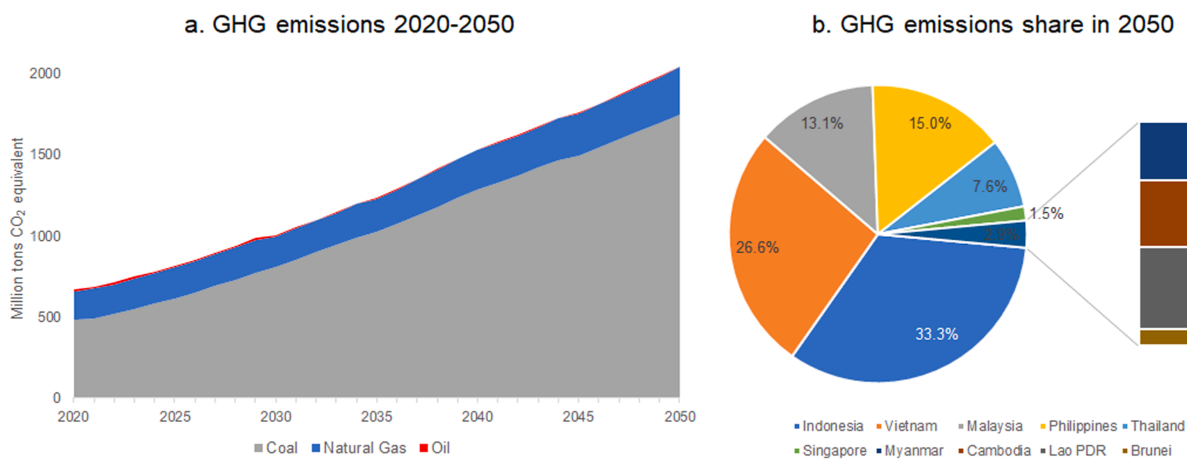

Fig. 5. GHG emissions in the REF scenario.

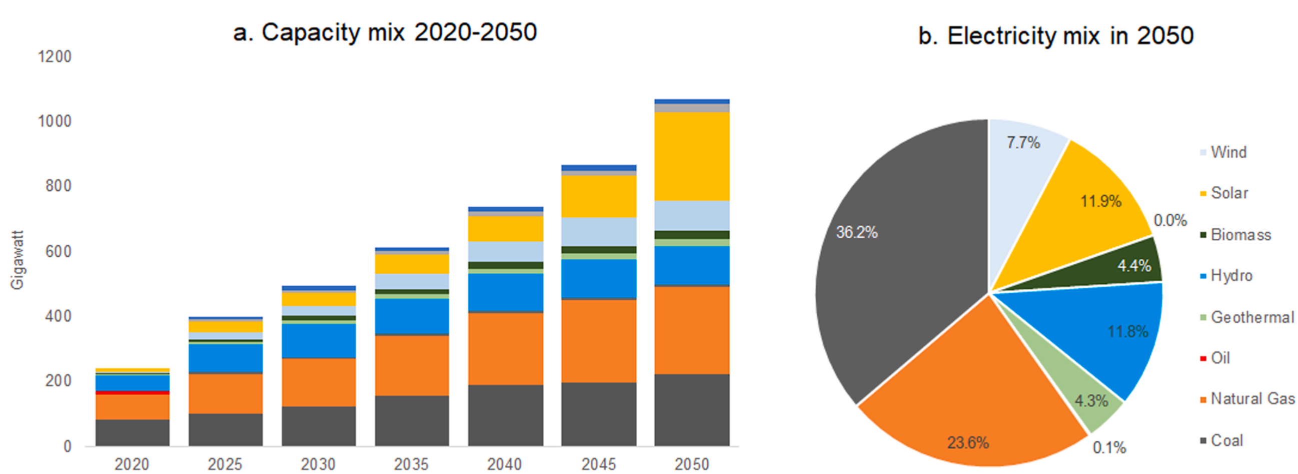

Fig. 6. Installed capacity and electricity generation mix in the RET scenario.

By 2050, electricity generation from coal rises more than four-fold from 492 TWh in 2020 to 2,055 TWh in 2050 (Fig. 4b). Coal contributes 57% of the ASEAN electricity mix, followed by natural gas, which accounts for 21% of the total electricity generation in the same year. Meanwhile, renewable energy constitutes 22% of the electricity mix, shared between hydro (10%), solar (5%), geothermal (3%), wind (3%), and biomass (1%). All ASEAN countries, except Singapore, generate hydropower. Meanwhile, the solar generation share is mainly attributed to Vietnam, assuming the constant growth from the 2020 capacity throughout the study period.

Between 2020 and 2050, GHG emissions more than triple, from 668 million tons CO_2e to 2,044 million tons CO_2e (Fig. 5a). Together, Indonesia and Vietnam contribute more than 60% of ASEAN power sector emissions in 2050 while Brunei, Cambodia, and Myanmar each generate less than 1% of the total emissions (Fig. 5b). Most of the CO_2 emissions (85%) are attributed to coal, while gas contributes 14% and oil less than 1% of the total CO_2 emissions. The total GHG emissions in the REF scenario is our baseline for calculating GHG emissions reductions in the two other scenarios and subsequently determining the corresponding GHG mitigation costs.

4.2. Renewable energy target scenario

The results of the LEAP simulations for the RET scenario indicate a significant alteration of the technology mix throughout the study period, following the current ASEAN member state policies of increasing renewable capacity. By 2050, coal capacity amounted to 222 GW, 35% lower than in the REF scenario (Fig. 6a). Thus, coal contributes 21% of the capacity mix while natural gas accounts for 25%. Meanwhile, renewable capacity reaches 531GW, 47% higher than in REF, and constitutes 50% of the total capacity in 2050. The renewable capacity consists of 271 GW solar PV, 121 GW hydro, 94 GW wind, 24 GW biomass, and 21 GW geothermal. Vietnam contributes 60% (317 GW) of ASEAN renewable capacity owing to its ambitious power development plan.

In the RET scenario, energy storage emerges to balance the variable renewable energy. By 2050, total storage capacity reaches 41.8 GW, comprising hydro pumped storage (15.8 GW) and Li-ion battery (26 GW).

Concerning electricity generation, in 2030, which is a target year for nearly half the renewable energy targets of the ASEAN countries, the share of renewable electricity generation increases to 35% from only 22% in 2020. Vietnam achieves the largest national renewable electricity share (nearly 51%), following the ambitious renewable capacity in the Vietnamese new draft PDP published in 2021 [47]. Looking further to 2050, the ASEAN renewable electricity generation increase to 1,466 TWh, comprising more than 40% of the total electricity generation (Fig. 6b). Solar and hydro lead with 11.9% and 11.8% shares, respectively, followed by wind (7.7%), biomass (4.4%), and geothermal (4.3%). The share of coal electricity generation reduces to 36.2% from 44% in 2020.

The GHG emissions in this scenario increase at a lower rate compared to REF. By 2050, GHG emissions reach 1,416 million tons CO_2e, 31% lower than that in REF (Fig. 7a). Coal still becomes the largest contributor of CO_2 emissions (76%) although its emissions share is 9% lower than that in the REF scenario. Indonesia remains the highest contributor of ASEAN GHG emissions while Vietnam's share drops to 14%, below both Malaysia and the Philippines (Fig. 7b).

4.3. Net-zero emission scenario

In the NZE scenario, installed capacity rises to 2,092 GW by 2050, more than double the REF scenario (Fig. 8a). This is because, in the NZE scenario, 81% of the capacity is comprised of variable renewable energy, which has lower capacity utilization than fossil fuels and thus requires more capacity to be installed. Solar PV together with energy storage represents 78% of total installed capacity in 2050, wind 10%, hydro 8%, biomass 2%, geothermal 1%, and nuclear 0.2%. The capacity mix of each country is shown in Appendix D.

To balance the variable renewable energy, a total of 156 GW energy storage capacity is added along the study period. Most of the storage capacities are deployed in Indonesia, Vietnam, the Philippines, Malaysia, and Thailand. All renewable technical potential in the ASEAN member states is sufficient to achieve zero emissions by 2050 except for Singapore, which needs to add nuclear due to a lack of renewable energy potential. Aside from nuclear, other options for Singapore could be importing renewable electricity from neighboring countries or deploying CCS and using carbon credits to offset residual emissions.

Electricity generation from fossil fuels decreases gradually and reaches zero by 2050. By contrast, renewable electricity generation increases sixteen-fold from 247 TWh in 2020 to 3,696 TWh in 2050. Renewables constitute 99.5% of the electricity generation in 2050 while the remaining 0.5% are attributed to nuclear. Solar leads with 61% share in the electricity mix, followed by wind (17%). This is because solar has the greatest resource potential across the ASEAN countries (Fig. 8b). While the majority of the countries rely on solar PV to reach net-zero emissions, Myanmar, Cambodia, and Lao PDR rely mainly on hydropower, which accounts for 80%, 77%, and 64% of their 2050 electricity

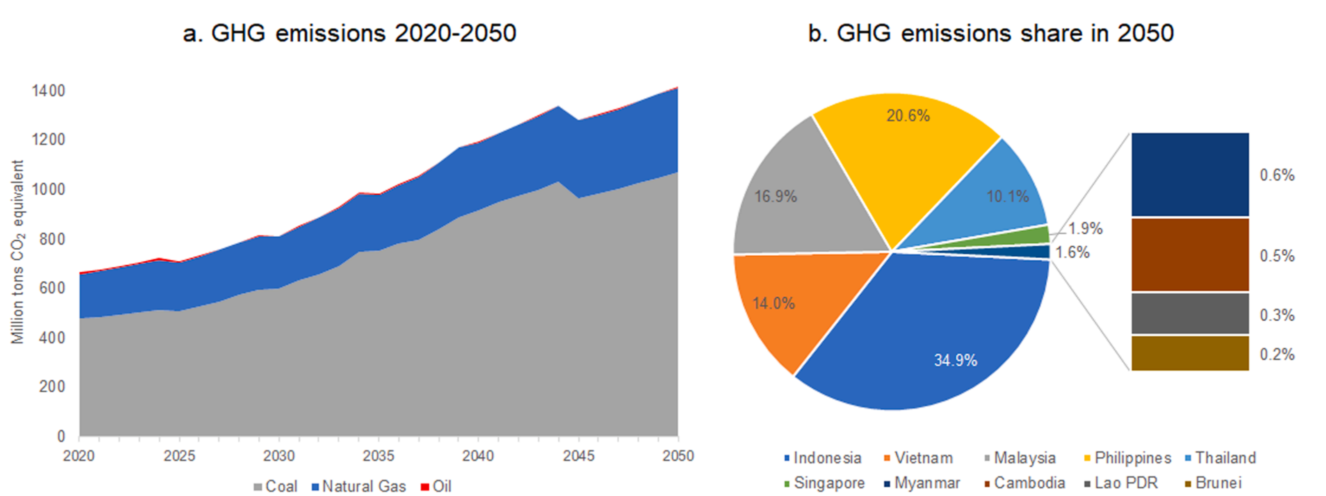

Fig. 7. GHG emissions in the RET scenario.

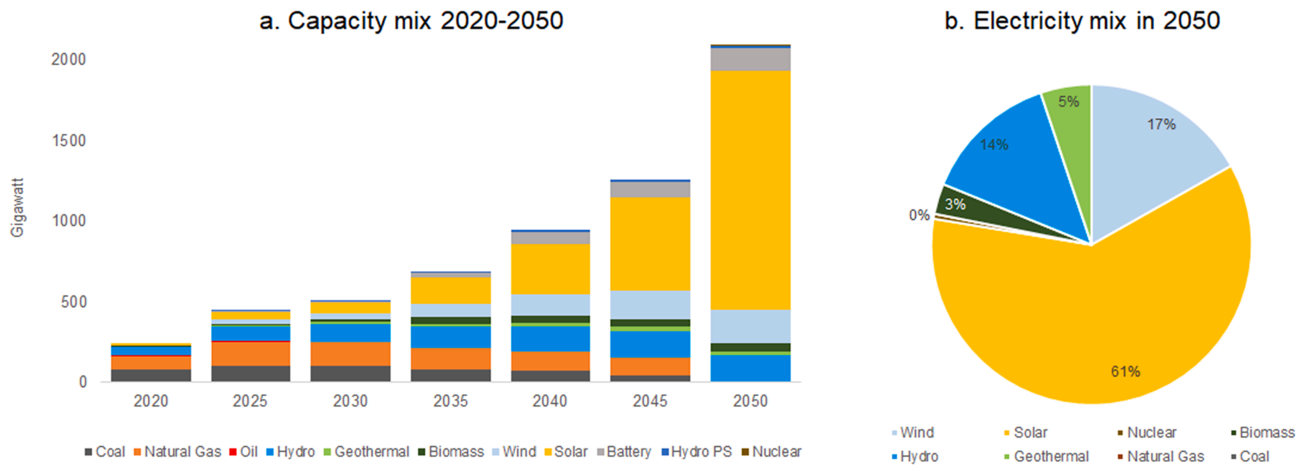

Fig. 8. Installed capacity and electricity generation mix in the NZE scenario.

mixes, respectively (see Appendix E).

4.3.1. The role of technology

The LEAP optimization simulations include 14 power generation and two energy storage technologies for ASEAN power sector expansion technology candidates. Existing renewable technologies such as hydro and biomass are favorable in terms of costs compared to other renewable technologies. However, their potentials are limited, needing additional capacity of variable renewables, which are still undermined in the base year's technology mix. Variable renewable energy, especially solar, plays a significant role in the future ASEAN power sector, owing to its vast technical potential. Furthermore, solar PV has the fastest learning rate among other renewable technologies. Thus, solar PV is the only viable option after all other renewable potentials have been utilized.

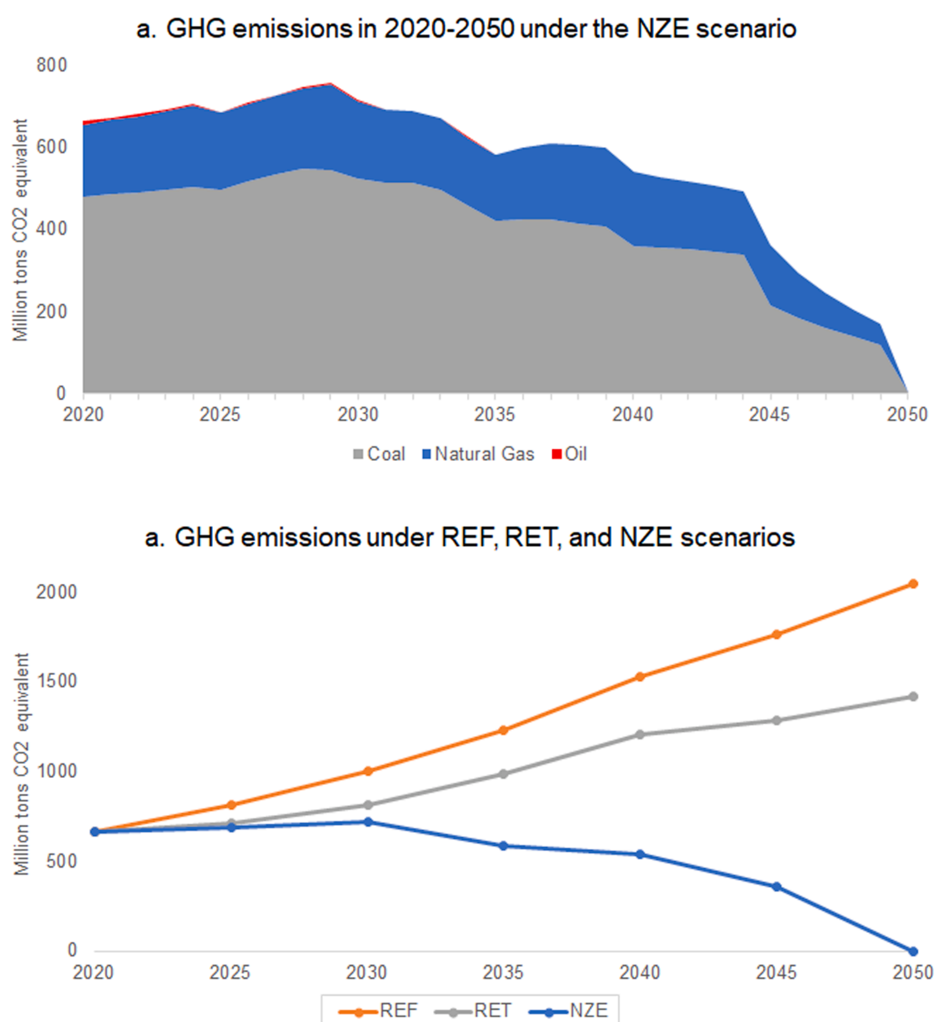

Fig. 9. GHG Emissions.

Energy storage technologies are primarily deployed to balance the variable renewable energy while the role of nuclear remains negligible for the ASEAN countries. Energy storage is less crucial in countries with a high share of hydropower such as Cambodia, Lao PDR, and Myanmar. Meanwhile, hydro pumped storage comes to play a role in Indonesia and Vietnam, which have been identified as having the greatest potential for this form of energy storage. These results indicate that deploying variable renewable energy in combination with energy storage is more financially attractive than deploying nuclear, which has a negative learning rate and uncertain construction period [58]. Nuclear only appears in Singapore's future technology mix due to the country's shortage of renewable energy potentials. However, Singapore could also opt to import clean energy from its neighboring countries. In this context, the ASEAN Power Grid role is critical to realizing the net-zero ASEAN power system.

Since the potential for hydro pumped storage is limited, battery storage is expected to play a critical role. Nevertheless, to date, Li-ion batteries are still expensive despite notable cost declines in recent years. Furthermore, Li-on is not recommended for long-term storage because the charge they hold dissipates over time [50]. Thus, technological learning curves for battery storage are keys for the long-term energy transition. Furthermore, hydro pumped storage potentials in countries other than Indonesia and Vietnam need to be explored considering the critical role of energy storage in the transition to the net-zero ASEAN power sector.

Another interesting finding of our simulations is the absence of GHG removal technology, i.e., CCS, for meeting the NZE target, despite allowing them in the simulation starting from 2035. Aside from being expensive, neither coal CCS nor NGCCS can eliminate all GHG emissions, necessitating negative emission technology such as BECCS to supplement them. Yet, the deployment of BECCS is constrained by the limited bioenergy potential in ASEAN member states. Our analysis shows that only Indonesia has a sufficient bioenergy potential for the deployment of BECSS to offset residual emissions from NGCCS. Yet, our simulation for Indonesia shows that deploying NGCCS in combination with BECCS entails higher costs than simply exploiting the renewable energy potential.

New construction of coal and natural gas power plants has to be avoided under the net-zero pathway as both types of power plant has a 30-year technical lifetime, while they should be retired before the end of their technical lifetime and become a financial burden for the power sector. Currently, coal and natural gas power plants are under construction in ASEAN member states or have been committed to being constructed. In our simulation, these power plants are forced to retire by 2050.

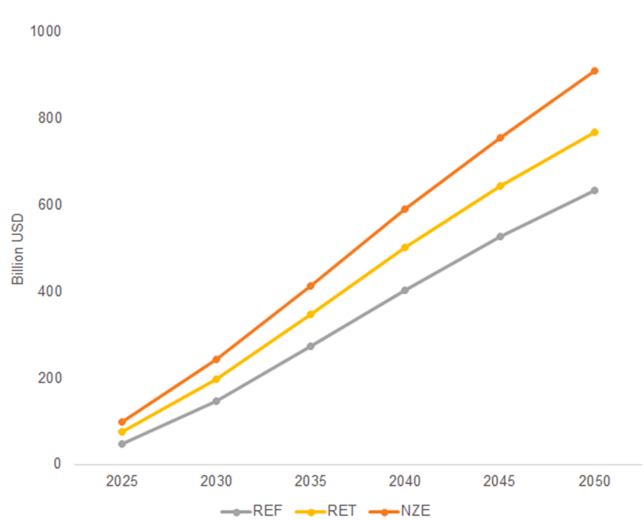

Fig. 10. Capacity expansion costs in REF, RET, and NZE scenarios.

Table 5
GHG mitigation costs.

Scenario	Cumulative GHG reduction 2021–2050 (million tons CO_2e)	GHG mitigation costs (billion US $)	Cost-effectiveness of GHG mitigation (US $/t$CO_2$e)
RET	8,358	134	16
NZE	22,534	277	12

4.3.2. *GHG emissions*

GHG emissions in the ASEAN power sector are mainly attributed to coal (Fig. 9a). In 2020, GHG emissions from coal accounted for 480 million tons CO_2e, or 71% of the total GHG emissions. Meanwhile, natural gas and oil constitute 176 million and 12 million tons CO_2e, respectively. GHG emissions decrease gradually during 2030 – 2050, following the gradual retirement of fossil fuel-based power plants.

Under the NZE scenario, the net-zero emission target is achieved by 2050 across ASEAN member states, primarily by halting the new construction of fossil fuels and switching to renewables. GHG emissions continue to rise from 668 million tons CO_2e in 2020, peaking at 759 million tons CO_2e in 2029 (Fig. 9b). Starting from 2030, GHG emissions decrease gradually, reaching zero by 2050. Moreover, as much as 2,044 million tons of CO_2e GHG emissions are to be avoided by 2050, which would otherwise be emitted if ASEAN member states continue the base year's technology portfolio. The GHG emissions profile for each ASEAN country is shown in Appendix F.

The LEAP modeling results indicate that the ASEAN power sector can reach net-zero solely by exploiting the region's abundant renewable energy potentials and nuclear, without needing carbon offset from other sectors.

4.3.3. *Costs of meeting the Paris climate goal*

We compare the total costs of capacity expansion for the three scenarios in Fig. 10. The total costs accounted for 633, 767, and 910 billion USD, respectively, under REF, RET, and NZE scenarios. It is worth noting that in Indonesia and Singapore, the RET scenario yields lower total costs compared to the REF scenario (see Appendix G). This indicates that the shift to a low-carbon power system is not only driven by the Paris Agreement. Instead, it is a realistic option given the declining cost of renewable energy technologies, which renders them more competitive in the long run compared to fossil fuels. It is worth mentioning that the costs of early retirement of fossil fuel-based power plants have not been included in the cost estimates due to methodological limitations. Thus, the total costs of the NZE scenario would have been higher if these costs were included.

Table 5 illustrates the GHG mitigation costs in RET and NZE scenarios. The mitigation costs are the difference between total costs in each alternative scenario compared to the reference scenario. The RET scenario and the NZE scenario require 134 billion USD and 277 billion USD incremental costs, respectively. We further calculated the cost-effectiveness of GHG mitigation in the two alternative scenarios by dividing the GHG mitigation costs by the cumulative GHG reduction throughout 2021–2050. The results indicate the cost-effectiveness of GHG reductions of 16 USD/ton CO_2e in the RET scenario and 12 USD/ton CO_2e in the NZE scenario. These values can be used as indications when determining the carbon price in ASEAN.

5. Conclusions

As one of the world's fastest-growing economic blocs, ASEAN contributes to increasing global GHG emissions while it is also more vulnerable to the impacts of climate change than most parts of the world. The primary goal of this article has been to assess the pathway of the ASEAN power sector toward net-zero emissions by 2050. This is the first study to analyze an ASEAN power sector's net-zero pathway to the best of our knowledge. On the methodological side, this study adds to the existing LEAP-based literature by employing the NEMO optimization framework. This enables endogenous energy storage capacity addition needed for variable renewable energy integration into the grid. We used a unique dataset on the power systems and resources of the ASEAN member states and carried out LEAP simulations for three scenarios for the period from 2021 to 2050. The reference scenario (REF) assumes continuing the base year's technology portfolio (business as usual) throughout the study period. The renewable energy target scenario (RET) analyzes the power system expansion to meet renewable energy policy targets of the ASEAN member states. Finally, the net-zero emissions scenario (NZE) assesses the power system expansion pathway beyond both the business as usual trajectory and the current policy targets.

The LEAP simulation for the net-zero pathway of the ASEAN power sector produced several findings. Firstly, the ASEAN power sector can reach net-zero emissions in 2050 by utilizing its abundant renewable energy potential. From a technological standpoint, solar PV plays a critical role in reaching the ASEAN net-zero emissions as it is the only viable option after all other renewable energy potentials have been utilized. Likewise, energy storage deployment becomes a necessity to balance the high penetration of variable renewable energy. Secondly, GHG emissions should peak before 2030 if net-zero emissions are to be realized by 2050. In that case, no construction of new fossil fuel-based power plants can be allowed starting from 2021 onwards. Finally, the NZE pathway entails higher total costs compared to RET, let alone to REF. However, the GHG abatement cost per ton of CO_2e under NZE is lower than that under RET. It is also worth noting that this does not take into account the climate change externalities in the form of the costs that will be brought by climate change, which will be particularly high for the ASEAN countries.

Concerning new technology, nuclear was found to be uneconomical and only adopted in Singapore due to the country's lack of renewable energy sources. However, Singapore could instead import electricity from the other ASEAN member states or hydrogen from more remote countries like Australia, which has published a vision for commercial renewable hydrogen by 2030 and set the target for hydrogen production at below $2 per kilogram [59]. CCS technology was also found to be uneconomical. Hence it does not appear in the technology mix although it was competed with other technologies in the LEAP simulation starting from 2035. Another concern with CCS is that it cannot eliminate all GHG emissions, necessitating carbon offsets from negative emission technologies such as BECCS or carbon offsets from other sectors. The former requires a significant amount of bioenergy—with knock-on effects for biodiversity and food supply—whereas the latter adds the cost of purchasing carbon credits.

Given the critical role of energy storage for the transition to net-zero, ASEAN should accelerate the adoption of energy storage to take benefit from technological learning. As a starting point, ASEAN could enhance studies on hydro pumped storage potentials in the region. Moreover, it could also take the lead in the research and development of energy storage considering the abundant potential of variable renewable energy resources. Indonesia has started by establishing Indonesia Battery Corporation, which can be emulated in other ASEAN countries. On the other hand, Vietnam has demonstrated leadership in the deployment of solar PV, reaching 16,5 GW by the end of 2020. Furthermore, the country's most recent draft PDP includes massive variable renewable energy development, resulting in the country having the highest share of non-hydro renewable energy in its national electricity mix among other ASEAN member states by 2030.

Meanwhile, Cambodia, Lao PDR, and Myanmar exploit their hydro potentials to realizing net-zero emissions by 2050. Hydro potentials of these countries are nearly sufficient to meet their future electricity demand, which constitutes only 4% of total ASEAN electricity demand in 2050.

Despite its important findings, this study has some limitations. First, the electricity demand projections in this study do not include the target/assumptions about the electrification of other sectors, which could have a significant impact on our analysis. This is an area for future research to analyze various demand scenarios, including the penetration rate of electric vehicles and the increased rate of industrial electrification.

On the supply side, this study does not include transmission and distribution simulations, nor does it consider constraints in transmission and distribution networks. Future studies could take into consideration the transmission and distribution investments required to realize net-zero emissions in the ASEAN power sector.

The study also does not take into consideration the possibility of additional power exchange between the ASEAN countries. An analysis of the net-zero ASEAN power sector pathway, taking into account increased interconnectivity between the grids of the ASEAN countries is a direction for future work and could change the picture substantially as far as the need for energy storage is concerned.

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CRediT authorship contribution statement

Kamia Handayani: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Pinto Anugrah:** Methodology, Formal analysis, Resources. **Fadjar Goembira:** Conceptualization, Resources. **Indra Overland:** Conceptualization, Writing – review & editing. **Beni Suryadi:** Conceptualization, Funding acquisition. **Akbar Swandaru:** Conceptualization, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

See Fig. A1.

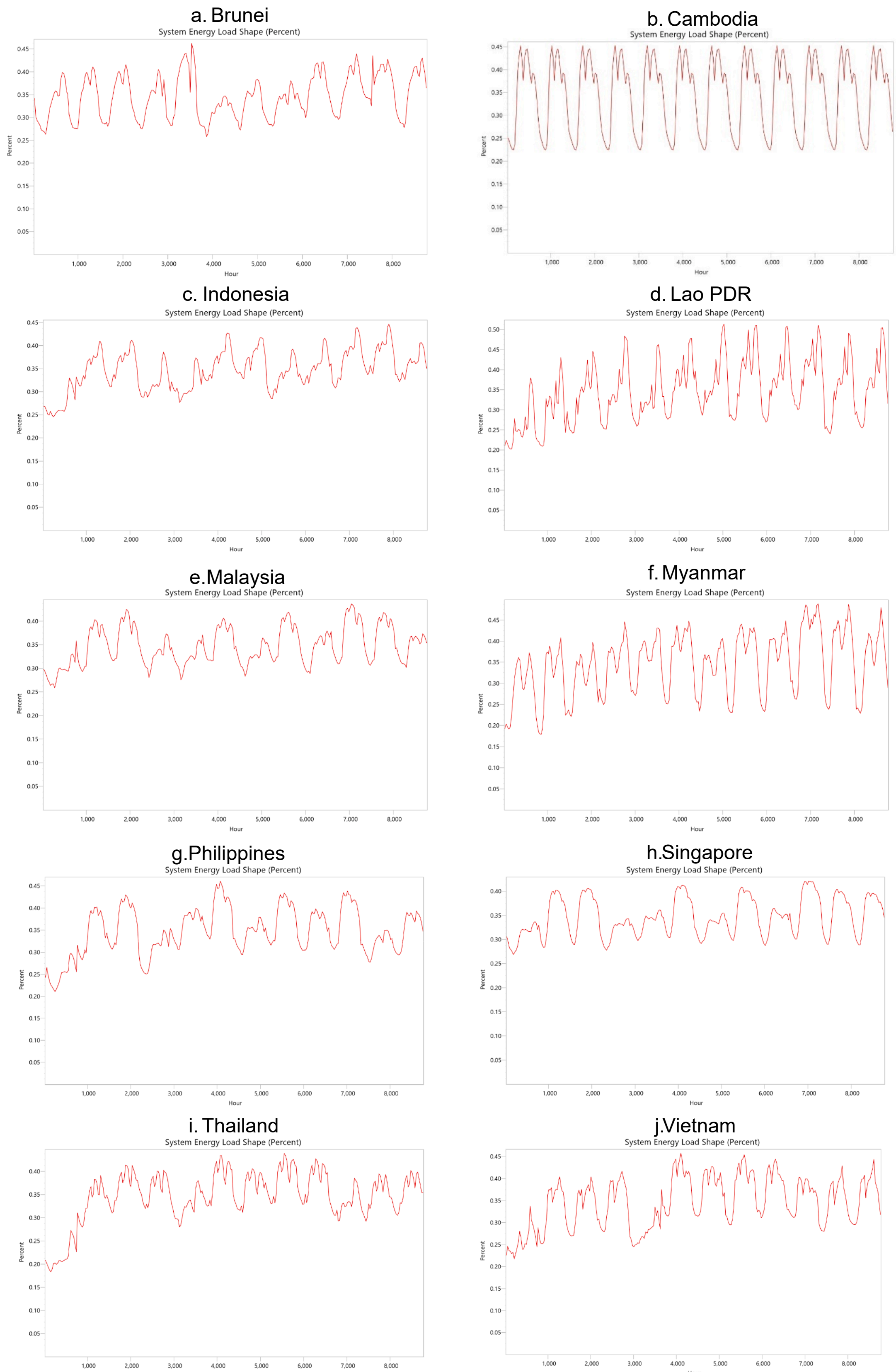


Fig. A1. System energy load shape [43,60].

Appendix B

See Table B1.

Table B1
Existing capacity of the ASEAN power system.

Power plants	Net capacity (GW)
Coal	82.1
Natural gas	77.9
Diesel	9.5
Geothermal	3.8
Hydro	48.9
Biomass	3.1
Solar	11.2
Wind	3.8
Total	240.3

Sources: [11,15,35,36,39,42,43,44,45].

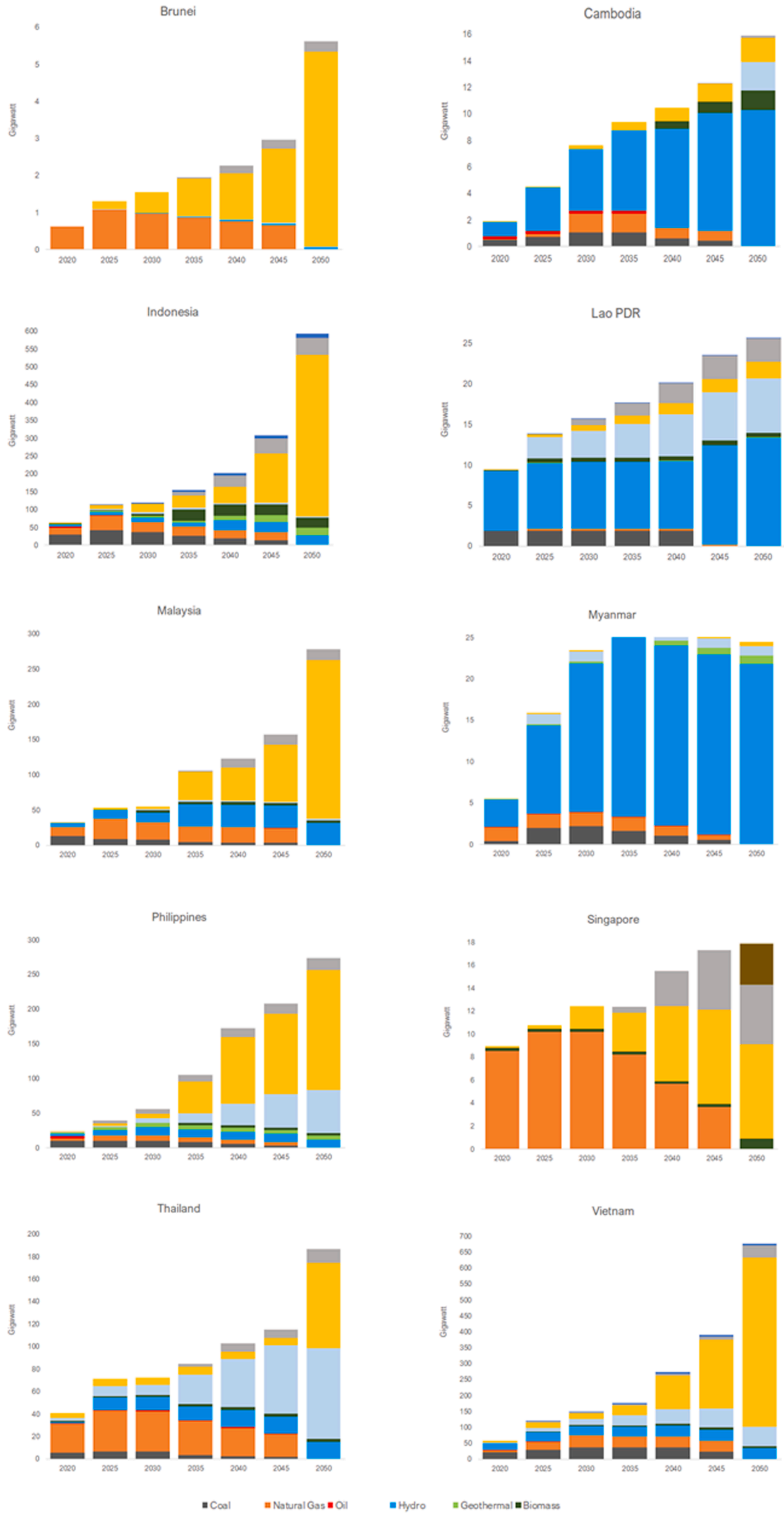
Appendix C

See Table C1.

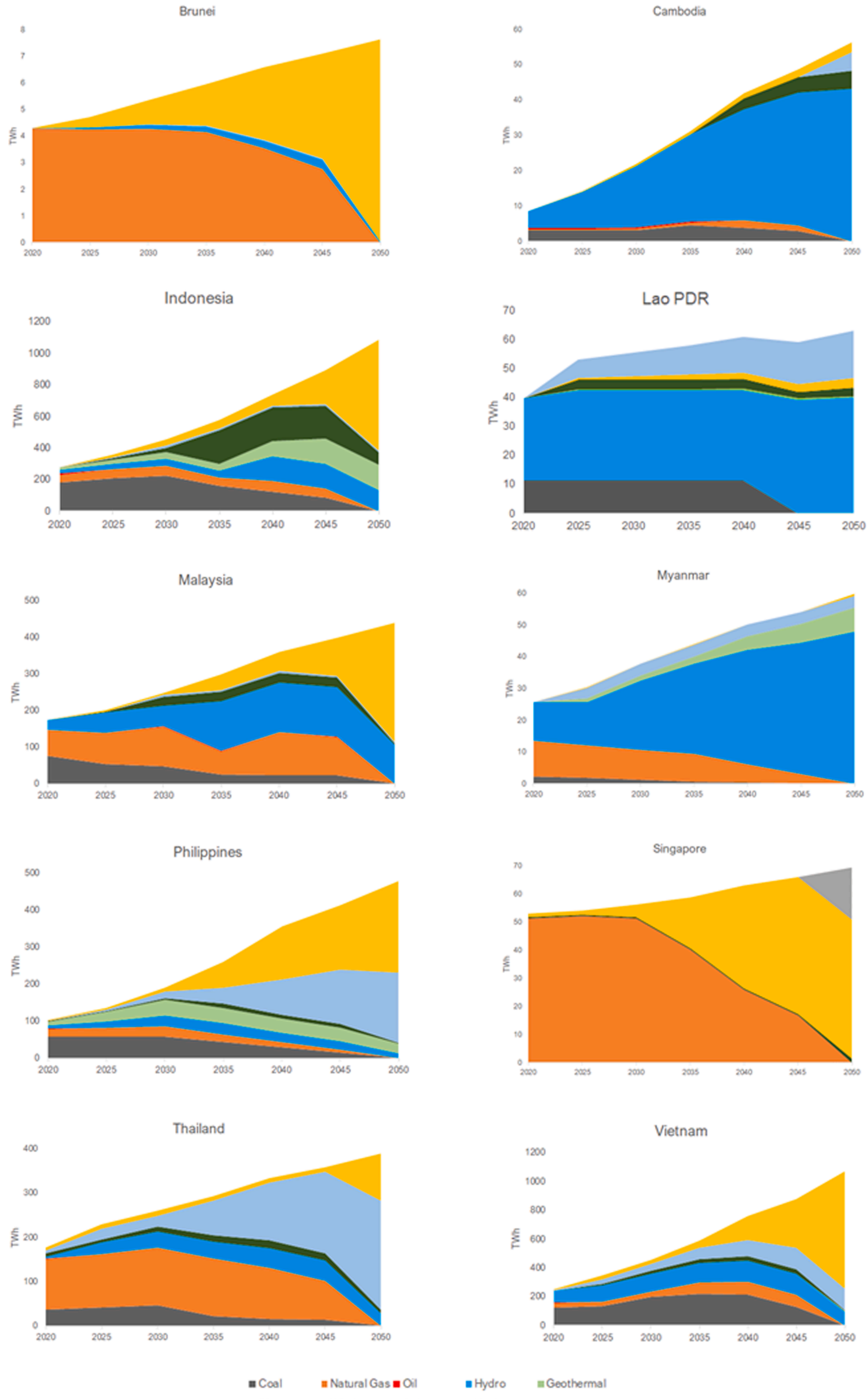
Table C1
Summary of LEAP outputs.

Country	Electricity demand in 2050 (TWh)	Electricity generation in 2050 (TWh)	GHG emissions in 2050 under RET scenario (ton CO_2e)
Brunei	7.2	7.6	3.3
Cambodia	51.4	56.3	7.0
Indonesia	983.8	1 083.5	494.2
Lao PDR	35.5	62.9	3.9
Malaysia	404.7	438.4	238.6
Myanmar	51.4	59.7	7.8
Philippines	435.5	477.0	291.7
Singapore	68.0	69.3	27.6
Thailand	361.8	388.5	143.0
Vietnam	924.0	1 071.3	198.8
Total	3 323.0	3 714.5	1 415.9

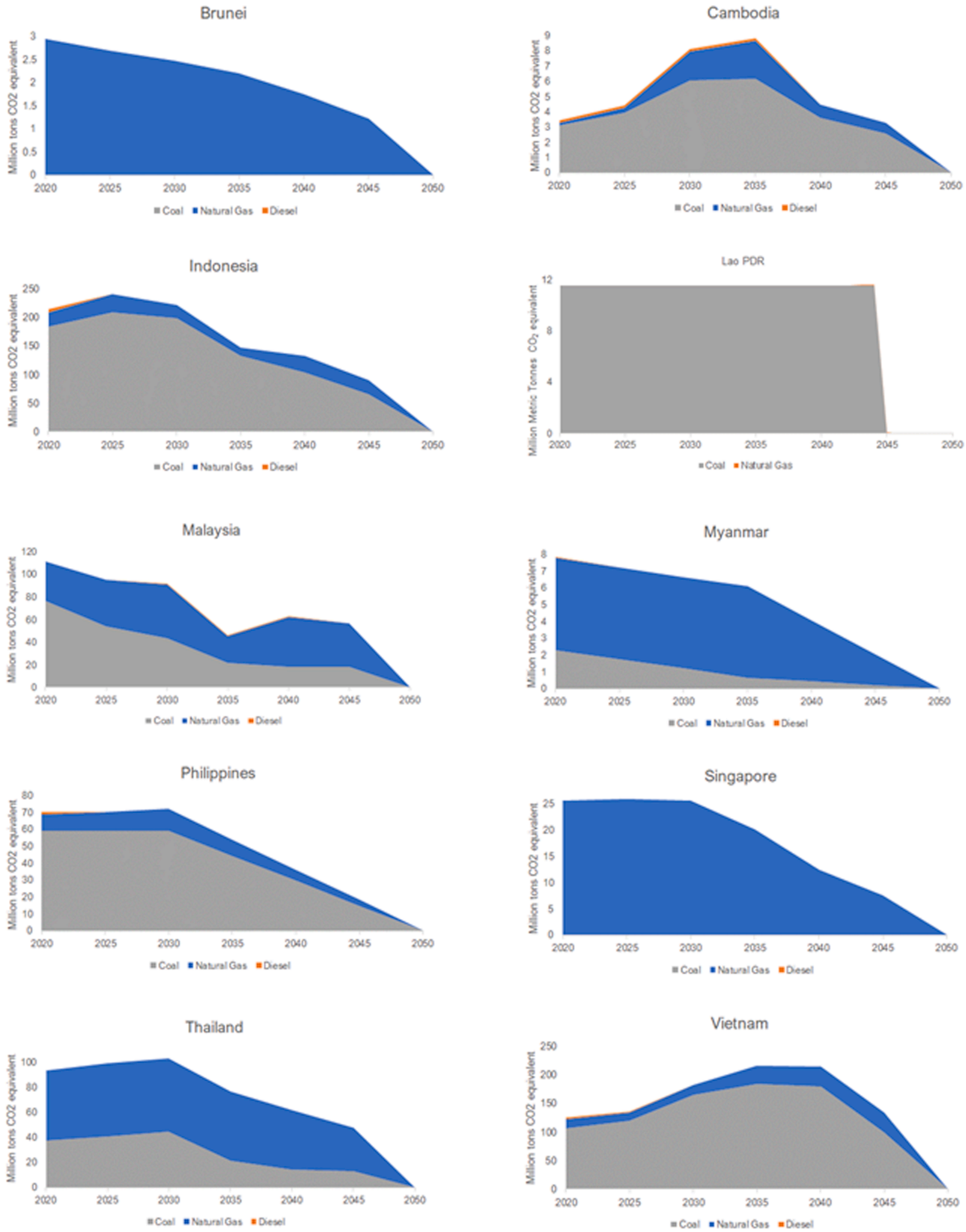
Appendix D. LEAP results: installed capacity – NZE scenario for each country



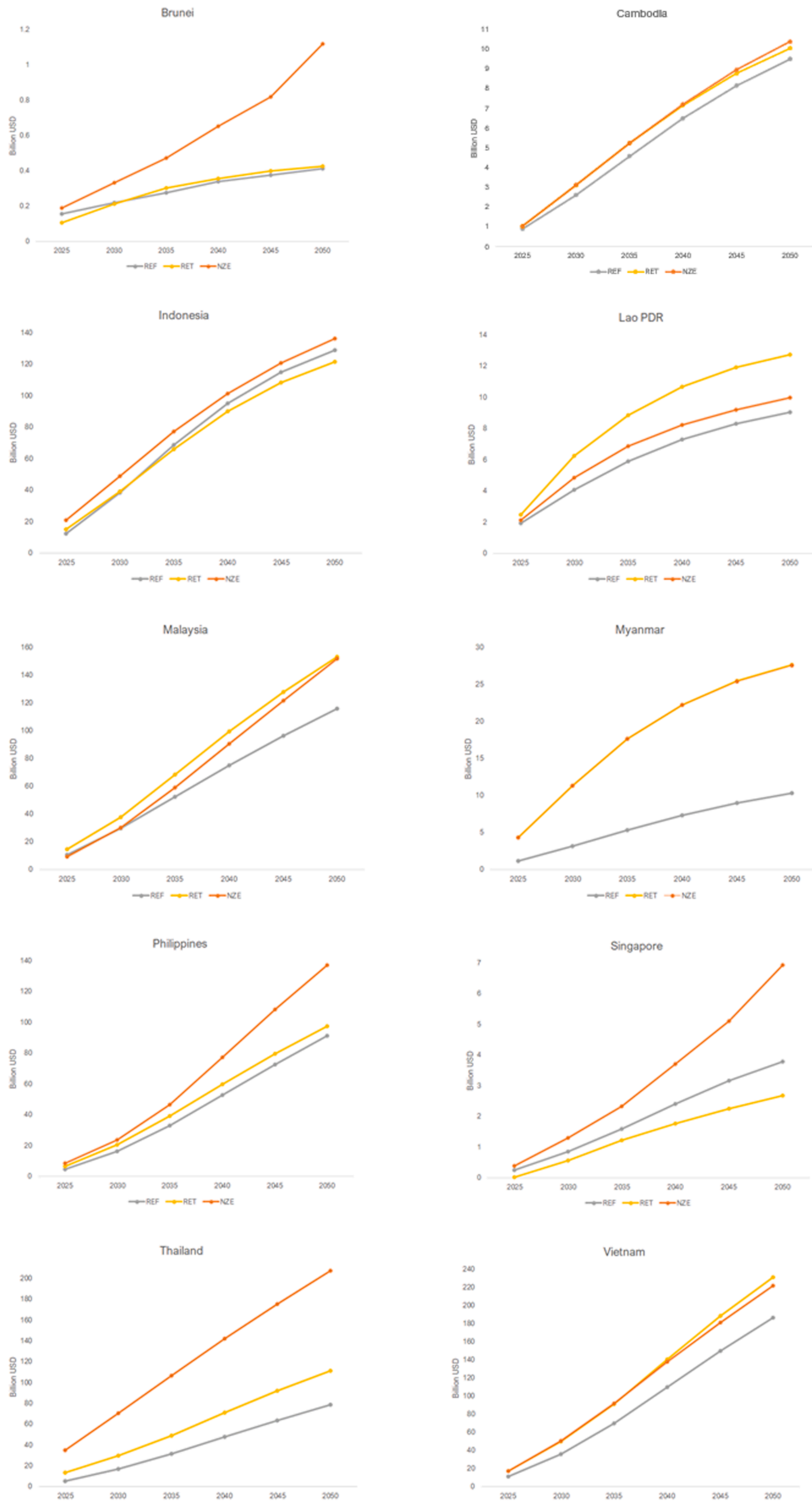
Appendix E. LEAP results: electricity generation – NZE scenario for each country



Appendix F. LEAP results: GHG emissions – NZE scenario for each country



Appendix G. LEAP results: total costs of capacity expansion for each country



References

[1] IPCC. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to. 2018.
[2] Energy and Climate Intelligence Unit. Net Zero emissions race 2021:1–4. https://eciu.net/netzerotracker (accessed August 21, 2021).
[3] Black R, Cullen K, Fay B, Hale T, Lang J, Smith S. Taking Stock: A global assessment of net zero targets; 2021.
[4] IEA. Southeast Asia Energy Outlook 2019 – Analysis; 2019.
[5] Statista. Total population of the ASEAN countries from 2011 to 2021 2021. https://www.statista.com/statistics/796222/total-population-of-the-asean-countries/ (accessed August 21, 2021).
[6] IEA. Data and statistics 2021. https://www.iea.org/data-and-statistics/data-browser?country=MASEAN&fuel=Energy consumption&indicator=ElecConsPerCapita (accessed August 1, 2021).
[7] Overland I, Sagbakken HF, Chan H-Y, Merdekawati M, Suryadi B, Utama NA, et al. The ASEAN climate and energy paradox. Energy Clim Chang 2021;2. https://doi.org/10.1016/j.egycc.2020.100019.
[8] Overland I et al. Impact of Climate Change on ASEAN International Affairs: Risk and Opportunity Multiplier, Norwegian Institute of International Affairs (NUPI) and Myanmar Institute of International and Strategic Studies (MISIS); 2017.
[9] Heaps CG. The Low Emission Alternative Platform. [Software version 2020.1.37] 2021. https://leap.sei.org.
[10] Handayani K, Krozer Y, Filatova T. Trade-offs between electrification and climate change mitigation: An analysis of the Java-Bali power system in Indonesia. Appl Energy 2017;208. Doi: 10.1016/j.apenergy.2017.09.048.
[11] ACE. The 6th ASEAN Energy Outlook (AEO6). Jakarta; 2020.
[12] Lee N, Flores-Espino F, Oliveira R, Roberts B, Bowen T, Katz J. Exploring Renewable Energy Opportunities in select Southeast Asian Countries: A Geospatial Analysis of the Levelized Cost of Energy of Utility-Scale Wind and Solar Photovoltaics; 2020.
[13] Government of The Republic of Indonesia. Government Regulation of Republic of Indonesia No. 79 Year 2014 regarding National Energy Policy 2014.
[14] The Government of the Lao PDR. Lao People's Democratic Republic: Voluntary National Review on the Implementation of the 2030 Agenda for Sustainable Development; 2018.
[15] Department of Energy Policy and Planning & Electricite du Laos. Lao PDR Power Demand and Supply Forecast 2016-2030; 2015.
[16] Suruhanjaya Tenaga. Report on Peninsular Malaysia Generation Development Plan 2020 (2021-2039); 2021.
[17] National Energy Management Committe of Myanmar. Myanmar Energy Master Plan; 2015.
[18] Department of Energy of the Philippines. Renewable Energy Plans and Programs (2011-2030); 2011.
[19] Ministry of the Environment and Water Resources and Ministry of National Development. Sustainable Singapore Blueprint 2015; 2014.
[20] Department of Renewable Energy Development and Energy Efficiency. Alternative Energy Development Plan: AEDP2015; 2015.
[21] The Prime Minister of The Socialist Republic of Vietnam. The Prime Minister Decision No.: 2068/QĐ-TTg: Approving the Viet Nam's Renewable Energy Development Strategy up to 2030 with an outlook to 2050; 2015.
[22] Pham TT. Vietnam Renewable Energy development project to 2030 with outlook to 2050; 2016.
[23] ACE. The 5th ASEAN Energy Outlook (AEO5). Jakarta; 2017.
[24] Huber M, Roger A, Hamacher T. Optimizing long-term investments for a sustainable development of the ASEAN power system. Energy 2015;88:180–93. https://doi.org/10.1016/j.energy.2015.04.065.
[25] PLN. Draft RUPTL 2021-2030 2020.
[26] IEA. Development Prospects of the ASEAN Power Sector: Towards an Integrated Electricity Market. France; 2015.
[27] Misila P, Winyuchakrit P, Limmeechokchai B. Thailand's long-term GHG emission reduction in 2050: the achievement of renewable energy and energy efficiency beyond the NDC. Heliyon 2020;6. https://doi.org/10.1016/j.heliyon.2020.e05720.
[28] Nong D, Siriwardana M, Perera S, Nguyen DB. Growth of low emission-intensive energy production and energy impacts in Vietnam under the new regulation. J Clean Prod 2019;225:90–103. https://doi.org/10.1016/j.jclepro.2019.03.299.
[29] Haiges R, Wang YD, Ghoshray A, Roskilly AP. Unconventional fuel pathways for decarbonizing the electrical power generation in Malaysia by 2050. Energy Procedia, vol. 158, Elsevier Ltd; 2019, p. 4238–45. Doi: 10.1016/j.egypro.2019.01.803.
[30] Mondal MAH, Rosegrant M, Ringler C, Pradesha A, Valmonte-Santos R. The Philippines energy future and low-carbon development strategies. Energy 2018;147:142–54. https://doi.org/10.1016/j.energy.2018.01.039.
[31] Malik AQ. Assessment of the potential of renewables for Brunei Darussalam. Renew Sustain Energy Rev 2011;15:427–37. https://doi.org/10.1016/j.rser.2010.08.014.
[32] Handayani K, Krozer Y, Filatova T. From fossil fuels to renewables: An analysis of long-term scenarios considering technological learning. Energy Policy 2019:134–46. https://doi.org/10.1016/j.enpol.2018.11.045.
[33] Stockholm Environment Insitute. NEMO model concept 2021. https://sei-international.github.io/NemoMod.jl/v1.2/model_concept/ (accessed November 28, 2021).
[34] Pfenninger S. Solar PV n.d. https://www.renewables.ninja/ (accessed June 28, 2021).
[35] KESDM. Draft Rencana Umum Ketenagalistrikan Nasional 2015-2034; 2015.
[36] Tenaga Suruhanjaya. Peninsular Malaysia Electricity Supply Industry Outlook 2019. Putrajaya 2019.
[37] EMA. Singapore Electricity Market Outlook. Singapore; 2016.
[38] MOEP. The Project for Formulation of The National Electricity Master Plan in The Republic of The Union of Myanmar. Nay Pyi Taw; 2014.
[39] DOE. Power Development Plan 2016-2040. Manila; 2016.
[40] MOIT. Vietnam Power Development Plan – Highlights of the PDP VII Revised. Hanoi; 2015.
[41] EPPO. Thailand's Power Development Plan 2018-2037. Bangkok; 2018.
[42] The World Bank Group. Data - Electric power transmission and distribution losses 2021. https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS (accessed June 18, 2021).
[43] ACE. ASEAN Interconnection Masterplan Study III. Jakarta, Indonesia; 2021.
[44] DJK KESDM. Statistik ketenagalistrikan; 2019.
[45] Suruhanjaya Tenaga. Malaysia Energy Statistics Handbook 2020. vol. 1. Putrajaya; 2021.
[46] DOE. Philippine 2020 Power Statistics 2021. https://www.doe.gov.ph/energy-statistics/philippine-power-statistics?ckattempt=1 (accessed June 18, 2021).
[47] Burke F, Thanh Hai N. Vietnam: Key highlights of new draft of national power development plan (Draft PDP8) 2021:1–5. https://www.globalcompliancenews.com/2021/03/13/vietnam-key-highlights-of-new-draft-of-national-power-development-plan-draft-pdp8-04032021-2/ (accessed July 5, 2021).
[48] The World Bank Group. Data - Real interest rate n.d. https://data.worldbank.org/indicator/FR.INR.RINR (accessed June 18, 2021).
[49] The World Bank Group. Inflation, GDP deflator 2021. https://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG (accessed June 18, 2021).
[50] DGE MEMR, Danish Energy Agency, Ea Energy Analysis. Technology Data for the Indonesian Power Sector - Catalogue for Generation and Storage of Electricity; 2021.
[51] Rothwell G, Rust J. On the optimal lifetime of nuclear power plants. J Bus Econ Stat 1997;15:195–208. https://doi.org/10.2307/1392305.
[52] Mongird K, Fotedar V, Viswanathan V, Koritarov V, Balducci P, Hadjerioua B, et al. Energy Storage Technology and Cost Characterization Report. Hydro Wires, U.S. Dpt. Of Energy, Rep. No: PNNL-28866. Richland, WA (United States): 2019. Doi: 10.2172/1573487.
[53] IEA, NEA. Projected Costs of Generating Electricity 2015 Edition. Paris: International Energy Agency Nuclear Energy Agency; 2015.
[54] Zakeri B, Syri S. Electrical energy storage systems: A comparative life cycle cost analysis. Renew Sustain Energy Rev 2015;42:569–96. https://doi.org/10.1016/j.rser.2014.10.011.
[56] Suruhanjaya Tenaga. Malaysia Energy Statistics Handbook 2019. Putrajaya; 2019.
[57] IEA. Net Zero by 2050 A Roadmap for the global power sector. Paris; 2021.
[58] Shirizadeh B, Quirion P. Low-carbon options for the French power sector : What role for renewables, nuclear energy and carbon capture and storage ? Energy Econ 2021;95. https://doi.org/10.1016/j.eneco.2020.105004.
[59] Australian Renewable Energy Agency. Hydrogen Energy 2021. https://arena.gov.au/renewable-energy/hydrogen/ (accessed November 28, 2021).
[60] Chugoku Electric Power Co. Power Development Master Plan in Kingdom of Cambodia. Hiroshima; 2015.
[61] PLN. PLN Management Report; 2021.
[62] BritCham Vietnam. Vietnam Renewable Energy Report; 2021.
[63] Tunpaiboon N. Industry Outlook 2021-2023 : Power Generation; 2021.
[64] OECD/IEA. World Energy Outlook - World Energy Model 2017; 2017. http://www.worldenergyoutlook.org/weomodel/.
[65] DEN. Indonesia Energy Outlook 2016. National Energy Council; 2016.
[66] PLN. RUPTL cost assumptions; 2017.
[67] PLN. Electricity Supply Business Plan (RUPTL) 2021–2030. Jakarta; 2021.