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International Renewable Energy Agency

RENEWABLE ENERGY OUTLOOK FOR ASEAN

TOWARDS A REGIONAL ENERGY TRANSITION

2ND EDITION

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

About ACE

Established on 1 January 1999, the ASEAN Centre for Energy (ACE) is an intergovernmental organisation within the ASEAN structure representing the 10 ASEAN Member States (AMS) interests in the energy sector. It is guided by a Governing Council composed of Senior Officials on Energy from each AMS and a representative from the ASEAN Secretariat as an ex-officio member. Hosted by the Ministry of Energy and Mineral Resources of Indonesia, the office is located in Jakarta. For more information, visit **www.aseanenergy.org**

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Disclaimer

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FOREWORD

The Southeast Asia region will see rapid economic growth in the coming decades and energy use is set to grow significantly. Today, the region stands at a crossroads. On the one hand, it can pursue a path of continued reliance on fossil fuels, most of which come from non-indigenous sources, increasing the region's emissions and exposure to volatile and increasingly expensive global commodity markets. On the other, the region could utilise its ample, affordable, indigenous renewable energy resources to lower energy costs, reduce emissions and drive regional economic development.

This second edition of the Renewable energy outlook for ASEAN was developed in collaboration the ASEAN Center for Energy (ACE) and the ASEAN Renewable Energy Sub-sector Network. It is guided by IRENA's *World energy transitions outlook* and builds upon the first *Renewable energy outlook for ASEAN*, released in 2016, by incorporating a net-zero pathway and a longer-term perspective to 2050.

As the region commits to ever more ambitious climate targets, including net-zero commitments, planning must begin now in earnest. While ASEAN has ambitious renewable energy goals in the near-term, the region needs to think and plan for the long-term. It has a unique opportunity to develop a sustainable energy system based on renewable energy resources that can support socioeconomic recovery and development while addressing climate change mitigation and adaptation strategies, and accomplishing energy security, universalisation and affordability goals.

This report provides a comprehensive renewables-focused energy pathway for the development of a cleaner and more sustainable regional energy system. It explores end-use sector electrification, the rapid expansion of renewable generation, energy efficiency solutions, the role of emerging technologies such as clean hydrogen and batteries, as well the importance of expanding regional power sector integration. It also presents sector-specific technological pathways and investment opportunities that will enrich the regional debate and help accelerate the energy transformation across ASEAN.

The engagement with ASEAN Member States was crucial to the development of this outlook. We also are grateful for the support of regional organisations such as ACE, and our Danish partners, who supported this project.

Accelerating the energy transition will require far-sighted choices, discipline and wise investments, backed by international co-operation and strong regional planning in ASEAN. IRENA stands ready to work with countries across ASEAN and our close regional partners, to help make the vision presented in this report a reality.

Francesco La Camera
Director-General, IRENA

FOREWORD

Following the first IRENA *Renewable energy outlook for ASEAN* published in 2016, the International Renewable Energy Agency (IRENA) and the ASEAN Centre for Energy (ACE) have co-developed the Renewable energy outlook for ASEAN: Towards a regional energy transition (2nd Edition). The outlook addresses potential solutions to the looming energy crisis in the wake of geopolitical conflicts, the COVID-19 pandemic and climate change by exploring how ASEAN may optimise the use of clean energy technologies, devise supportive policy measures and determine effective timelines for financing.

The report discusses challenges to achieving the targets of the ASEAN Plan of Action for Energy Cooperation (APAEC) Phase II: 2021–2025. These include the aspirational goals to increase the share of renewables in primary energy and total installed capacity whilst reducing energy intensity.

Reflecting recent net zero pledges, this second edition also explores a pathway to expand the share of renewables in supply and end-uses as part of a just transition. This pathway could enable ASEAN to accelerate the energy transition and strengthen energy resilience through greater innovation and cooperation.

The report complements the launch of ACE's flagship publication, the 7th ASEAN Energy Outlook (AEO7), with both studies raising concerns about regional energy security. Coal's share remains dominant in the power sector, as does oil in transportation, and ASEAN desperately needs to diversify its energy mix. On the contrary, the intermittency of renewable energy sources, particularly solar and wind, remains an obstacle owing to the strain on the power grid. The potential of bioenergy feedstocks is not yet fully assessed or utilised, with only a 7% share of the transport fuel mix by 2020. In short, ASEAN needs to improve regional cooperation to speed up the establishment of flexible and reliable power infrastructure and the higher adoption of energy-efficient technologies through end-user electrification.

In developing this report, IRENA and ACE received support from the Renewable Energy Sub-Sector Network (RE-SSN). This specialised working group consists of government officials from ten ministries of energy in ASEAN member states. We hope the findings of this study will provide insightful analysis for the consideration of RE-SSN and receive positive feedback. We also sincerely hope it will offer encouraging messages on the promise of the clean energy transition to all stakeholders, from private companies and academia to professional associations.

Dr. Nuki Agya Utama
Executive Director, ASEAN Centre for Energy

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COUNTRY CODES

SHORT NAME	OFFICIAL NAME	COUNTRY CODE
Brunei Darussalam	Brunei Darussalam	BN
Cambodia	Kingdom of Cambodia	KH
Indonesia	Republic of Indonesia	ID
Lao PDR	Lao People's Democratic Republic	LA
Malaysia	Malaysia	MY
Myanmar	Republic of the Union of Myanmar	MM
Philippines	Republic of the Philippines	PH
Singapore	Republic of Singapore	SG
Thailand	Kingdom of Thailand	TH
Viet Nam	Socialist Republic of Viet Nam	VN

ABBREVIATIONS

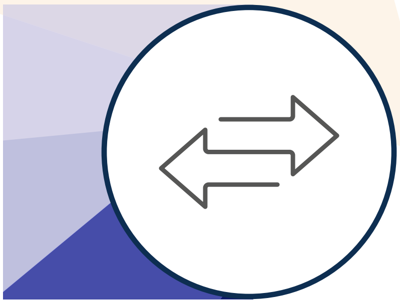
1.5-S	1.5°C Scenario for ASEAN aligned with the WETO targeting net-zero emissions globally by 2050
1.5-S RE90	sensitivity for the power sector with 90% renewable power generation
1.5-S RE100	sensitivity for the power sector with 100% renewable power generation
ACE	ASEAN Centre for Energy
AFOLU	agriculture, forestry and other land use
AIC	average investment cost
AMS	ASEAN Member States
APAEC	ASEAN Plan of Action for Energy Cooperation
ASEAN	Association of Southeast Asian Nations
BAU	business as usual
BECCS	bioenergy with carbon capture and storage
BES	Baseline Energy Scenario
°C	degree Celsius
CCS	carbon capture and storage
CHP	combined heat and power
CO_2	carbon dioxide
COP	Conference of Parties
COP26	26th United Nations Climate Change Conference
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSP	concentrated solar power
ACCS	direct carbon capture and storage
ESG	environmental, social and governance
EJ	exajoule
EV	electric vehicle
FOLU	forestry and other land use
GBEP	Global Bioenergy Partnership
GCC	Gulf Cooperation Council
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
Gt	gigatonne
$GtCO_2eq$	gigatonne of carbon dioxide equivalent
GW	gigawatt
GWh	gigawatt hour
Hz/s	Hertz per second
JPY	Japanese yen
kg	kilogramme
km	kilometre
kt	kilotonne
$ktCO_2eq$	kilotonne of carbon dioxide equivalent
kW	kilowatt
kWh	kilowatt hour
IRENA	International Renewable Energy Agency
LCOE	levelised cost of electricity
LED	light-emitting diode
LME	London Metal Exchange
LNG	liquified natural gas
LOHC	liquid organic hydrogen carrier
LPG	liquefied petroleum gas
LULUCF	land use, land-use change and forestry
MEPS	minimum energy performance standard
MJ	megajoule
Mt	million tonne
$MtCO_2$	million tonne of carbon dioxide
MW	megawatt
NDC	Nationally Determined Contribution

NEU	non-energy use
NPI	nickel pig iron
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PES	Planned Energy Scenario
PJ	petajoule
PLN	Indonesia's state-owned electricity utility
PST	Power System Transformation
PV	photovoltaic
R&D	research and development
RE-SSN	Renewable Energy Sub-sector Network (ASEAN)
RED	Renewable Energy Directive
REE	rare earth element
RoCoF	Rate of Change of Frequency
SAF	sustainable aviation fuel
SDG	Sustainable Development Goal
tCO_2eq	tonnes of carbon dioxide equivalent
TES	Transforming Energy Scenario
TFEC	total final energy consumption
TPES	total primary energy supply
TSO	transmission system operator
TW	terawatt
TWh	terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
VLSFO	very low sulphur fuel oil
VRE	variable renewable energy
WACC	weighted-average cost of capital
WETO	World Energy Transition Outlook

KEY FINDINGS

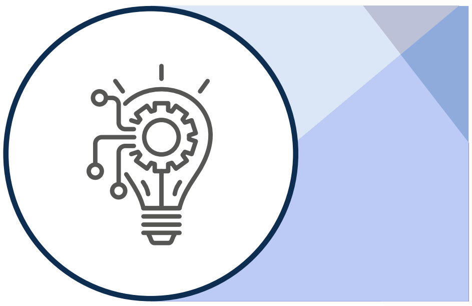
The Association of Southeast Asian Nations (ASEAN) is at a pivotal point in its collective energy future. This report outlines energy transition pathways that focus on renewables, end-use electrification, energy efficiency and emerging technologies, such as hydrogen. The main focus of this report is the 1.5°C Scenario (1.5-S), an energy pathway for ASEAN that is aligned with IRENA's global 1.5-degree pathway from the *World Energy Transitions Outlook*.

This report shows how the region can transition from just 19% **renewable energy share** in final energy in 2018 to 65% by 2050, and in the process reduce energy-related carbon dioxide (CO_2) emissions by 75% compared to current policies.



In the near-term to 2030, emphasis should focus on key transition technologies such as increasing solar PV to over 240 gigawatts (GW) of installed capacity, putting over 13 million battery-electric vehicles on the road with 3.7 million charging stations, and widescale efforts focusing on improving energy efficiency, materials efficiency and circular economy, and scaling up sustainable bioenergy, hydropower and geothermal energy sources.

In the longer-term, regional **power system integration** should be fostered and improved to further utilise a total renewable energy power expansion reaching around 2 770 GW to 3 400 GW by 2050 in the 1.5-S. Coal power plant phaseout should be expedited in the near-term, and expansion of fossil fuel dependent infrastructure avoided wherever possible to avoid stranded assets.



Transmission and distribution grids will need expansion and reinforcement to meet growing electricity consumption and enable more efficient and reliable system operation. This sees an international expansion of lines nearing a total 200 GW by 2050 in the 1.5-S, deepening power system integration across ASEAN.

Renewable power capacity, power grids and infrastructure, and enabling technologies (*e.g.* storage), will need to see over USD 5 trillion (United States dollars) in **investment** over the period to 2050, making up two-thirds of total energy investment.

Energy efficiency measures and technology standards should be considered a first principle, with corresponding cumulative investments of USD 1 616 billion until 2050, which in turn will bring energy intensity down 45% by 2050, compared to 2018 levels.

In transport, **EVs will need to grow** to more than 100 million battery-EV cars, and almost 300 million electric two- and three-wheelers by 2050.

Bioenergy is also important in all end-use sectors, particularly for modes such as aviation and for some industrial sectors. Domestic bioenergy use will need to more than double to 7.6 exajoules (EJ) by 2050.

Clean hydrogen and its derivatives provide an alternative solution for decarbonising shipping and are important for some heavy manufacturing industrial processes. Hydrogen demand for domestic uses will exceed 11 million tonnes (Mt), while additional fuel will be needed for international bunkering.

The 1.5-S can **reduce total costs related** to energy supply by as much as USD 160 billion cumulatively to 2050. Additionally, avoided externalities resulting from 1.5-S range from USD 508 to USD 1 580 billion cumulatively to 2050. All in all, the transition can be achieved at a lower cost than the Planned Energy Scenario, this report's reference case.

EXECUTIVE SUMMARY

The Southeast Asia region is expected to see rapid economic growth over the next few decades. Driven by this, as well as population growth, energy demand in the region will grow rapidly too. Today's energy supply, meanwhile, is dominated by fossil fuels, which make up over 85% of primary energy.

Southeast Asia therefore stands at a crossroads. It can go down a path of continued reliance on fossil fuels – more of which are coming from non-indigenous sources (ACE, 2020a) – and thereby increase its exposure to volatile, and increasingly expensive, global commodity markets. Or, alternatively, the region can choose to use its ample, affordable and indigenous local renewable energy resources.

By the end of 2018, the total installed electricity generation capacity of all ten ASEAN member states was 252 GW, with 28% of that capacity coming from renewable sources, mostly hydropower. In 2020, that share had increased to 33.5% (ACE, 2022a), due in part to the rapid expansion of solar photovoltaics (PVs). The power sector is one of the major sectors contributing to ASEAN's energy-related CO_2 emissions as a result of it being heavy reliant on fossil fuels.

Coal retirement, coupled with the continued expansion of renewables, is one important step in aligning with net-zero targets. Half of ASEAN member states are signatories to the international effort to end coal utilisation in the power sector. Brunei Darussalam, Indonesia, the Philippines, Singapore and Viet Nam signed on to the Global Coal to Clean Power Transition statement during the 26th United Nations Climate Change Conference (COP26) (ACE, 2022a). These commitments cover three-quarters of ASEAN's coal emissions. Many are also participating in an early coal retirement initiative under the leadership of the Asian Development Bank, which has signed up around 25 GW for early retirement.

Taking these efforts to achieve these commitments into account, renewable energy has never been so important, and the region has seen a growing deployment of renewable energy. Between 2015 and 2021, the total installed capacity from renewables jumped from 55 GW to 97 GW (IRENA, 2022a). By the end of 2021, Viet Nam, Thailand and Indonesia were leading the regional race with a total of 43 GW, 12 GW and 11 GW of installed renewable energy capacity, respectively.

ASEAN has ambitious renewables goals in the near term which, when leveraged with its huge untapped potential renewable sources, can provide local and affordable alternatives to fossil fuels. The region has aspirational targets aiming to have 23% of primary energy accounted for by renewable energy by 2025, along with a 35% share of renewable energy in installed capacity. However, investments in recent years show mixed progress on the 2025 objectives. ASEAN only had a 14.3% share of renewable energy in primary energy in 2021 (ACE, 2022a), a share that has remained more or less constant for half a decade. Yet the region also had a 33.5% share of installed renewable power capacity in 2020 (ACE, 2022a), a substantial increase just over the last couple of years. Therefore, while the installed capacity share looks within reach, the primary energy target will be a challenge.

Over the longer term, ASEAN Member States (AMS) have a wide range of both conditional and unconditional climate targets that set out levels of emission reductions. Also in the last year, many have indicated a desire to achieve net-zero emissions around mid-century. These long-term commitments require concerted and accelerated action that must begin now.

AN ENERGY TRANSITION ROADMAP FOR THE REGION'S SUSTAINABLE FUTURE

IRENA's roadmaps consider multiple possible future energy pathways. The two main scenarios are the Planned Energy Scenario (PES), which considers current and planned policies, and the 1.5°C Scenario (1.5-S), which follows IRENA's *World Energy Transition Outlook* (WETO) 1.5-S scenario aiming to reach net-zero emissions globally by 2050. For the 1.5-S, multiple power sector supply scenarios are considered for ASEAN, one with 90% renewable power generation (1.5-S RE90) and one with 100% renewable power generation (1.5-S RE100).

The ASEAN region will be a key driver of global energy-demand growth over the next three decades. Projections under the PES show that total final consumption (TFC) will increase more than 2.5-fold by 2050. The region's demand will grow about 3% annually, driven by population and economic growth, reaching over 50 exajoules (EJ) by 2050, while an energy transition effort detailed by the 1.5-S will drive a slower demand growth of 2.4% annually and save 19% of total consumption compared to the PES in the same year.

To realise the 1.5-S outlined in this report, efforts are needed across the entire energy system of ASEAN. The following table outlines some of the key indicators needed to achieve the 1.5-S. While these are not exhaustive, they outline how much of the transition is based on renewable energy use and electrification.

A wide range of measures are needed, but renewable energy will be the crucial driver in ASEAN to meet the 1.5-S.

Table 1 Select key actions for achieving the 1.5-S by 2050

KEY ACTIONS				REFERENCE TIMEFRAME OR YEAR	BASE VALUE	WHERE WE NEED TO BE IN 1.5-S IN 2050
	1	**Clean Electricity**	With electricity generation growing up to five-fold by 2050 in the 1.5-S, renewables must provide between 90-100% of the total electricity supply by 2050, up from 26% in 2019.	2019	26%	90-100%
	2	**Maximise indigenous use of renewables**	The share of renewables in TFEC will need to increase from 19% in 2018 to 65% by 2050. Direct electrification with renewables is the largest contributor, followed by bioenergy, but geothermal, green hydrogen and solar play important roles.	2018	19%	65%
	3	**Scale investment sustainably**	Average annual investment in renewable power capacity should scale five times from now until 2050 compared to the 2019-2021 annual average.	2019-2021 average	USD 15 billion/year[1]	USD 73 billion/year
	4	**Electrify end-uses**	The share of electricity in TFEC should increase from 22% in 2018 to 52% by 2050.	2018	22%	52%
	5	**Energy efficiency**	Energy efficiency measures and efficient technology are crucial. The energy intensity improvement rate will need to almost double compared to the 1.1%/year expected in the PES to 2050, to 1.9%/year in 1.5-S.	PES to 2050	1.1%/year	1.9%/yr
	6	**Invest in disruptive technologies**	The production of clean hydrogen and its derivative fuels must ramp up from negligible levels in 2020 to at least 11 Mt by 2050.	2020	< 0.1 Mt	11 Mt
	7	**Carbon management solutions**	While the measures outlined in this report reduced emissions by 75% compared to the PES, to reach net-zero emissions, CO_2 capture will be required via carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS), or other carbon removal and storage measures.	PES	-	-700 million tonnes of carbon dioxide in 2050 ($MtCO_2$)

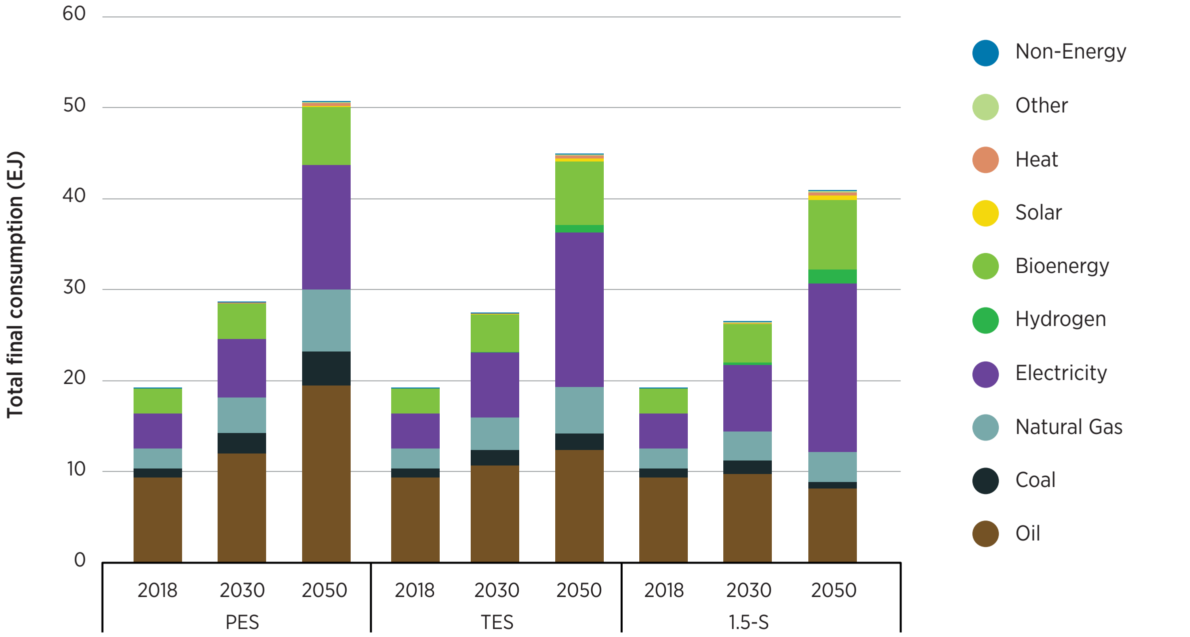
[1] *Source:* (BloombergNEF, 2022) (ASEAN & UNCTAD, 2021).

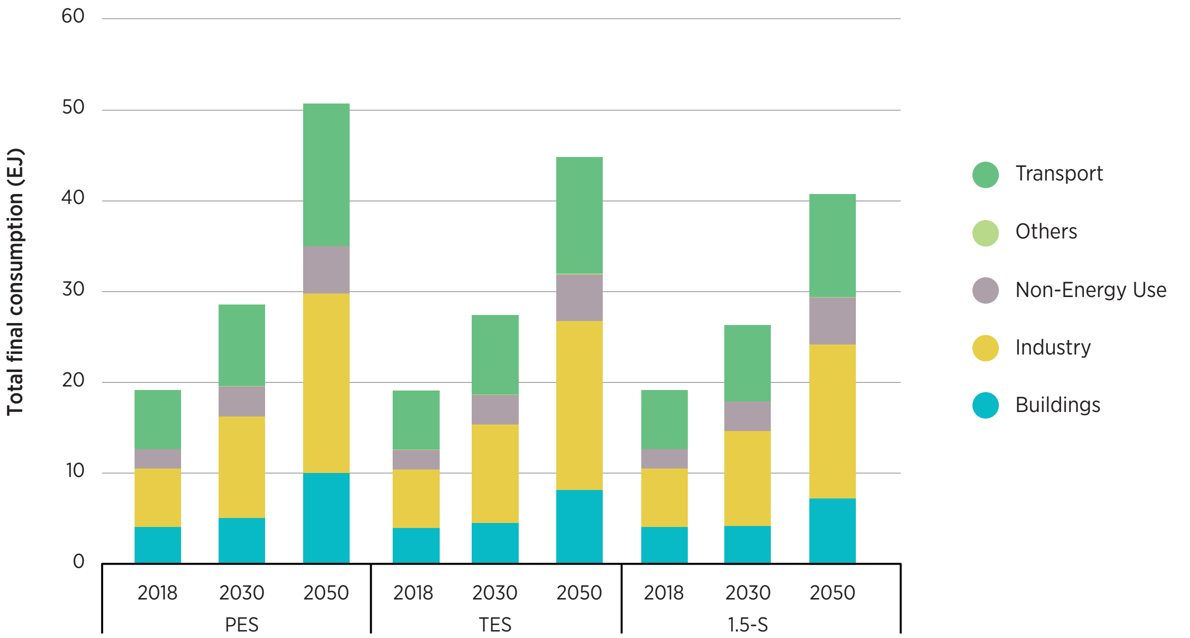
The energy mix in ASEAN will transform significantly in the 1.5-S. Renewables, both direct-use and from renewable-based electrification, will make up two-thirds of energy demand. Electricity, which is largely renewable based in the 1.5-S by 2050, makes up 52% of final energy demand. Meanwhile, overall bioenergy use will need to more than double and will be crucial in some end-use sectors, such as industry.

This report also assesses a scenario called the Transforming Energy Scenario (TES), which is less ambitious than 1.5-S and considers the readily available, and affordable, technologies at the expense of slightly higher emissions (around 1 gigatonne [Gt] vs 0.7 Gt for 1.5-S). While both the PES and TES require removal of CO_2 emissions through carbon management solutions, TES would require about 50% more removals to enable net-zero emissions.

The energy mix in ASEAN will grow but will also need to be substantially transformed by 2050.

Figure 1 Southeast Asia's total final consumption, by scenario, 2018, 2030, 2050





Industry energy demand will increase 3.6% per year. In the 1.5-S, the sector will become considerably less reliant on fossil fuels, which currently dominate the sector's energy supply. Instead, industrial process heat will transition towards the use of electricity, biomass and green hydrogen. A wide mix of technologies are necessary for industry, which includes hard-to-electrify industrial processes and feedstock requirements. ASEAN industry can also benefit from the technologies found in the 1.5-S. With a significant supply of critical materials needed for many energy transition technologies, the region could become a powerhouse of manufacturing.

The transport sector will see two parallel paths, one focused on electrifying modes such as passenger road vehicles, and another that will require cleaner fuels. The car fleet will need to grow to more than 100 million battery EV cars and almost 300 million electric two- and three-wheelers. Biofuels are also important for some modes, such as freight, aviation and inland shipping. Meanwhile, hydrogen and its derivatives are important for international shipping.

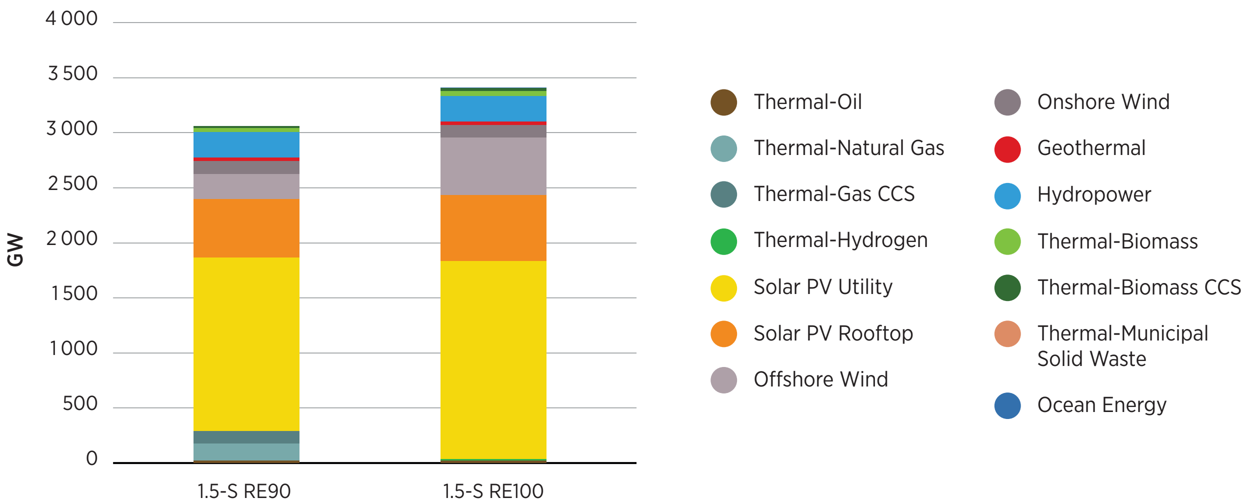
The building sector's energy demand will grow nearly 3% annually, reaching 10 EJ by 2050 in the PES. Space cooling will dominate energy demand in buildings, growing from 17% share in 2018 to almost half in 2050. The share of cooking energy demand will fall below 20% mainly due to the phaseout of traditional biomass and the transition towards clean cooking technologies, mainly liquefied petroleum gas (LPG) in the PES and electrification in the 1.5-S. Overall electrification, and more stringent energy efficiency standards and technology, will reduce the building sector's energy consumption by 27% in the 1.5-S compared to the PES, with electricity becoming the dominant fuel consumed in the sector.

Electricity consumption in ASEAN today is around 1 100 terawatt hours (TWh)/year. Electricity will become the dominant energy carrier in 1.5-S, increasing fivefold compared to today. Even in the PES it will still rise considerably to become the second-largest carrier, growing nearly fourfold under the current policy trajectory. How power generation capacity is expanded to meet this will be instrumental with regard to CO_2 emissions.

To chart possible alternatives to a reliance on fossil fuels in power generation, this report presents two routes forward for the region's power system: a 100% renewables system, and one that reaches 90% renewables and allows some remaining fossil fuel generators (mostly natural gas). The differentiation may not seem large, but in practice closing the remaining 10% gap requires significant additional storage and transmission expansion. Solar PV is key across all scenarios due to its abundant resources across the region. However, the 100% renewable energy scenario will need a very significant expansion of solar, up to 2 400 GW, and a similarly large expansion of battery storage.

The power sector will see demand increase fivefold; in the 1.5-S, solar PV will be the crucial technology.

Figure 2 Southeast Asia's power capacity alternatives for 1.5-S, in 2050



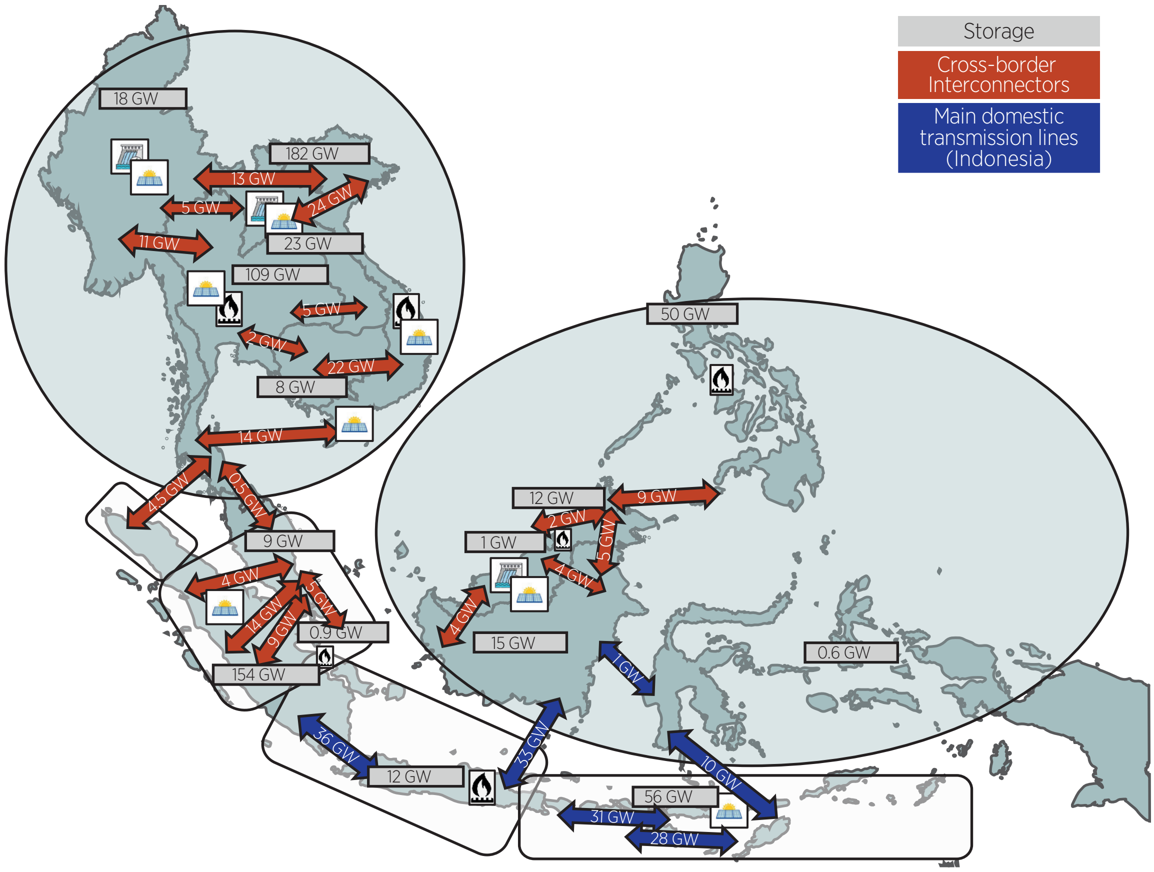
The significant level of growth in renewable electricity in the 1.5-S requires flexibility of the power system, particularly in transmission and storage assets. Tailoring consumption to when the sun is shining with smart charging of EVs and power-to-X helps harness the most solar resources while alleviating the need for additional storage. Hydropower and bioenergy help to balance supply and demand. Batteries will have a key role to play starting in the 2030s and beyond but will be deployed this decade in some applications.

Given the need for sizeable power assets, strategic considerations need to be applied in carrying out capacity expansion plans to operate the system by 2050. Potential issues can be addressed by opting for more circuits of lower capacity in the case of transmission lines, rather than a few larger ones, and by adopting fast-frequency reserves for small and medium grids in the medium term and large grids in the long term. Also in the long term, the system should be planned to enable it to cope with fewer synchronous power producers, with grid forming inverters likely to play a leading role.

Importantly, the full potential of renewables requires open markets and the alignment of regulations between national transmission system operators (TSOs). The former ensures that the least-cost merit order based on short-run marginal cost is followed across the region, and eventually also is followed even for ancillary services. Common regulations secure reliability across the region by setting norms for the provision of services (energy, regulation, reserves), the amount to be procured at each time scale, and the practices followed by TSOs. The region should also significantly expand transmission capacity in the 1.5-S, including both cross-border interconnectors and domestic transmission lines.

Transmission expansion will be critical for tapping resources across ASEAN and bringing electricity to load centres.

Figure 3 Transmission lines and batteries in 2050, 1.5-S RE90



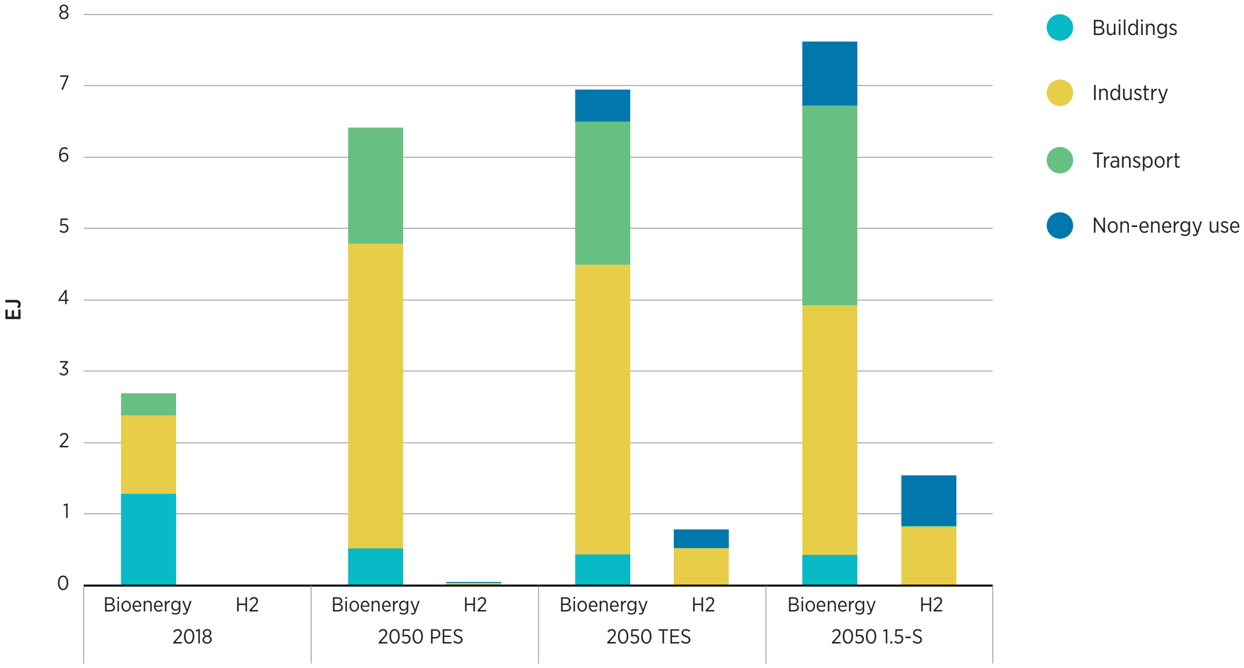
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

According to WETO, bioenergy makes up over 50% of renewable energy use globally today. Achieving the net-zero goal will not be possible with renewable electricity and energy efficiency alone. Bioenergy will represent 25% of total primary energy supply globally by 2050 in IRENA's 1.5°C Scenario (IRENA, 2022b). In ASEAN, bioenergy plays an important role today, and that will continue. In absolute terms, the increase will be from around 2.7 EJ (primary) in 2018 to 7.6 EJ by 2050 in the 1.5-S. In 2018, around 14% of final energy came from bioenergy sources in the region, with a little under half from traditional sources of bioenergy. By 2050 in the 1.5-S, the share will increase to 19%, with all traditional uses of bioenergy replaced with modern bioenergy. Scaling up bioenergy use will therefore be crucial for the region to meet its energy and climate goals, and doing so must coincide with bioenergy use that is sustainable and affordable (IRENA, 2022c).

Clean hydrogen will provide a complementary solution in the region's ambitious climate objectives. Hydrogen is clean when its manufacture results in no CO_2 emissions. Two main routes to clean hydrogen are producing it via carbon-free electricity (green hydrogen) and producing it from fossil fuels, typically natural gas, combined with CCS (blue hydrogen). The majority of clean hydrogen produced in ASEAN in the 1.5-S is green hydrogen. Clean hydrogen will play a role in industry sectors such as iron and steel, aluminium, chemicals and international bunkering for shipping. The 1.5-S shows more than 11 Mt of demand for domestic uses alone, in addition to further demand for international bunkering fuels (namely for international shipping).

Biofuels and hydrogen have an important role to play in sectors where direct electrification is not possible.

Figure 4 Bioenergy and hydrogen use in the end-use sectors, by scenario, 2018, 2050

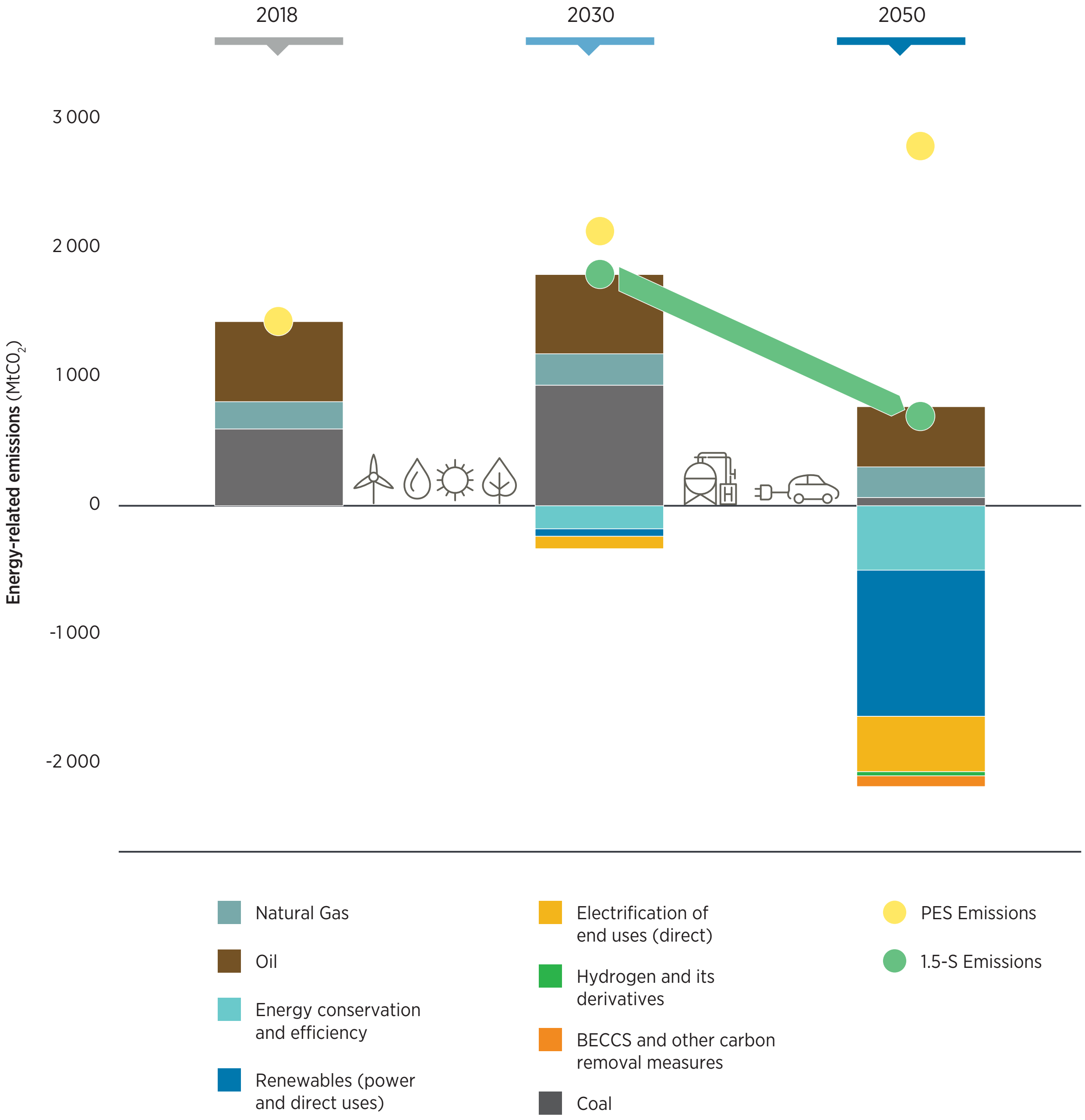


Note: International bunkering is excluded from the figure.

ASEAN's energy-related CO_2 emissions in 2018 were just under 1.5 Gt – around 4% of global emissions. In the near term to 2030, emissions will rise to 2.1 Gt in the PES in 2030, and to 1.8 Gt in the 1.5-S. Looking out to 2050, in the PES emissions will reach almost 2.8 Gt. The power sector will be the largest emitter, followed by transport and industry. These three together make up over 90% of the region's energy-related CO_2 emissions. By mid-century, the region's emissions under the 1.5-S will be reduced by 75% compared to the PES level in 2050 and reduced to half of today's emissions. A little over half of that reduction will be the result of renewables used in both power generation and direct use, with another 20% resulting from direct electrification (powered by renewables), and around 25% coming from energy efficiency measures. To reach net zero, carbon dioxide removal will be required on the order of around 0.7 Gt in 2050, which is consistent with the pathway to net-zero emissions that is outlined globally in IRENA's WETO.

The bulk of energy-related CO_2 emissions savings will come from renewables, energy efficiency, and direct electrification.

Figure 5 Energy-related CO_2 emissions and savings, by technology type, 2018, 1.5-S in 2030 and 2050



Wide-scale investment is needed across the entire energy system in ASEAN, from supply to infrastructure to the end-use sectors. Significant investment of about USD 200 billion to USD 245 billion annually will need to be directed into renewables, energy efficiency and enabling technologies and infrastructure over the period to 2050 to achieve the 1.5-S. In cumulative terms, the 1.5-S foresees investment of about USD 6.3 trillion to USD 7.3 trillion to reach the RE90 and RE100, respectively – about 2.5 to 3 times the investment needed in the PES.

In the nearer-term to 2030, solar PV installed capacity will need to reach 240 GW across the region, requiring investment of USD 150 billion within this decade. Grid investment will require nearly USD 200 billion, including national and international transmission expansion. Significant additional investment is needed in key enabling technologies such as EVs and charging stations, biofuel supply, and energy efficiency.

Wide-scale and significant investment scale-up will be required.

Table 2 Select technology scale-up and cumulative investment needs to 2030 and 2050

				SHORT TERM TO 2030 (1.5-S)		LONG TERM TO 2050 (1.5-S RE90)		LONG TERM TO 2050 (1.5-S RE100)	
				PARAMETER	TOTAL INVESTMENT 2018-2030 (USD BILLION)	PARAMETER	TOTAL INVESTMENT 2018-2050 (USD BILLION)	PARAMETER	TOTAL INVESTMENT 2018-2050 (USD BILLION)
INVESTMENT REQUIREMENT	POWER	**Solar PV**	Total Installed capacity (GW)	241	156	2 108	1 083	2 402	1 245
INVESTMENT REQUIREMENT	POWER	**Other renewable energy** (non-hydro)	Total Installed capacity (GW)	56	90	2 769	706	3 390	1 793
INVESTMENT REQUIREMENT	POWER	**Hydro**	Total Installed capacity (GW)	73	56	227	368	227	368
INVESTMENT REQUIREMENT	GRID AND FLEXIBILITY	**Transmission** (intl.)	km (thousand)	34	13	665	252	755	285
INVESTMENT REQUIREMENT	GRID AND FLEXIBILITY	**Transmission** (national)	km (thousand)	247	92	1 247	461	1 247	461
INVESTMENT REQUIREMENT	GRID AND FLEXIBILITY	**Distribution**	km (thousand)	2 739	69	13 811	346	13 811	346
INVESTMENT REQUIREMENT	GRID AND FLEXIBILITY	**Storage**	GW	15	8	666	161	1 175	306
INVESTMENT REQUIREMENT	BIOFUELS SUPPLY	**Biofuels**	million litres	57 475	66	118 133	235	118 133	235
INVESTMENT REQUIREMENT	ELECTRIFICATION	**EV chargers**	million units	3.7	47	35	419	35	419
INVESTMENT REQUIREMENT	ELECTRIFICATION	**EV cars**	million units	13	652	109	6 390	109	6 390

Note: GWh = gigawatt hours; km = kilometre.

When considering a wider cost perspective that includes fuel costs, operation and maintenance (O&M), and financing costs, over the period to 2050 the region will spend USD 28.3 trillion on its energy system in the PES. Of the transition scenarios, TES has the lowest cost, at USD 27 trillion, but it also has the highest emissions. Of the 1.5-S cases, RE90 is the lowest cost – USD 28.1 trillion – around USD 0.16 trillion lower than the PES, and 1.5-S RE100 has the highest cost – USD 29.4 trillion – or USD 1.1 trillion higher than the PES.

The Southeast Asia region must act now to reverse its reliance on fossil fuels, more of which are coming from non-indigenous sources, thereby increasing exposure to volatile and increasingly expensive global commodity markets. The region should transition towards energy transformation pathways utilising ample, affordable and indigenous local renewable energy resources, using technologies applicable to the energy supply and end-use sectors, while respecting the context, status and characteristics of each country and the region as a whole.

With more renewable energy projects, higher ambition targets for EV implementation, and several ASEAN countries being home to the world's largest nickel and other key mineral resources, foreign investment in energy transformation will benefit the countries in developing their industrial sectors, increasing their human resources capacity and receiving technology transfer. Policies will need to support expanding local industries to take advantage of the significant value chain that will need to be created. The market needs signals that allow investments in competitive GW-scale manufacturing capacity from technologies ranging from solar PV modules to larger balance of system components, batteries and EVs.

The findings outlined in this report highlight the pivotal role that renewables will need to play in the ASEAN region. The study shows that renewable potentials are vastly underutilised and most can be expanded for less cost to end-consumers than conventional energy sources. They also present significant economic opportunity as well as opportunities to create local value chains and industries.

INTRODUCTION

1

1. INTRODUCTION

In early 2022, the International Renewable Energy Agency (IRENA) released the most recent edition of the *World Energy Transitions Outlook* (WETO). The outlook shows that a drastic reduction in greenhouse gas (GHG) emissions is needed to meet the Paris Agreement goal of keeping the rise in global temperature well below 2 degrees Celsius (°C) and limited to 1.5°C. Key to this emission reduction over the coming decades will be increased investments in energy transition technologies, focused heavily on greater deployment of renewable energy, significant changes in energy infrastructure, higher energy efficiency, as well as some utilisation of carbon management solutions.

IRENA's renewable energy roadmaps programme, REmap, provides strategies for the energy transition at the country and regional levels, with perspectives up to 2050. IRENA's Power System Transformation (PST) programme provides technical analysis and perspectives on electrification, hydrogen and power system operation. Both of these programmes were used to conduct the analysis that forms the basis of this report. Separate IRENA efforts will examine the socio-economic benefits of the transition, as part of IRENA's Renewable Energy Benefits series, and a report on this topic is forthcoming.

Regional studies can clarify how a region can promote an energy transition pathway collectively, while respecting countries' unique energy resources, socio-economic status, and institutional and regulatory aspects. This can be achieved while contributing to the global emission reduction objective and leveraging opportunities to meet regional energy and investment goals.

While the ASEAN region accounts for around 5% of global energy demand and is responsible for about 4.6% of global energy-related CO_2 emission, the per capita emission is only 1% of the global total in 2020 (Ritchie and Roser, 2022).

With growing energy demand and increasing import dependency, the region will benefit from a shift to clean, indigenous and affordable energy resources. Therefore, the energy transition in ASEAN should not be viewed alone as an effort in reducing emissions; rather as a necessary step towards better energy security, more widespread energy access, more affordable energy and a healthier local environment.

With this in mind, IRENA is releasing this new outlook for the region's energy transition. In parallel, IRENA conducted an in-depth study on the country-based transition for two key ASEAN countries, Indonesia and Malaysia. Dedicated energy transition outlooks for these two countries are forthcoming.

FOCUS OF THE REPORT

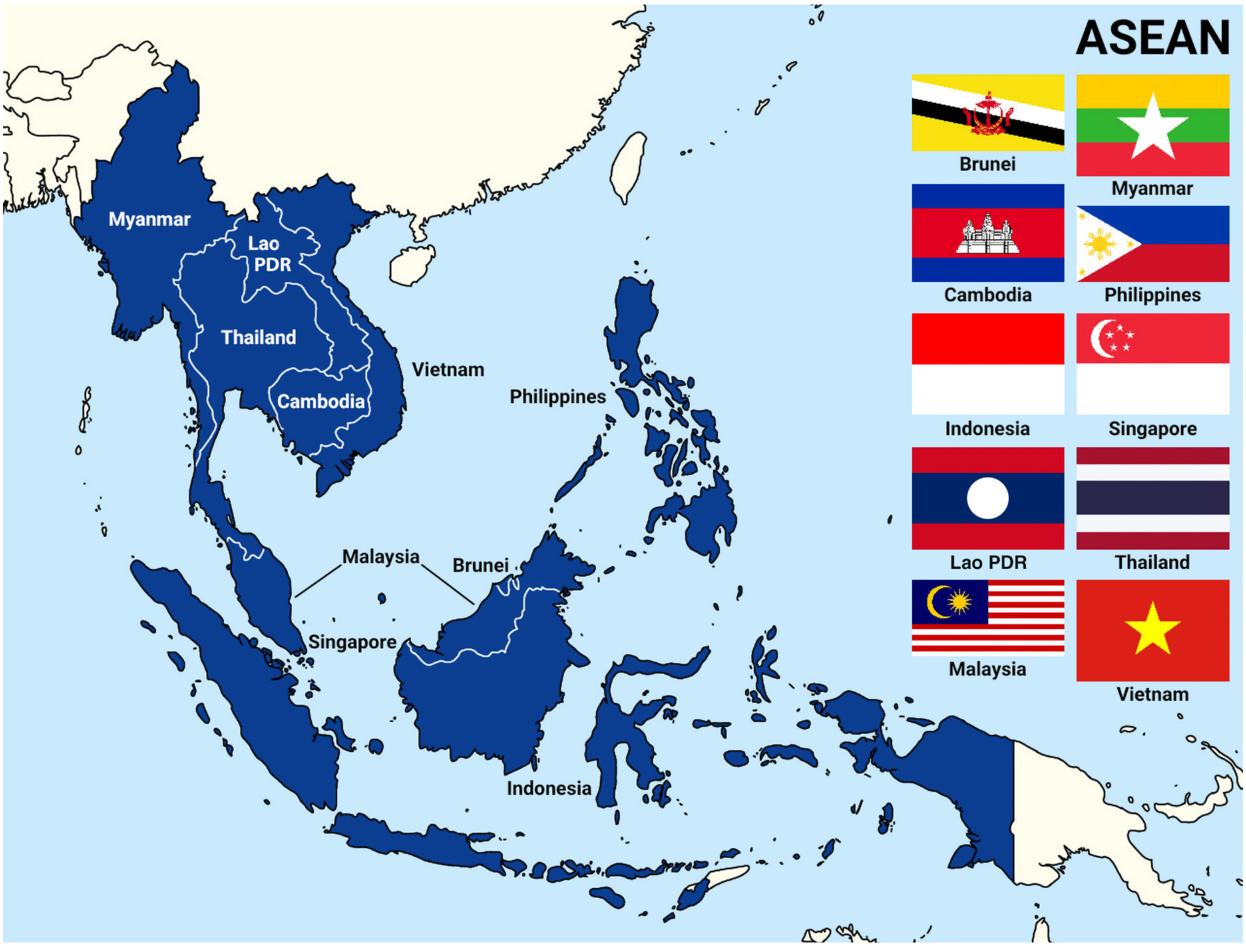
This report evaluates several potential pathways of renewable and low-carbon technologies in the end-use and power sectors in the ten ASEAN Member States (AMS), with a medium-term focus to 2030 and a long-term focus to 2050. The analysis is focused on energy-consuming sectors and their supply, and the associated energy-related carbon dioxide (CO_2) emissions. This analysis provides a perspective that can support the decision-making process of policy makers, energy planners, government institutions and the private sector to define a low-carbon development energy pathway in the region.

The study was developed in consultation with the ten AMS and supported by the ASEAN Centre for Energy (ACE). The engagement process included multilateral consultation and feedback through the ASEAN Renewable Energy Sub-sector Network (RE-SSN) and bilateral consultation with country-based representatives and energy specialists. The funding for this work was provided by a voluntary contribution from the government of Denmark.

This engagement resulted in regional and country-based visions and strategies for the energy transformation pathway. Outcomes include proposing technologies applicable to the energy supply and end-use sectors while respecting the context, status and characteristics of each country and the region and considering activity-level parameters and investment needs; identifying data and information gaps and providing recommendations; and supporting the development of energy transition strategies through workshops and outreach, and the provision of inputs to energy sector planning.

The ten ASEAN Member States make up around 8% of global population.

Figure 6 ASEAN countries considered in the REmap and FlexTool analyses



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Source: Wikimedia Commons.

METHODOLOGY AND PROCESS

The analysis is based on a technology modelling framework called REmap. This includes a detailed, bottom-up demand analysis for end-use sectors (industry, building and transport) for all ten AMS, and power system capacity expansion planning and operational analysis using an industry-standard modelling tool, PLEXOS, in combination with a supplementary power system flexibility analysis using FlexTool. One power system model was developed for ASEAN that represents all countries individually, and two more detailed power system models were developed for Indonesia and Malaysia within the same regional model. The models draw on unique IRENA datasets for resource endowment and technology cost data. In addition, an assessment of associated costs, investments and benefits was conducted. The work was performed in close collaboration with countries' energy experts through a series of multi-stakeholder consultative workshops and expert meetings.

This process includes the following methodological steps:

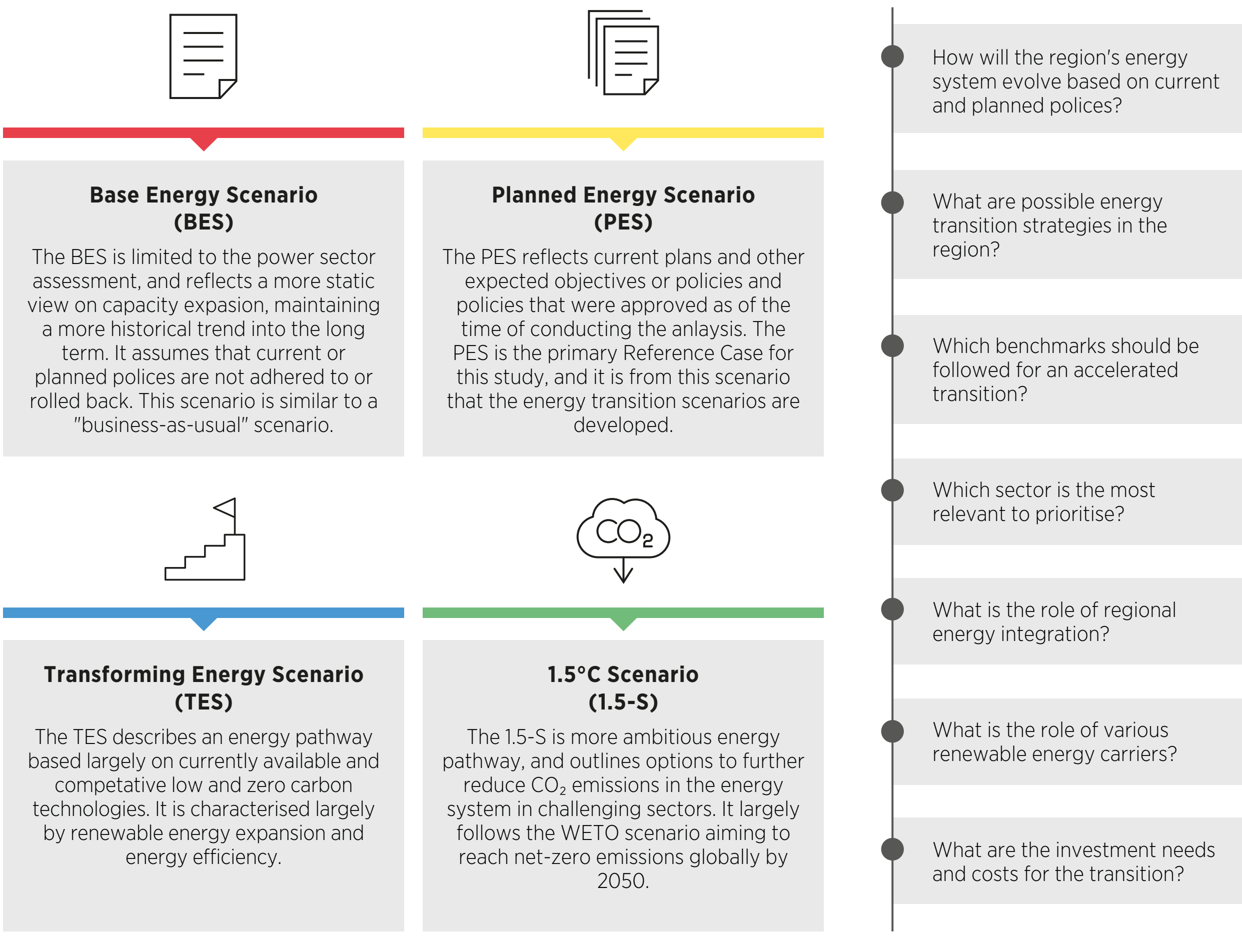
1. The **Planned Energy Scenario (PES)**, the primary reference case, is assessed. This scenario reflects energy and climate policies in place at the time of analysis. Policies or targets that have not been translated into law or planning structures are not considered. Additionally, in the power sector, a **Baseline Energy Scenario (BES)** is considered that reflects a more static view of capacity expansion based on historical precedent. BES is not considered the primary reference case but rather is used to show possible energy pathway development if policies and targets are rolled back or not adhered to. The BES pathway is only presented in certain cases in the power sector discussion.

2. An assessment of energy transition scenarios is conducted. These include the **Transforming Energy Scenario (TES)**, which largely considers "low-hanging" currently available and competitive low- and zero-carbon technologies, and a more aggressive energy transition scenario, the **1.5°C Scenario (1.5-S)**. The 1.5-S follows IRENA's WETO 1.5-S aiming to reach net-zero emissions globally by 2050. For 1.5-S, multiple power sector supply scenarios are considered for ASEAN, one with 90% renewable power generation (1.5-S RE90) and one with 100% renewable power generation (1.5-S RE100). The 1.5-S is considered the primary energy transition scenario and is largely the focus of this report.

3. Finally, an analysis of costs, investments and benefits (avoided negative externalities) of the two transition scenarios is presented. This provides a high-level, first assessment of the total investment needs, costs and benefits resulting from the energy pathways of the two transition scenarios.

This report provides multiple possible energy pathways increasing in energy transition ambition.

Figure 7 Description of the scenarios in the REmap study



Stakeholder engagement is an important part of IRENA's work when performing country and regional analysis and energy transition studies. A country and regional engagement process was conducted for the assessment of the energy scenarios presented in this study. Representatives from government ministries or institutions were the main stakeholders involved in the process. Additionally, key partners included ACE and, in the case of the work for Indonesia, Danish institutions due to their long-term engagement in creating the Indonesia energy outlook and supporting the Indonesian government with energy scenarios and planning. After an initial inception workshop conducted in July 2020, further consultation workshops were held at a regional level, such as ASEAN RE-SSN at the Senior Officials of Energy Meetings. For individual country consultation, bilateral meetings with AMS countries were also part of the engagement route to ensure close participation from ASEAN countries in the development of the study. More in-depth engagement with Indonesia and Malaysia also took place as part of their country energy transition reports, which required further discussion of scope developments and more detailed consultations about demand and power sectors. In many cases, the engagement process also involved other national, regional and international organisations and key actors working in the energy transition at country or regional levels.

Due to the timeframe of this assessment coinciding with the COVID-19 pandemic, and with international travel and in-person meetings generally restricted, consultation and engagement were largely done virtually through bilateral and multi-stakeholder meetings and workshops from 2020 to early 2022.

Box 1 REmap Toolkit and power sector analysis

The REmap Toolkit is a software environment that allows for the development of full energy balances covering the whole energy system, including energy demand, energy transformation and losses, and primary energy supply. The Toolkit is based on modules that can be used depending on the specific requirements and data availability of each project.

The toolkit is a parametric model where future energy demand and supply are assessed based on input parameters, such as activity levels, energy service penetration, technology shares and fuel mixes. These are all exogenous inputs to the model, and energy demand is fully determined from those inputs through deterministic model equations. The toolkit's demand analysis does not rely on cost-optimisation or multi-criteria decision algorithms to assess energy demand. Those are determined from expert judgement in consultation with literature and country experts.

The main group of modules of the REmap Toolkit is called the REmap Activity Tool and covers the assessment of energy demand for end-use sectors. The Activity Tool is flexible and can accommodate a detailed bottom-up analysis based on granular activity and technical parameters or a top-down analysis based on aggregated socio-economic information. The choice of the method and level of detail depends on the availability of information and was decided as the analysis developed. For this report, the analysis was based largely on a bottom-up assessment.

Energy demand is broken down into four main sectors: buildings, transport, industry and other consumption. Each in turn can be further divided into sub-sectors such as residential and commercial buildings, passenger and freight transport, and different types of industry. In the bottom-up approach each sector/sub-sector is analysed based on detailed activity and technology characterisation of energy demand. This is a data-intensive approach that depends on the availability of an extensive set of information such as population, households, floor area, transport demand in passenger-kilometres (km) and tonne-km, energy service penetration rates, technology penetration rates, fuel mixes, specific energy consumption by technology type, etc. The top-down approach is based on aggregated socioeconomic data such as population, gross domestic product (GDP), number of households and aggregated energy intensity indices.

Box 1 REmap Toolkit and power sector analysis (continued)

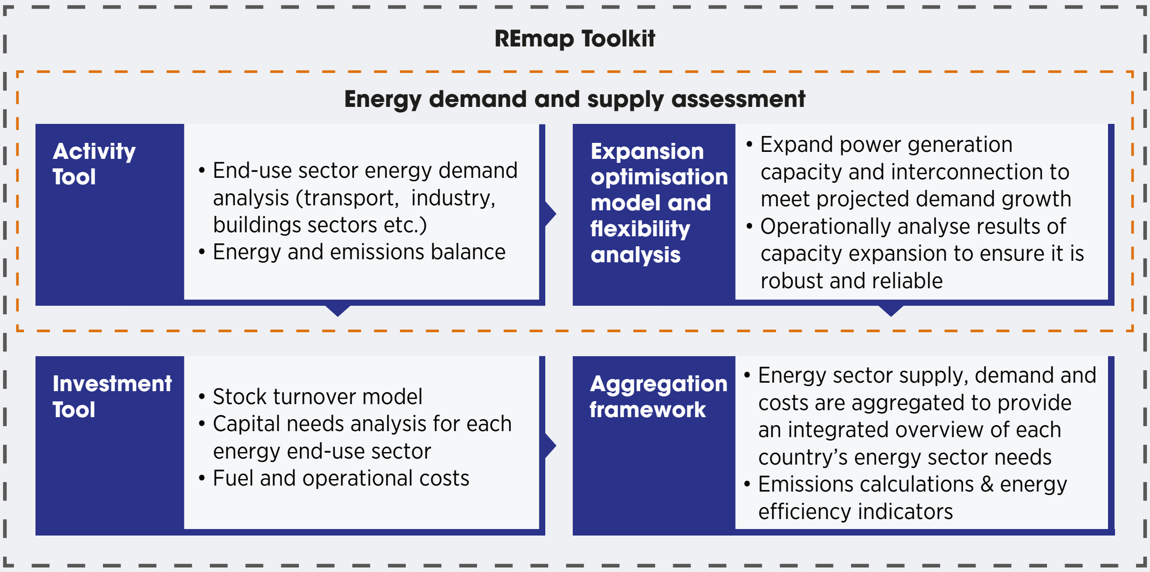
Energy demand was estimated on a yearly basis, year-by-year, throughout the timeframe of the analysis, with special attention paid to the base year (2018) and two future years (2030 and 2050). Yearly data for electricity demand are then used in the supply-side models. For other, non-electricity carriers, the REmap Toolkit offers a simplified supply-side assessment for different carriers, including bioenergy, hydrogen, e-fuels and fossil fuels. The REmap Toolkit also includes the estimation of CO_2 emissions and an assessment of costs, investments and benefits in terms of avoided externalities.

For the power sector, this study uses the commercial software PLEXOS for both the long-term capacity expansion and operational analysis. Additionally, IRENA's FlexTool (which is free and open-source) performs power system flexibility assessments based on the resulting capacity expansion in key milestone years. The FlexTool assessments reflect full power system dispatch and offer a detailed view of flexible generation options, demand flexibility and energy storage, along with sector-coupling technologies such as power-to-heat, electric vehicles (EVs) and hydrogen production through electrolysis.

Figure 8 shows the interaction of the different tools to perform energy analyses of the end-use and power sectors, as well as estimations of investment, for the regional assessment.

The analysis presented in this report is based on numerous models and tools.

Figure 8 REmap tools for analysis of the end-use and power sectors



THE ROADMAP FOR ASEAN

2

2. THE ROADMAP FOR ASEAN

CURRENT STATUS AND THE PES

Under the PES, the region will continue its reliance on fossil fuels, with renewable energy and electricity consumption growing modestly and energy consumption per capita more than doubling from 30 gigajoules (GJ) in 2018 to 63 GJ in 2050.

The region's continued reliance on fossil fuels in the PES will result in total energy-related CO_2 emissions doubling today's level to almost 2.8 gigatonnes (Gt) of CO_2, driven mainly by transport, power and the industrial sector.

The PES will see growth in some renewable energies, namely solar photovoltaic (PV), which will grow to over 1 000 gigawatts (GW); however, this will not be sufficient to reduce the overall growth in power sector emissions.

In 2020, ASEAN was home to around 680 million people, with a regional GDP of nearly USD 3 trillion (United States dollars). This report uses GDP growth rate projections from the government studies and plans that form the basis of the PES. It is necessary to align the GDP growth from these studies with the energy demand projections that form the basis of the PES. Based on those projections and scenarios, by 2050 the region's population will increase to slightly over 800 million inhabitants, and regional GDP will more than triple to over USD 11 trillion, increasing at a compound annual growth rate of 4.6%.

ASEAN will continue to see robust economic growth along with a growing population.

Table 3 Regional population and GDP, 2020, 2030 and 2050

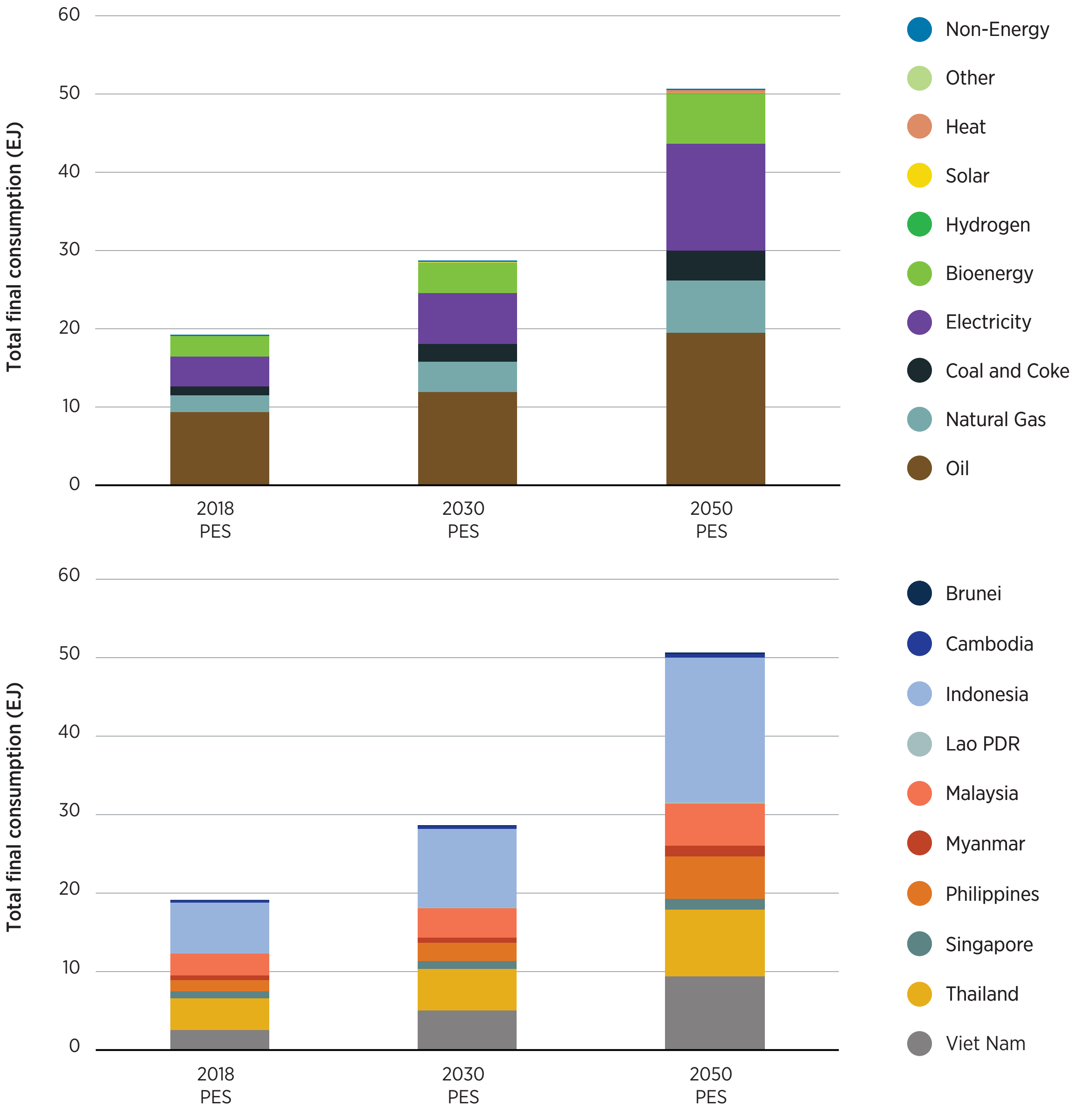
	2020	2030	2050
Population (millions)	660	722	802
GDP (billions, constant 2015 USD)	2 880	4 600	11 110
GDP per capita (constant 2015 USD/capita)	4 350	6 380	13 750

Total final consumption in the region was around 19 000 petajoules (PJ) in 2018, with the building sector consuming around 20%, the transport and industry sectors around one-third each, and non-energy the remainder. Oil and its products made up the majority share of energy consumption, followed by electricity, natural gas, biofuels and coal. Over the period to 2050 in the PES, energy consumption will increase 2.5 times to more than 50 exajoules

(EJ). All energy carriers grow, with electricity and natural gas seeing the largest in growth terms, but oil will remain the primary energy carrier. By country, energy consumption is largely focused on Indonesia, Malaysia, the Philippines, Thailand and Viet Nam, with the most growth seen in Indonesia, the Philippines and Viet Nam.

Coinciding with robust economic growth, ASEAN will also see energy demand increase 2.5-fold up to 2050.

Figure 9 Total final consumption by carrier and country, PES, 2018-2050

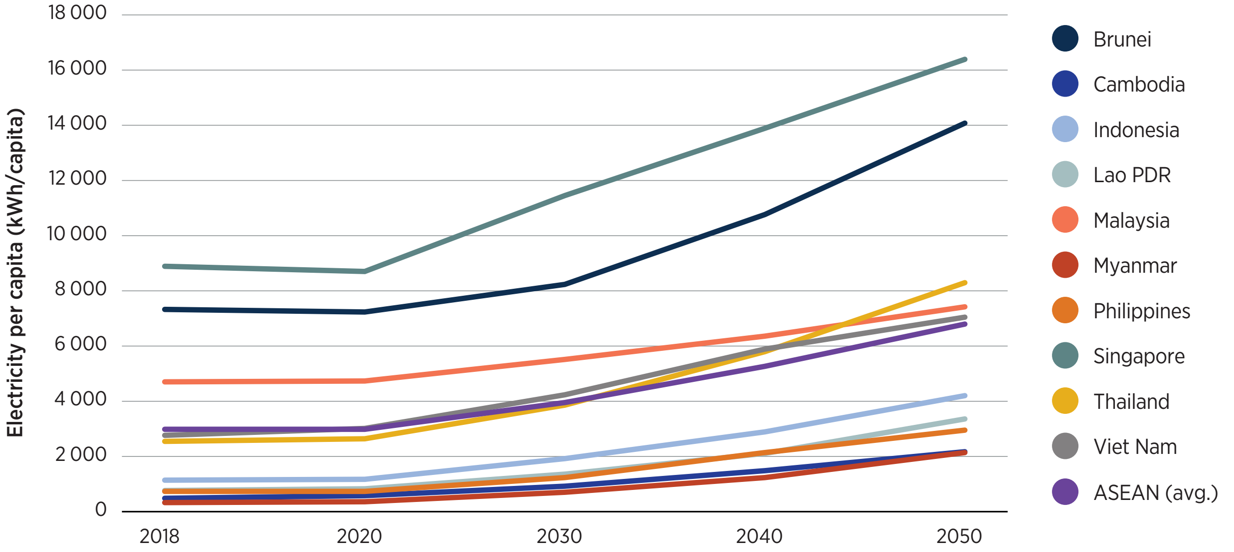


Per capita annual electricity consumption in the region has increased over the last two decades, reaching an average of 1 630 kilowatt hours (kWh) in 2018; this is around one-fifth of the per capita electricity consumption in member countries of the Organisation for Economic Co-operation and Development (OECD). Per capita total final energy consumption (TFEC) in the region was an estimated 29.5 GJ in 2018 and is expected to increase 35% by 2030 and 210% by 2050 under current national energy policies (the PES), with the region's per capita annual electricity consumption reaching 6 815 kWh. Myanmar, Lao PDR and Cambodia are the countries in which per capita electricity consumption grows the most.

These demographic and energy statistics demonstrate the need for integrated energy planning not only on the supply side (to cover rising energy demand in an optimal way), but also in the end-use sectors, ensuring the rational use of energy while also considering potential environmental and socio-economic impacts.

Electricity consumption per capita will rise over 50% in the coming decades.

Figure 10 Annual electricity consumption per capita, PES, by country, 2020-2050

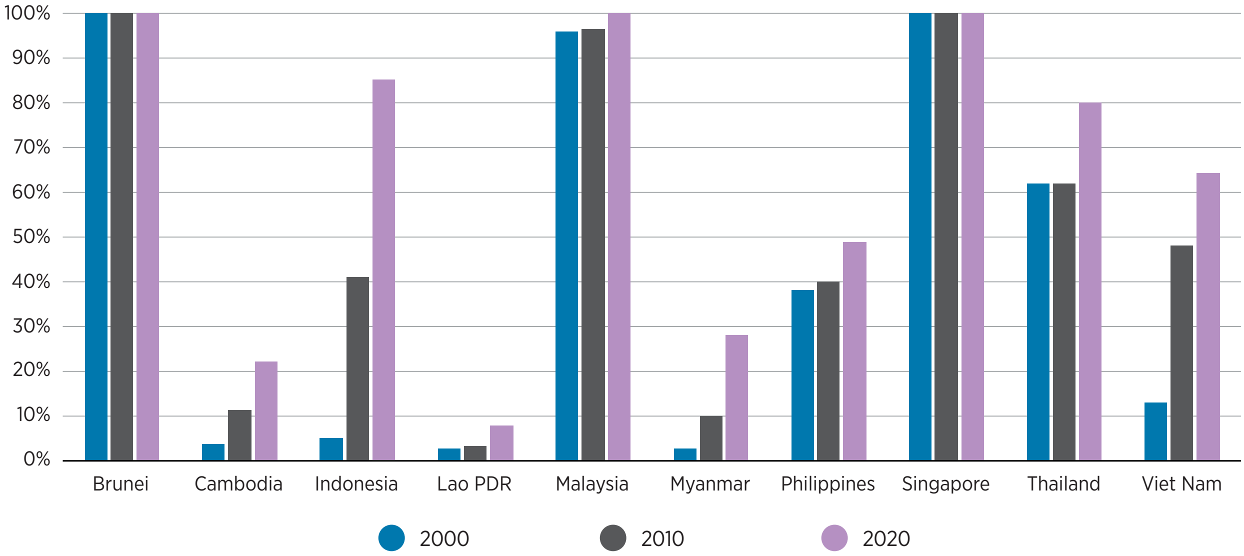


Most countries in the region had reached 100% or near-100% electrification rate as of 2020, apart from Myanmar at 70% (IEA, IRENA, UNSD, World Bank, WHO, 2022). Indonesia and Lao PDR aim to achieve 100% electrification by the end of 2022, while Myanmar targets full electrification by 2030. With more rural areas achieving last mile connectivity to the national grid, efforts must be in place to ensure access to good, reliable and affordable electricity.

The share of the population in ASEAN that has access to clean cooking varies greatly between countries. Only three countries have reached shares close to, or at, 100%. Significant improvement in the last two decades as seen in Indonesia and Viet Nam (see Figure 11) are due to LPG programmes, while some countries promote the use of efficient cookstoves. According to ACE, as of 2017 around 60 million households, or 240 million people, still cook with traditional biomass or non-modern fuels in ASEAN (ACE, 2020a).

Access to clean cooking fuels is one area where many ASEAN countries need to improve.

Figure 11 Share of population with access to clean cooking

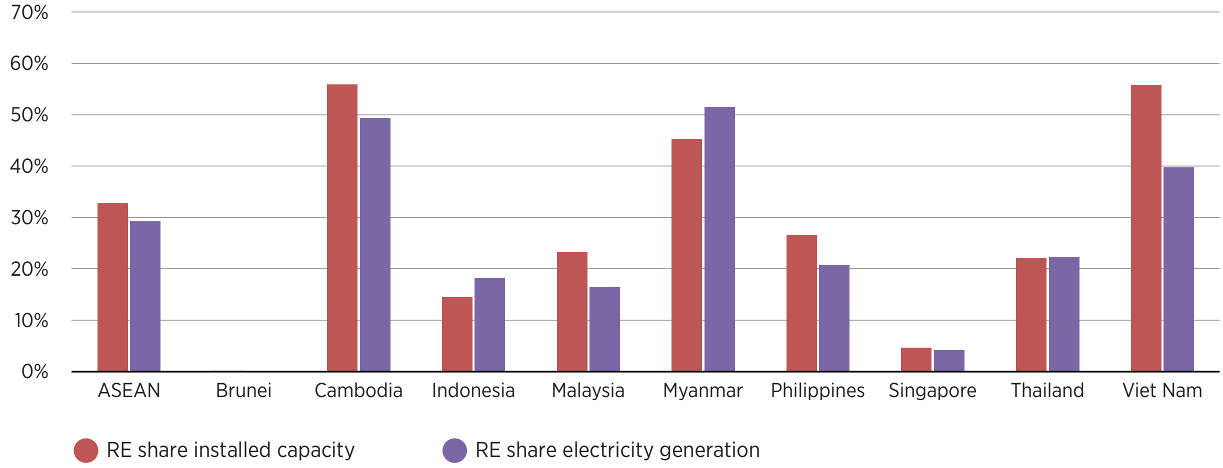


Source: WHO (2022).

As of 2020, renewable shares in power generation varied significantly among AMS, with some as high as 56% and others lower than 1%. Generally high renewable energy shares are the result of hydropower generation, though some have sizable geothermal and bioenergy production which also contribute to these higher renewable energy shares at a national level. Notable also is how in recent years, Viet Nam has made great strides in increasing its generation from solar PV and wind. The total renewable share in ASEAN for capacity and generation is 33.5% and 29%, respectively. The disparity in renewable shares at the national level is due to a range of factors, but all countries have the ability to significantly expand their renewable power portfolios.

Renewable shares range from below 1% to as high as 56% in 2018.

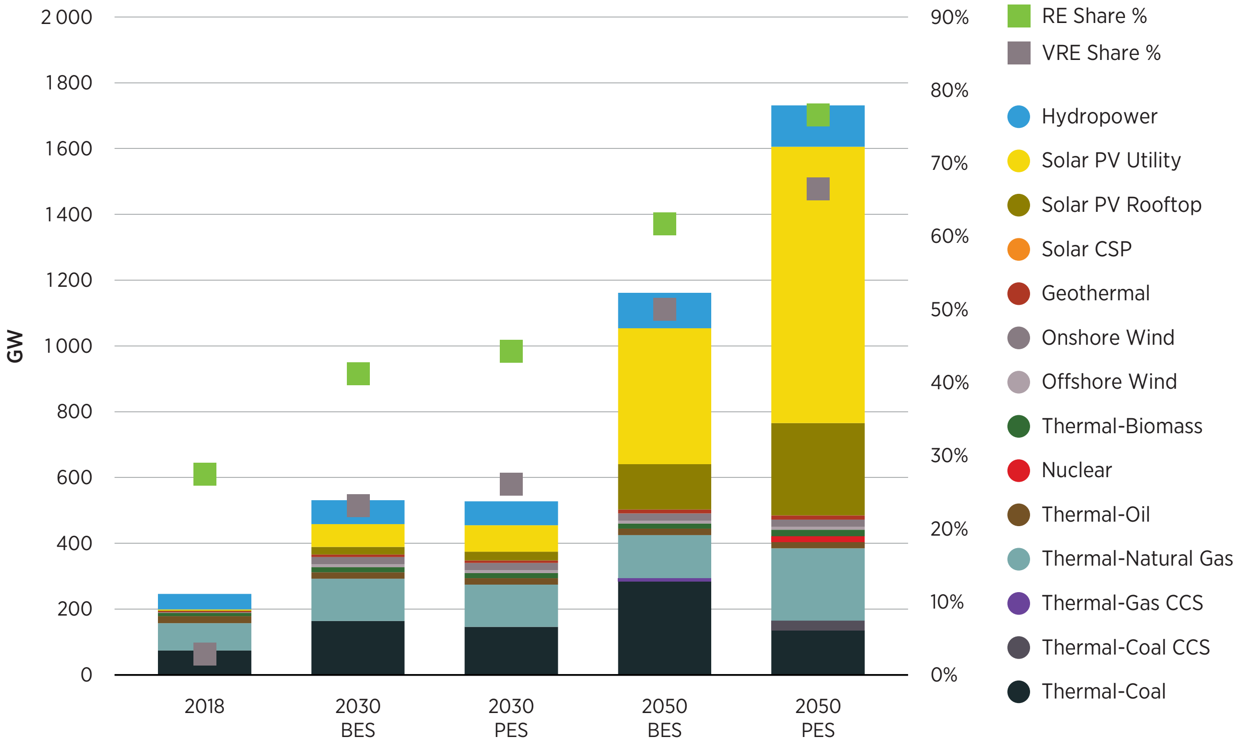
Figure 12 Share of renewable power capacity and generation in ASEAN and AMS, 2020



Source: (IRENA, 2022a).

Solar PV installed capacity will dominate the region's power sector.

Figure 13 ASEAN power sector capacity in the BES and PES

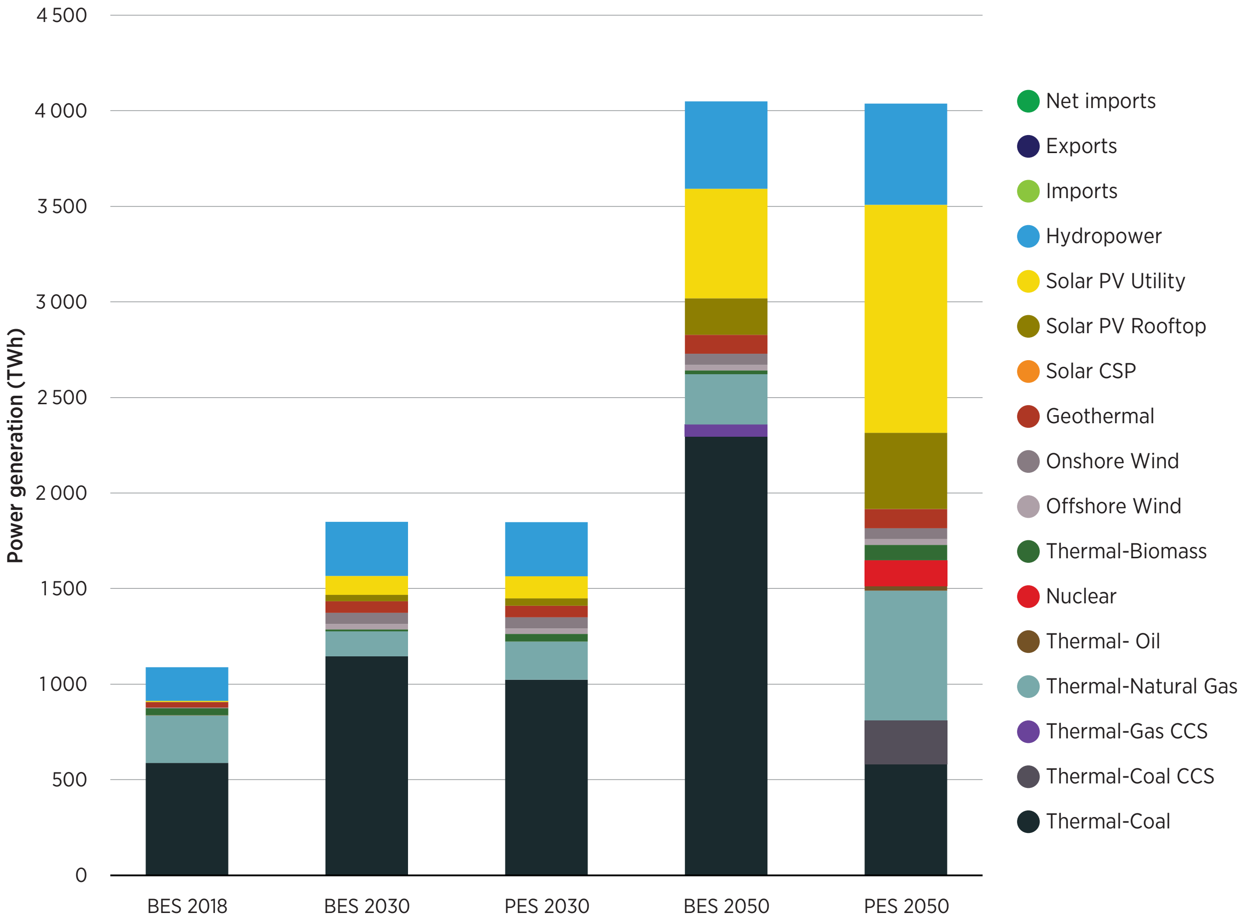


Note: RE = renewable energy; VRE = variable renewable energy.

Under current policies (PES), a short-term projection resulted in coal and natural gas comprising more than half the share of ASEAN's power system capacity in 2030. Solar PV installations are projected to reach about 100 GW, with three-quarters of the installations being utility scale. Renewables will account for only one-third of the region's total power generation in 2030. In the long term, more than three-quarters of ASEAN's installed capacity will be renewables. About 1 100 GW of this will be variable renewables dominated by solar PV, while the share of coal will fall below 10%. Solar PV will make up a large share of the region's electricity generation, nearly 1 600 TWh in 2050, with hydropower and geothermal also playing important roles. The low cost of solar PV is the main driver (see Chapter 3). Under the business as usual scenario (BES) when AMS fail to implement their renewable energy targets the region's electricity generation will continue be dominated by coal, with only 550 GW of solar PV installed capacity by 2050. However, it is important to note that in BES this solar PV enters the mix in the model for this scenario on a cost basis without any incentives because it undercuts the cost of fossil fuel generation expansion.

Solar PV, hydropower and geothermal energy will play important roles in the region's electricity generation under the PES. Under the BES, the region will continue be dominated by coal and natural gas.

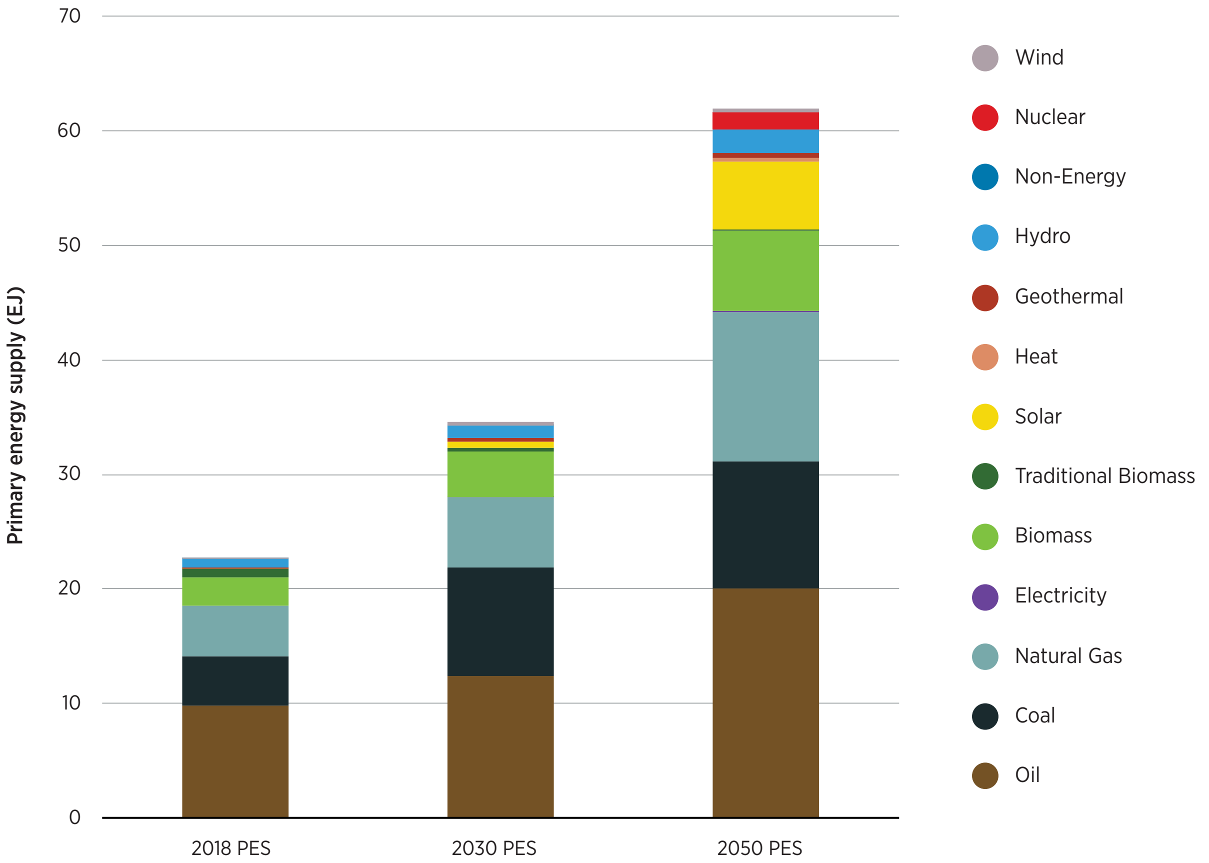
Figure 14 ASEAN power sector generation under the BES and PES



Primary energy supply under the PES in ASEAN will grow 2.8-fold from 2018 to 2050, reaching 62 EJ. Fossil fuel demand is expected to grow overall 2.5-fold by 2050, driven by a doubling of oil consumption, in large part from the transport sector. Natural gas demand is expected to grow threefold, while coal demand is expected to grow 2.5-fold, both of which are mainly used in industry and the power sector. While some AMS have domestic natural resources to cater to some growing fossil fuel demand, overall import dependency is expected to rise – as has been the case in the last decade. The volatility in global commodity prices means that becoming increasingly reliant on non-indigenous fossil fuels risks potential supply security issues and cost uncertainty.

Primary energy supply is expected to increase 2.8-fold by 2050 under the PES.

Figure 15 Primary Energy Supply, PES, 2018, 2030, 2050



CLIMATE PLEDGES

AMS take part in global climate discussions as part of the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) process. As of early 2022, all ASEAN countries had submitted Nationally Determined Contributions (NDCs) that set out either firm or aspirational commitments to reducing greenhouse gas (GHG) emissions. These commitment vary greatly in scope and ambition, ranging from all GHG to only energy, and from a few percentage points reductions to significantly more. Many reference increased ambition as part of conditional commitments that make reference to international support. Table 4 presents an overview of the broad NDC commitments of AMS as of the first half of 2022.

ASEAN Member States are committed to reducing their emission

Table 4 ASEAN Members States' NDCs

COUNTRY	MITIGATION TYPE	TYPE OF COVERAGE	SECTORAL SCOPE	MITIGATION TARGET	MITIGATION DETAILS
Brunei Darussalam	Relative emission reduction	Economy-wide	Energy, Agriculture, Transport, Waste, LULUFC (land use, land-use change and forestry), Industry	20% reduction in GHG emissions	Reduce GHG emissions by 20% below business-as-usual (BAU) levels by 2030.
Cambodia	Relative emission reduction	Economy-wide	Energy, Agriculture, Transport, Waste, LULUFC, Industry	41.7% reduction in GHG emissions	By 2030, forestry and other land use (FOLU) is expected to reduce emissions by roughly 64.6 million tonnes of CO_2 equivalent ($MtCO_2eq$)/year under the NDC scenario (41.7% reduction, of which 59.1% is from FOLU).
Indonesia	Relative emission reduction	Economy-wide	Energy, Agriculture, Transport, Waste, LULUFC, Industry	29% reduction in GHG emissions (unconditional), 41% reduction in GHG emissions (conditional)	Committed to unconditionally reducing 29% of its GHG emissions by 2030, compared to the BAU scenario, which forecasts roughly 2.87 gigatonnes of CO_2 equivalent ($GtCO_2eq$) in 2030. Indonesia might reduce its emissions by 41% by 2030, depending on foreign support for finance, technology transfer and development, and capacity building.
Lao PDR	Relative emission reduction	Economy-wide	Energy, Agriculture, Transport, Waste, LULUFC, Industry	60% reduction in GHG emissions (unconditional)	Unconditional aim for 2030: 60% reductions in GHG emissions relative to the baseline scenario, or approximately 62 000 kilotonnes of CO_2 equivalent ($ktCO_2eq$) in absolute terms.
Malaysia	Carbon intensity reduction	Economy-wide	Energy, Agriculture, Transport, Waste, LULUFC, Industry	45% reduction in GHG emissions (unconditional)	Aims to cut its economy's carbon intensity (as a percentage of GDP) by 45% by 2030, compared to 2005 level.
Myanmar	Policies and actions	Sectoral	Energy, AFOLU (agriculture, forestry and other land use) (Myanmar aspires in the NDC to further engage in other sectors to establish a base for setting an economy-wide target in the future)	Emissions reductions contributions by 244.52 million tCO_2eq (unconditional), and 414.75 million tCO_2eq (unconditional) by 2030	Total emissions reductions are 244.52 $MtCO_2eq$ unconditionally, and a total of 414.75 $MtCO_2eq$ conditionally by 2030. In the energy sector, a conditional target of avoiding 144.0 $MtCO_2eq$ emissions by 2030 compared to BAU by increasing the share of renewable energy (solar and wind) to 53.5% (from 2 000 megawatts [MW] to 3 070 MW) by 2030, and decreasing the share of coal by 73.5% (from 7 940 MW to 2 120 MW) by 2030.

Table 4 ASEAN Members States' NDCs (continued)

COUNTRY	MITIGATION TYPE	TYPE OF COVERAGE	SECTORAL SCOPE	MITIGATION TARGET	MITIGATION DETAILS
Philippines	Relative emission reduction	Economy-wide	Energy, Agriculture, Transport, Waste, Industry	2.71% reduction in GHG emissions (unconditional), 72.29% reduction in GHG emissions (conditional) compared to BAU scenario by 2030	Commits to a projected 75% reduction and avoidance of GHG emissions, of which 2.71% is unconditional and 72.29% is conditional, in the sectors of agriculture, waste, industry, transport and energy from 2020 to 2030. This commitment is measured against predicted cumulative economy-wide emissions of 3 340.3 $MtCO_2eq$ over the same time under BAU conditions.
Singapore	Peak of carbon emissions	Economy-wide	Energy, Agriculture, Waste, LULUFC, Industry	Intends to peak emissions at 65 $MtCO_2eq$ around 2030	Intends to peak emissions at 65 $MtCO_2eq$ around 2030. Note: Based on current projections, this will allow Singapore to achieve a 36% reduction in emissions intensity from 2005 levels by 2030.
Thailand	Relative emission reduction	Economy-wide (excl. LULUCF)	Energy, Agriculture, Transport, Waste, Industry	20% reduction in GHG emissions (unconditional), 25% reduction in GHG emissions (conditional) compared to BAU level by 2030	Reduce its GHG emissions by 20% from the projected BAU level by 2030. The level of contribution could increase up to 25%, subject to adequate and enhanced access to technology development and transfer, financial resources and capacity building support.
Viet Nam	Relative emission reduction	Economy-wide	Energy, Agriculture, Transport, Waste, LULUFC, Industry	7.3% and 9% (unconditional) reductions in GHG emissions, and a 27% reduction in GHG emissions by 2030 (conditional)	By 2025, decrease total GHG emissions by 7.3% (52.9 $MtCO_2eq$) compared to BAU, and by 2030, reduce total GHG emissions by 9% compared to BAU (83.9 $MtCO_2eq$). The 9% contribution could increase to 27% by 2030 (250.8 $MtCO_2eq$) with international support.

Note: Status as of June 2022.

As seen in Table 4, the ASEAN region has outlined in their NDCs reductions of GHG emissions in different sectors and in varying quantities. Generally these NDCs were submitted in the lead-up to the COP26 in November 2021. At that conference, and in the succeeding months, many of the countries in the ASEAN region declared even more aggressive targets, with Singapore aiming at net-zero emissions by or around in the middle of this century.

For instance, the Indonesian government has increased its climate ambition to reach net-zero emissions by 2060 or sooner. Indonesia has not yet communicated an explicit net-zero target, but explores scenarios that could lead to net zero by 2060 in its long-term strategy. The National Energy Council announced it will further assess net-zero scenarios prepared in collaboration with several line ministries and the state-owned electricity utility, PLN, to later commit to a pathway (Climate action tracker, 2021).

Thailand has also committed to avoid the potential adverse impacts of climate change from global warming. It is suggested that the target of net-zero emissions should be reached by mid-century. Thailand is aiming to achieve carbon neutrality by 2050 (Diewvilai, R., Audomvongseree, K., 2022).

Viet Nam announced a net-zero target by 2050 during the COP26. The new pledge marks a major shift in the development of the economy, especially in the energy sector.

Brunei Darussalam, whose economy has been dominated by the oil and gas industry, declared its net-zero target by 2050. The country only contributes about 0.025% of global GHG emissions. Still, the country is committed to making a substantial positive difference, as expressed in the COP26.

Malaysia has also echoed the language of countries in the region with a goal to achieve net-zero emissions by 2050. This plan has been announced in the 12th Malaysia Plan, though the two are not necessarily the same.

Finally, the Lao Ministry of Natural Resources and Environment has unveiled new measures in relation to climate change, targeting net-zero GHG emissions by 2050.

RENEWABLE ENERGY ROADMAP

Key highlights:

Renewable energy should become the primary energy source across ASEAN. In 2018, 19% of the region's final energy consumption came from renewable sources; in the 1.5-S, this share will increase to 65% by 2050.

Electrification of end-uses is a major driver, with scale-up in applications ranging from road transport, to cooking and industrial processes. The share of final energy coming from electricity will increase to almost one-half, from below one-fifth in 2018. This pairing must coincided with widescale scale up of renewable electricity.

In the 1.5-S, electrification, fuel switching to modern and renewable fuels, and energy efficiency will reduce ASEAN's total consumption by 20% relative to the PES in 2050.

The regions total emissions will increase in the short term, but under the 1.5-S they will decline to 50% below today's value by 2050 and 75% below the PES in 2050.

The Southeast Asia region will see rapid economic growth averaging 4.6% annually in the coming decades. In turn, energy use will grow rapidly. Today's energy supply is dominated by fossil fuels, which make up over 85% of primary energy. Southeast Asia stands at a crossroads. Either it can continue its reliance on fossil fuels – more of which are coming from non-indigenous sources, thereby increasing exposure to volatile, and increasingly expensive, global commodity markets – or the region can utilise the ample, affordable and indigenous local renewable energy resource in an energy transition pathway.

This chapter outlines how the region could pursue that energy transition pathway. In the most ambitious of those energy transition scenarios, the 1.5-S, renewable energy can meet two-thirds of final energy demand, cutting energy-related CO_2 emissions by 75% compared to the PES, or less than half compared to today's energy and process CO_2 emissions. This would occur while GDP increases significantly over the period. However, as is the case in the 1.5-S in WETO, other mitigation technologies will be required to reach net-zero emissions by 2050.

The energy transition will require a holistic and multifaceted transition across the entire energy system

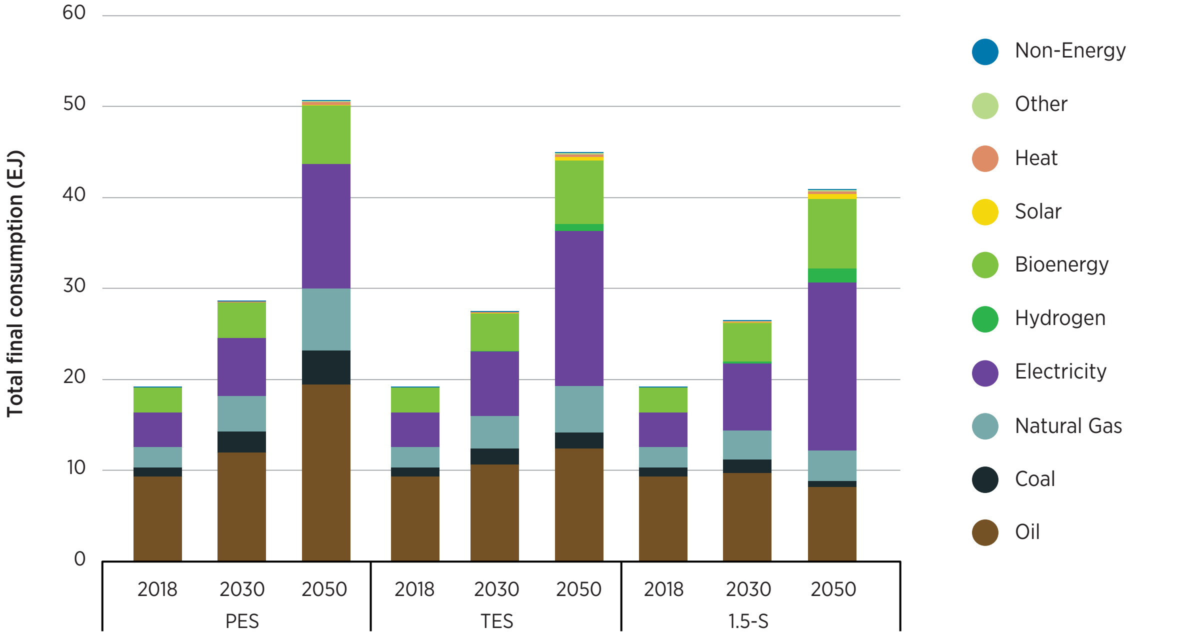
Table 5 Summary of key indicators by scenario, 2018, 2030, 2050

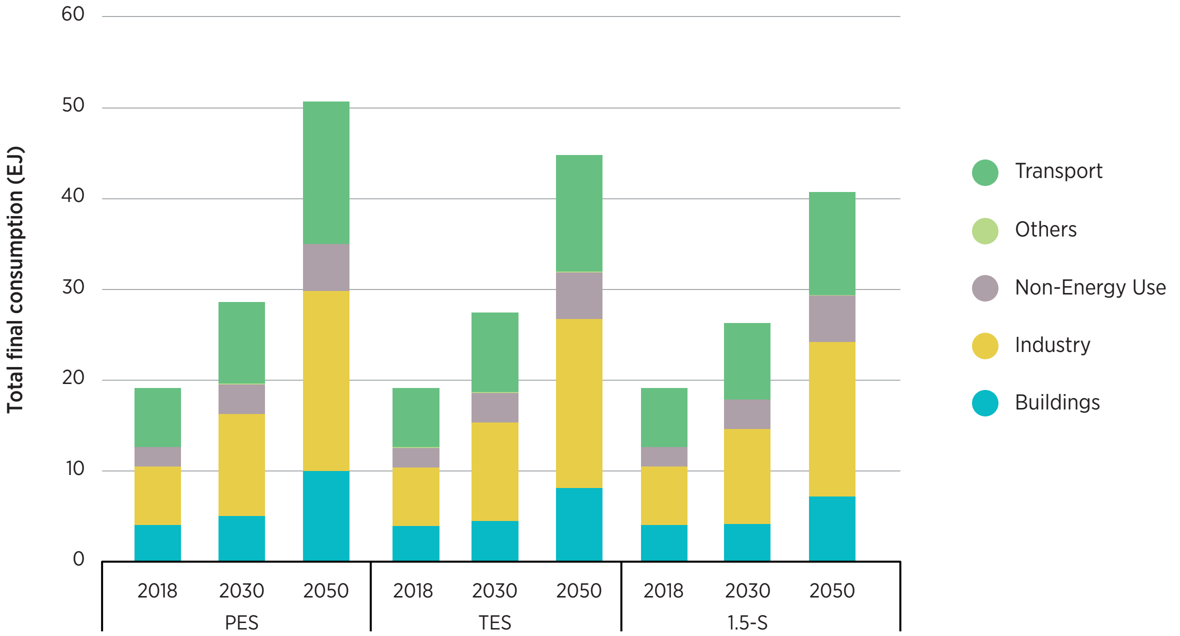
		2018	2030			2050			
		Base year	PES	TES	1.5-S	PES	TES	1.5-S RE90	1.5-S RE100
POWER	**Renewable energy installed capacity** (%)	30	46	53	57	77	86	88	99
	Renewable energy installed generation (%)	23	34	41	39	60	76	90	100
	Total Installed solar PV (GW)	5	107	142	241	1 121	1 730	2 108	2 402
SUPPLY	**Total primary supply** (EJ)	23	35	33	32	62	54	49	
	Renewable energy share (%), PECM*	18	19	24	26	25	42	60	
DEMAND	**Final energy consumption** (EJ)	17	24	24	23	45	40	36	
	Renewable energy share, fuels (%)	16	15	17	19	14	18	23	
	Renewable energy share, fuels & electricity (%)	19	21	26	27	29	45	60	65
	Electricity consumption share (%)	22	25	29	32	30	43	52	
INDICATORS	**TPES* energy per capita** (GJ/capita)	35	48	45	44	77	67	61	
	TFEC energy per capita (GJ/capita)	26	35	33	32	57	49	44	
	TPES energy intensity (MJ/USD)	8.0	7.5	7.1	6.9	5.6	4.9	4.4	
	Energy intensity improvement rate (%/year)		0.5%	0.9%	1.3%	1.1%	1.5%	1.9%	
	Electricity consumption per capita (kW/capita)	1 631	2 473	2 720	2 824	4 734	5 856	6 394	
EMISSIONS	**$GtCO_2$ – energy related**	1.4	2.1	1.8	1.7	2.8	1.2	0.7	

*TPES = total primary energy supply; kW = kilowatt; PCEM = physical energy content method.

In the 1.5-S, energy demand will double, and electricity will become the dominant energy carrier.

Figure 16 Total final consumption by scenario, 2018-2050





Total final consumption in Southeast Asia is expected to grow 2.5 times in the PES scenario from 2018 to 2050. With electrification across all sectors and energy efficiency measures, the final consumption will grow more slow to 2.3 and 2.1 times in the TES and 1.5-S. Electricity demand in the region is expected to grow on average 4.1%, 4.7% and 5.0% in the PES, TES and 1.5-S, respectively. The additional demand growth is mainly driven by EVs in the transport sector, where almost 80% of the total road fleet by 2050 will be EVs. Hydrogen will also have a growing importance, especially in the industry and non-energy sector within the region, with a lesser role in transport, accounting for 3.7% of total final consumption by 2050 in the 1.5-S. Bioenergy use will also triple from 2018 to 2050 across all scenarios, with a slightly higher share in the 1.5-S (19%) to meet more ambitious biofuel blending rate targets, and increased use in the industrial sector. A breakdown of measures across each sector for each of the scenarios is provided in the following sections.

Box 2 What the scenarios say about attaining ASEAN's near-term aspirational targets

In 2016, the ASEAN region set the aspirational goal of increasing the renewable share in primary energy to 23% by 2025 and increasing the share of renewable energy in the capacity mix to 35% by 2025. Over the past few years, the share in TPES has remained flat at around 14%, while the share of renewables in capacity has increased considerably, reaching 33.5% in 2020 (ACE, 2020a).

Based on the PES, the region can expect to meet and exceed the renewable capacity target, reaching 41% of capacity by 2025. In the 1.5-S, the target is surpassed by a considerable margin, reaching 47% of capacity.

However, the renewable share in the primary energy target will not be achieved in the PES, reaching a share of only 17%, considerably lower than the 23% target. This is also incidentally the same share that was projected in the main reference case of the 2016 ASEAN outlook (IRENA & ACE, 2016). While progress has been made in deploying renewables, namely in the power sector, overall energy demand has risen, offsetting the increase in renewables consumption. Attaining the aspirational 23% goal in the PES is not achieved because when interpreting government plans across ASEAN, which form the basis of the PES, the total share across the region does not meet that target. However, in the 1.5-S, the renewable share reaches 20% by 2025, below the target but a considerable and substantial increase of six percentage points over the current share of just 14%. Over the succeeding five years to 2030, the share will increase to 26% in the 1.5-S, exceeding the target. Therefore, the target is estimated to be achieved in the timeframe 2025-2027.

The ASEAN region is on track to meet its renewable capacity target by 2025.

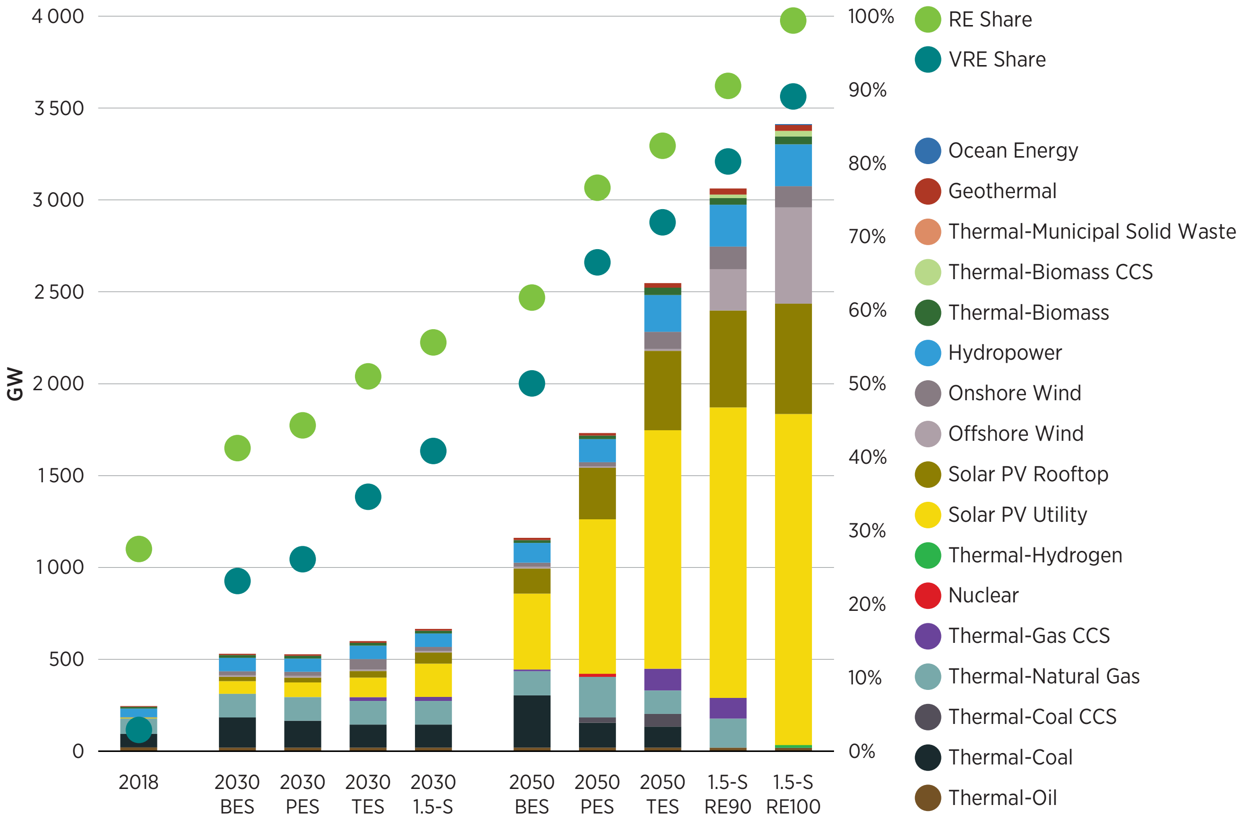
Table 6 Views on attaining ASEAN Member States' near-term targets

	2018	2020	2025		
			ASEAN target	PES	1.5-S
Renewable energy share TPES	14%	14%	23%	18%	20%
Renewable energy capacity power	28%	33.5%	35%	41%	47%

Note: The 2025 shares for the PES and 1.5-S are adjusted based on the latest shares available for 2020.

Solar PV capacity expansion will be dominant by 2050 regardless of the scenario.

Figure 17 Power capacity and renewable share by scenario, 2018-2050



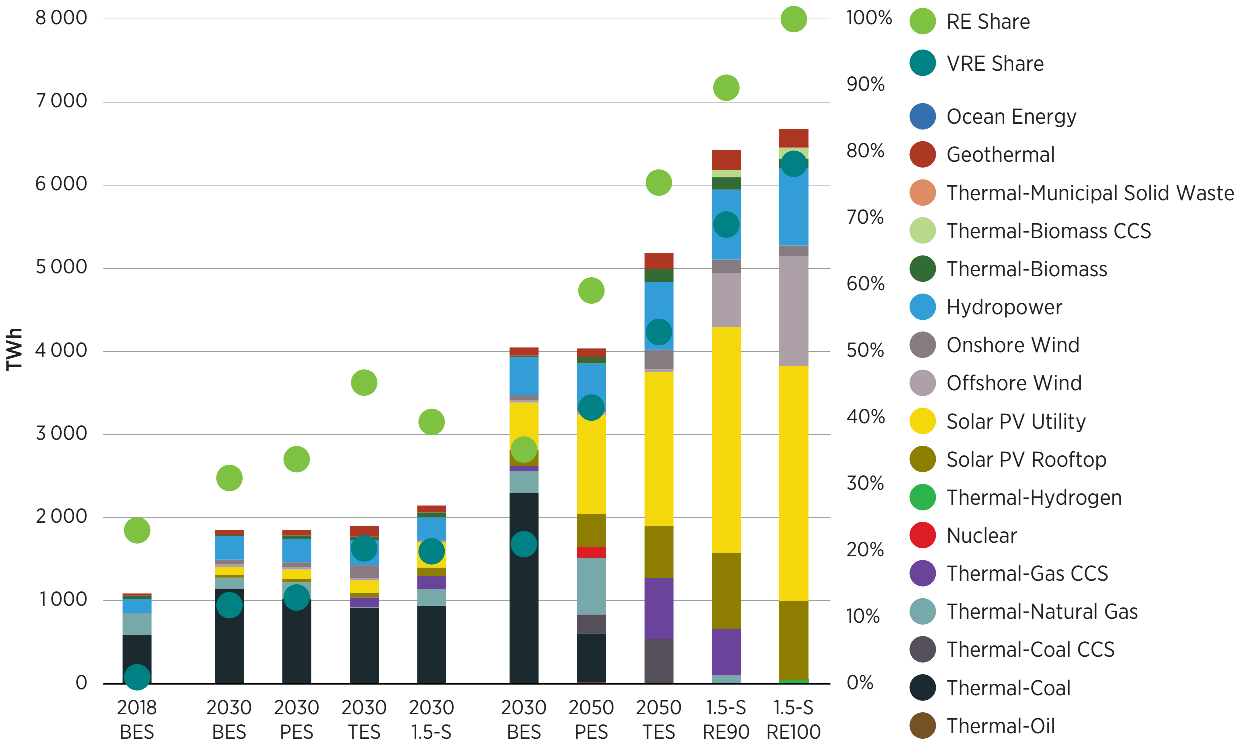
Note: RE = renewable energy; VRE = variable renewable energy.

Total renewable energy installed capacity grows substantially, reaching 62%, 77% and 82% in the BES, PES and TES, respectively, by 2050 from 27% in 2018, with variable renewable energy (VRE; mostly PV) accounting for one-half to nearly three-quarters of this renewable capacity. The two 1.5-S cases see VRE installed capacity grow to become between 80% and 90% of total installed capacity by 2050, with total renewable energy installed capacity in both the 1.5-S cases reaching above 90%. The non-renewable installed capacity will still be present in the form of natural gas, together accounting for 12%, 13% and 9% in the BES, PES and TES. The 1.5-S RE90 case sees an 8% share of these technologies in the system, while it is 0% in the 1.5-S RE100.

Electricity generation in 2050 will be dominated by renewable energy in all the scenarios except the BES, from 60% in the PES to 100% in the 1.5-S RE100. The TES will see three-quarters of ASEAN's electricity generation produced by VRE sources, and this value reaches almost 80% in the 1.5-S RE100. Achieving all these generation mixes will require significant expansion of the power system, and most will need a transformation in system operation to integrate an increasingly variable supply and demand by making and valuing flexibility as a cornerstone of system operation.

Power generation grows to over 6 000 TWh/year in the 1.5-S.

Figure 18 Power generation and renewable share by scenario, 2018-2050



Note: RE = renewable energy; VRE = variable renewable energy.

ASEAN's total energy sector emissions in 2018 were 1 434 $MtCO_2eq$, with power, transport and industry the most emitting sectors. Voluntary mitigation targets towards short-term emission reductions have been announced by several AMS.

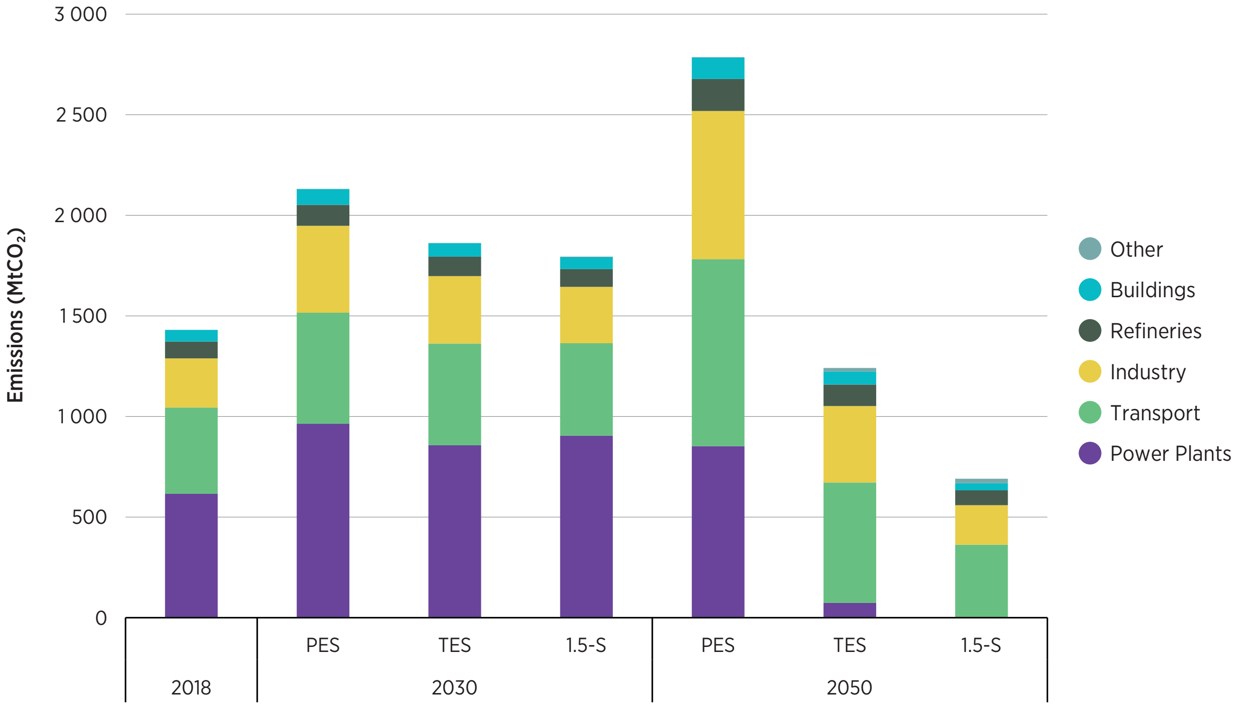
In the PES, emissions are expected to rise, reaching 1.5 times their 2018 value, at a rate of 3.4% annually until 2030, before slowing down to 1.3% annually towards mid-century. ASEAN's energy sector emissions in 2050 will be about double 2018's value under the current policy (PES). As hard-to-decarbonise sectors, industry and transport emissions grow the fastest at average rates of 3.5% and 2.4%, respectively, over 30 years. The industry sector increases its emission share from 17% in 2018 to 27% in 2050. ASEAN's aspirational target to increase renewables' share of capacity to 23% by 2025 will result in the power sector's emissions growing at a slower rate of around 1% annually and reducing its total emissions share from 43% in 2018 to less than one-third of total energy sector emissions by mid-century.

After 2030, when the established energy targets in the 1.5-S have been met and the investments in end-use technology have been made, gains in emission reductions can be expected. Emissions in 2050 may be reduced by more than one-half and three-quarters in the TES and 1.5-S, respectively, over the PES. The power sector provides the largest emission reduction gains, remaining at only about 15 $MtCO_2eq$ in the 1.5-S by 2050, coupled with the rapid deployment of renewable energy, in particular solar PV and battery storage, to curb the use of fossil fuel power plants.

The transport sector will account for half of the region's remaining emissions in the 1.5-S, followed by industry, emitting 28% of the total energy sector's emission by mid-century. Despite an increasing share, both of the sectors' emissions will reach 16% and 19% below today's level by 2050, driven by massive development of EVs, electrification of industrial activities, use of bioenergy and direct use of renewables, as well as the transition towards energy efficient technologies. The remaining emissions come from fossil fuel consumption in the heavy duty transport sector – mainly large trucks and high-temperature industry processes.

Energy-related CO_2 emissions will almost double in the PES but can be reduced 75% in the 1.5-S.

Figure 19 Total energy-related CO_2 emissions, by scenario, 2018-2050



Box 3 Regional renewable energy aspirational targets: Their status and pathways towards achievement – a view from ACE's 7th ASEAN Energy Outlook (AEO7)

Authored by the ASEAN Centre for Energy

ASEAN energy landscape and renewable energy targets

As a region with emerging economies, the energy consumption across all AMS has increased rapidly since 2005. The ASEAN total final energy demand grew 1.6 times in 2019 from 2005. It then declined by about 6.8% to 384 million tonnes of oil equivalent in 2020 due to the COVID-19 pandemic. Responding to this growing demand, ASEAN TPES has increased sharply.

Fossil fuels dominate the region's energy mix, which accounts for about 83%, of primary energy compared to 14% renewables in 2020. ASEAN has been a net oil importer since before 2005, without any significant additional reserves identified in the last decade due to exploration challenges, especially in deep-water areas. With a growing reliance on fossil fuel imports, ASEAN could face serious energy security challenges. Since the fossil fuel markets are volatile, the fluctuating prices could affect the affordability of fuels needed by the ASEAN economies.

All ten AMS have recognised the urgency of energy security and decarbonisation, which is reflected in their energy-related targets and policies. The energy transition policies range from increasing the share of renewables in the electricity mix to reducing the energy intensity in all sectors. To further support the AMS national targets and to guide the region towards enhanced energy security, accessibility, affordability and sustainability, the ASEAN Plan of Action for Energy Cooperation (APAEC) was established. Now in its second phase, APAEC 2016-2025 reaffirms the strong commitment of AMS to accelerate the energy transition and strengthen energy resilience through greater innovation and co-operation (ACE, 2020b). It sets the target to increase the renewable energy share to 23% of TPES and 35% of installed capacity by 2025. Although the renewable energy share in installed capacity has almost reached the 2025 target, more ambitious efforts from the AMS are needed to realise its renewable energy target in TPES.

Box 3 Regional renewable energy aspirational targets: Their status and pathways towards achievement – a view from ACE's 7th ASEAN Energy Outlook (AEO7) (continued)

Status and projection of regional renewable energy targets: Insights from the 7th ASEAN Energy Outlook (AEO7)

Despite the global pandemic, renewable energy growth in ASEAN has shown resiliency. According to the renewable energy target monitoring in 2022, the region achieved 33.5% renewable energy share in installed power capacity in 2020, which means only 1.5 percentage points are required to achieve the regional target.

Among these, hydro led the way with 20.9%, followed by solar with 8%. Bioenergy and geothermal are underutilised with 2.1% and 1.4%, respectively. Based on the AMS power development plans, 60% of the newly installed capacity between 2021-2025 will be from renewables. With these, 37.6% of installed capacity in 2025 will be in the form of renewable energy. This is 2.6 percentage points higher than the regional target of 35%.

Meanwhile, the renewable energy share in TPES in 2020 was recorded as reaching 14.2%, an increase of 0.7 percentage points from its reported value in 2019. Compared to the AMS National Target Scenario of the 6th ASEAN Energy Outlook, such a feat exceeded 0.6% of the projection value in 2020 (13.6%). Even so, it is still lagging behind. Therefore, to achieve the 2025 target of 23%, prompt actions and efforts to increase the renewable energy share are required.

To support AMS, the 7th ASEAN Energy Outlook (AEO7) provides the latest status of regional energy targets and explores the potential pathways toward achieving those targets. Part of this is the evaluation of the national targets and policies toward regional targets, the potential gaps, and the strategies to close such gaps. The Baseline Scenario of the 7th ASEAN Energy Outlook (AEO7) projects that in 2025, only 14.4% of the TPES will be in form of renewable energy. Assuming the AMS manage to achieve their national renewable energy targets, the AMS National Target Scenario projects that a total of 17.5% share of renewable energy in TPES can be achieved in 2025. This, of course, still leaves a gap of 5.5 percentage points to reach the regional renewable energy target. To fill the gap, a more ambitious APAEC Regional Target Scenario shows the potential pathways to achieve the 23% share of renewable energy in TPES by 2025.

Towards the achievement of the aspirational targets

The COVID-19 pandemic and the geopolitical conflict between Russia and Ukraine have caused the recent energy crunch and the economic slowdown. The declining energy consumption during the pandemic implies less supply, limiting the need for capacity expansion. Although renewable energy development has demonstrated better resiliency than fossil fuels, policy intervention is still essential to maintain the growth of renewable energy capacity. For example, the inclusion of renewable energy as part of the framework of AMS' green recovery should be considered.

However, the existing national policies are insufficient to achieve the APAEC targets. With only a few years remaining until 2025, a more ambitious renewable energy target, robust policy implementation and enhanced co-operation among AMS are necessary. Focusing the effort on increasing the renewable energy share of installed capacity is not enough. It should be translated into electricity dispatch. In addition, electrification of end-use sectors and higher bioenergy utilisation in the transport and industrial sectors should complement the decarbonisation of the supply side, because these two are the most energy-intensive sectors.

The promotion of EV use and higher biofuel blending should work together to effectively increase the intake of renewable energy supply in the transport sector. With the domination of motorcycles and private vehicles in ASEAN, the improvement of fuel economy and EV adoption offer significant room for the share of renewable energy share to shift the sector away from oil use and achieve better efficiency. This is especially true given that biofuel use is not yet optimised, with only a 7% share of transport fuel mix by 2020.

The intermittency issue of wind and solar is often raised as the main bottleneck to decarbonising the power system fully. However, commercial development of energy storage technologies has opened the possibility of elevating renewable energy's role as the baseload generation. Though current energy storage costs are not low enough for the renewable energy project to reach price parity with fossil-based generation, grid improvement could be a low-hanging fruit to ramp up the dispatch rate of renewable energy immediately. In addition, ASEAN still has many untapped geothermal and bioenergy resources to leverage renewable energy utilisation as baseload generation alongside hydropower.

In conclusion, achieving the regional target is within reach if AMS improve their collaboration to strengthen policies for end-use renewables, smarter and flexible infrastructure to allow high renewable energy penetration in the future, and diversification away from coal and gas.

DEMAND SECTORS

Key highlights:

- In the 1.5-S, the renewable energy share in TFEC will increase to cover 65% of the region's 2050 energy demand, led by wide-scale scale up of direct-use of renewables, and electricity.
- Electricity will become the dominant energy carrier consumed by the region in the 1.5-S 2050, growing its share from around 22% in 2018 to 52% in 2050 in TFEC.
- Industry is projected to be the most energy-consuming end-use sector by mid-century, increasing its share in the region's total final consumption from around 33% in 2018 to about 40% in 2050 under all the scenarios analysed.
- Demand for sustainable bioenergy will grow almost 2.5-fold by 2050 under the PES and nearly 3-fold under the 1.5-S, in the form of modern biomass and liquid biofuel in the industry and transport sectors. Overall bioenergy demand will only slightly more than double due to the phase out of traditional uses of bioenergy.
- Fuel switching to renewables, electrification and increased energy efficiency will reduce the region's total energy demand by 20% in the 1.5-S compared to the PES in 2050.

The end-use demand sectors, which include buildings, industry and transport, are the key drivers for energy demand growth in ASEAN. ASEAN's energy demand will grow 3% annually, reaching over 2.8 times today's value in the PES by 2050. Energy efficiency, fuel switching and electrification in the 1.5-S will slow down energy demand growth by around 20% compared to the PES, yet growth even in the 1.5-S will be significant and require energy sources that are zero carbon.

Electricity dominates end-use energy consumption in both the TES and the 1.5-S. Industry will be the major consumer of end-use sectors' energy demand in all the scenarios, followed by transport. The building sector's energy demand will grow overall but will reduce demand in the 1.5-S by 27% over the PES in 2050 due largely to electrification and energy efficiency improvements.

Building sector

Key highlights:

- The share of renewable fuels and electricity will grow from 78% to 84% in the PES and to 92% in the 1.5-S in 2050. The building sector has a traditionally high share of renewable energy due to biomass consumption.
- The share of space-cooling energy demand grows from 17% to about 50% of the total building sector's energy demand in the 1.5-S in 2050, highlighting the key importance of considering cooling needs in future building construction and retrofitting.

Electricity is the key to decarbonising the building sector.

Table 7 Building sector summary, by scenario, 2018-2050

BUILDING SECTOR	2018	2030 PES	2030 TES	2030 1.5-S	2050 PES	2050 TES	2050 1.5-S
Final energy consumption (PJ)	4 093	5 080	4 522	4 256	9 983	8 210	7 318
Renewable energy component – incl. traditional biomass (%)	31%	14%	12%	12%	5%	6%	7%
Solar thermal (PJ)	-	2	8	12	16	53	82
Electricity shares in buildings (%)	46%	62%	65%	67%	78%	82%	85%
Clean cooking (%)	64%	73%	80%	84%	78%	84%	85%
Electric stove (million units)	17.6	32	58	70	67	123	160
Solar water heaters (million units)	0.04	0.3	0.7	1.1	2.4	5.4	8.6
CO_2 emission ($MtCO_2eq$)	271	370	312	296	333	66	42

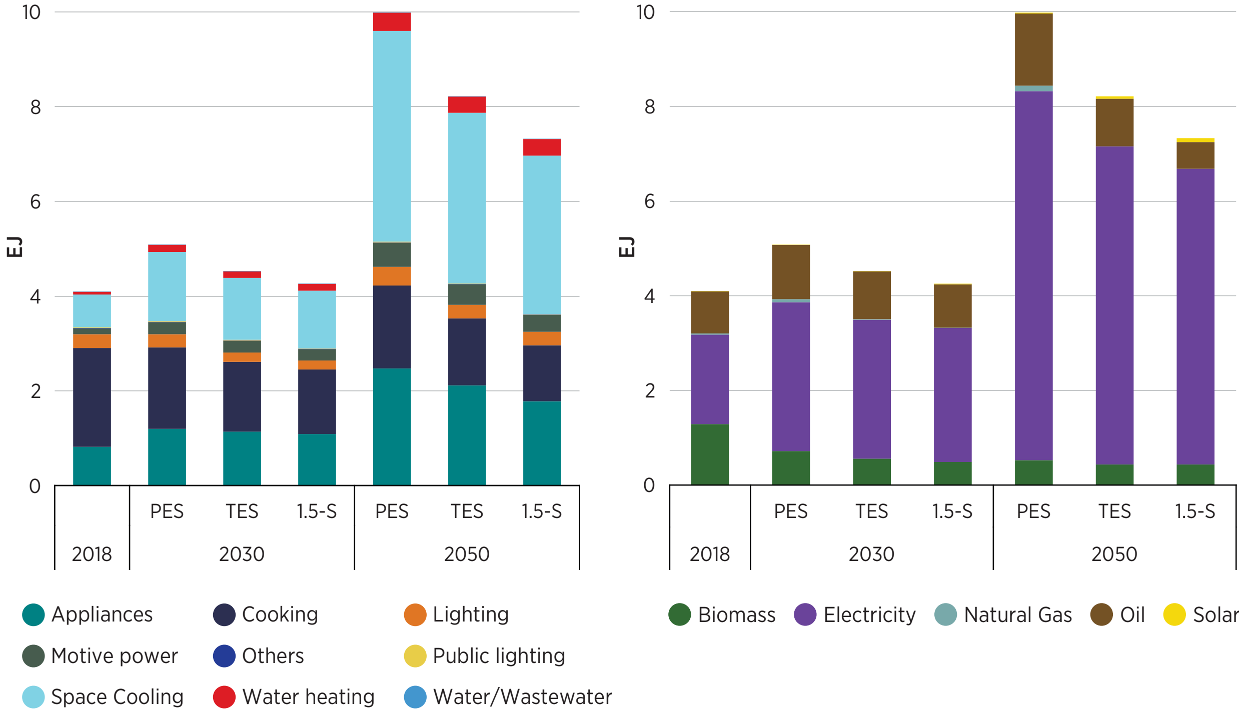
Driven by floor areas almost doubling and the total population reaching more than 800 million by 2050, ASEAN's building sector energy demand will grow nearly 3% annually, reaching 10 EJ by 2050 under the PES. Space cooling and appliances will grow the fastest, spurred by economic and population growth. Space cooling will dominate the building sector's energy demand, growing from a 17% share in 2018 to almost 50% in 2050. Overall, this represents a growth of over six times 2018's energy consumption.

More stringent energy efficiency standards will be necessary. If implemented, they will reduce electricity demand from space cooling by about one-quarter and one-fifth in the 1.5-S and TES, respectively, over the PES by mid-century. The share of cooking energy demand will fall below 20% in 2050, mainly due to the phaseout of traditional biomass and the transition towards clean cooking technologies, mainly LPG in the PES and electric cooking in the 1.5-S. Both of IRENA's transformation scenarios emphasise the utilisation of electric stoves, mainly in the residential sector and small commercial businesses, substituting LPG as the main carrier. Overall electrification, and more stringent energy efficiency implementation, will reduce the building sector's energy consumption by 18% and 27% in the TES and 1.5-S, respectively, over the PES.

Electricity will be the building sector's dominant carrier in the future. Oil products will account for about 15% by 2050 in the PES, but will decrease below 10% in the 1.5-S. The utilisation of biomass will decrease significantly from about 33% of buildings' total energy demand to only about 5% in all the scenarios, in the form of modern biomass.

Electrification and energy efficiency reduce buildings' energy demand by one-quarter in the 1.5-S in 2050 over the PES.

Figure 20 Building sector consumption, all scenarios, 2018-2050

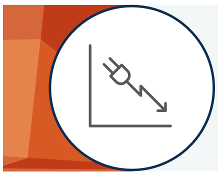


Industry sector

Key highlights:

Industry consumed over one-third of the region's energy demand in 2018 and will continue as the largest consuming sector in 2050, rising to over 20 EJ of demand in the PES.

Under the PES, the sector continues its reliance on fossil fuels with over half of the sector's energy coming from fossil fuels, and a quarter of the sector's energy in the form of electricity.



Renewable fuels, electrification, hydrogen and efficiency allow the sector to reduce its total energy demand in the 1.5-S by 15% over the PES in 2050, with electricity accounting for over 50% of demand and renewable fuels and hydrogen making up a 30% share.

The industry sector accounts for one-third of the region's energy demand in the end-use sectors. This trend will continue in the future driven by rapid economic development and manufacturing in the ASEAN countries. In the PES, the industry sector's energy demand will grow over 3.6% annually until mid-century, rising to over 20 EJ. The fuel mix will continue to be majority fossil fuels, with over half of the sector's energy coming from fossil fuels. In the 1.5-S, energy efficient technology, electrification and the direct use of renewables will see total industry sector energy demand reduced by 15% in the 1.5-S in 2050 and the share of renewable energy in the total energy demand of the sector rise to three-quarters.

Electrification, bioenergy and hydrogen are the key drivers for the energy transition in the industry sector.

Table 8 Industry sector summary, by scenario, 2018-2050

INDUSTRY SECTOR	2018	2030 PES	2030 TES	2030 1.5-S	2050 PES	2050 TES	2050 1.5-S
Total energy consumption (PJ)	6 048	11 027	10 591	10 175	20 138	18 602	16 951
Non-energy consumption (PJ)	2 142	3 261	3 257	3 257	5 162	5 154	5 139
Electricity share (%)	29%	27%	34%	37%	25%	43%	53%
Renewable energy share (incl. electricity)	46%	47%	57%	61%	47%	67%	76%
Renewable energy direct use (PJ) (biomass + solar thermal)	1 011	2 045	2 053	1 967	4 115	3 169	2 705
Hydrogen (PJ)	-	-	26	43	22	441	628
Hydrogen in non-energy use (PJ)	-	-	38	97	4	261	703
Energy intensity (GJ/USD)	2 146	2 395	2 300	2 209	1 812	1 674	1 525
Emissions ($MtCO_2eq$)	480	748	700	675	892	380	205

Fossil fuels make up the majority of the industry sector's carrier consumption. The share of fossil fuels in ASEAN's industry sector was 53% in 2018. Natural gas alone accounted for 21% of the sector's energy consumption in 2018. Despite reducing its share, fossil fuel will continue accounting for over half of the sector's energy consumption in the PES by 2050. Electricity use will grow, and will be the largest, non-fossil fuel carrier consumed, covering about a quarter of the sector's energy consumption in 2050.

The electrification of process heat in the 1.5-S will see electricity account for over half of the sector's energy consumption by mid-century. The utilisation of solar thermal offers additional options in decarbonising low-temperature process heat. Fossil fuels still play a role, but their share will fall to less than one-fifth of total energy demand, more than half of which will come from natural gas. These fossil fuels are used for high-temperature industrial process. The availability of biofuel in ASEAN allows the sector to benefit from the utilisation of modern biomass and reduce dependency on fossil fuels for some high-temperature processes. The region will also see the role of green and blue hydrogen increase for some industry segments starting around 2030.

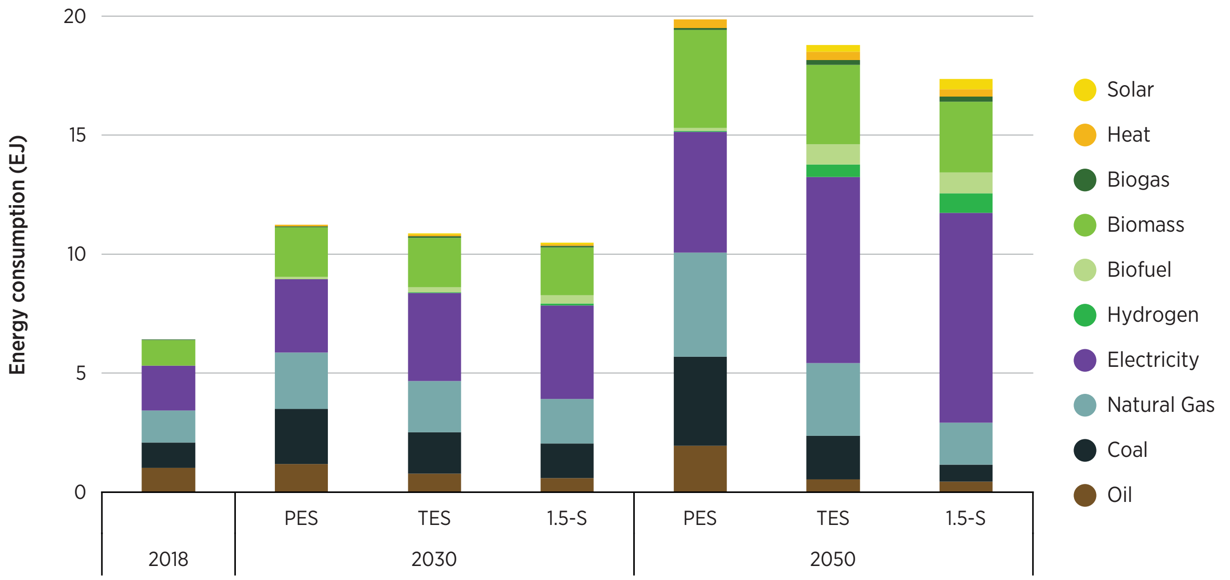
Modernising infrastructure and new growth across ASEAN is a driver for growth in iron and steel as well as cement. Data from the Southeast Asia Iron and Steel Institute showed total steel consumption in Indonesia, Malaysia, Philippines, Singapore, Thailand and Viet Nam and was about 80 million tonnes in 2019 (SEAISI, 2021). Indonesia, Thailand and Viet Nam were the largest steel consuming countries in the same year. The ASEAN region is seen as attractive for steel investment and many of the ASEAN countries also foresee expansion of integrated carbon steel mills in the future (SEAISI, 2020). Further development could be spurred through comprehensive economic partnerships among the member states, which are aiming to eliminate 90% of tariffs in 20 years.

Eight ASEAN countries have a significant cement industry with considerable production of clinker (Singapore and Brunei are exceptions due to their small size and land mass). The cement industry can be categorised as "mature" in Malaysia and Thailand; "emerging" in Indonesia, the Philippines and Viet Nam; and "frontier" in Cambodia, Lao PDR and Myanmar (SEAISI, 2020). Overall, energy demand in ASEAN for the iron, steel and cement industries will grow 3.2% annually to 2050, reaching nearly 2 EJ in the PES.

The petrochemical sector will see an average growth of 2.7% per annum in the region to 2050, especially driven by Brunei, Malaysia, Thailand and Viet Nam. In the 1.5-S, a larger proportion of the petrochemical feedstock will need to come from green hydrogen and biobased fuels by 2050, especially in the production of ammonia and methanol, in line with the announced net-zero targets from the oil and gas companies in the region.

Electricity and the direct use of renewables will play important roles in decarbonising the industry sector.

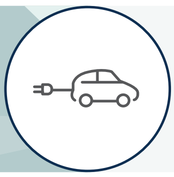
Figure 21 Industry energy consumption, all scenarios, 2018-2050



Transport sector

Key highlights:

Oil products continue their dominance in the transport sector in the PES, with only 5% of the sector electrified by 2050. Biofuels grow to 10% of sector energy by 2050 in the PES.



Many AMS have initiated a policy to transition towards EVs, and in the 2050 1.5-S the share of the sector's energy that comes from electricity will increase to 30%; however, over 80% of passenger road activity will be electric.

Due to the need to look for alternatives to oil products for heavy road transport, shipping and aviation, the share of biofuel consumption in the sector will grow from 5% today to 25% in 2050 under the 1.5-S.

Electrification, biofuel and energy efficiency improvements will reduce the sector's energy demand by 27% in the 1.5-S over the PES by mid-century, with the share of electricity reaching 30% of total fuel consumption.

The transport sector made up the largest share of the region's end-use energy demand in 2018, with road transport making up 90% of the sector's energy consumption. Driven by population and economic growth, the sector is projected to grow on average 3% annually, reaching almost 2.5 times today's energy consumption by 2050 under the PES. Gasoline and diesel comprised about 85% of the sector's total energy demand, whereas biofuel's share was around 5% in 2018. The share of oil products will fall from 93% in 2018 to 83% in the PES by 2050 but will still make up the majority share. The share of gasoline reduces from 50% to about 39%, while diesel consumption will continue to account for one-third of the sector's energy demand.

The transition to EVs for light-duty transport and biofuel for heavy-duty transport is key to the energy transition in the transport sector.

Table 9 Transport sector summary, by scenario, 2018-2050

TRANSPORT SECTOR	2018	2030			2050		
		PES	TES	1.5-S	PES	TES	1.5-S
Total energy consumption (PJ)	6 444	8 933	8 708	8 362	15 583	12 835	11 353
Electrification of transport (%)	-	2%	5%	7%	5%	18%	30%
Biofuels in transport (million litres)	9 957	39 183	47 866	57 017	64 867	93 175	111 904
Biofuel share in transport fuels (%)	4.8%	11%	13%	15%	10%	16%	25%
EVs - motorcycles (millions)	-	21	53	71	83	246	299
EVs - cars (millions)	-	2.6	8.9	13	19	86	108
Installed EV chargers (millions)	-	0.7	2.3	3.6	5.0	22.4	31.1
Emissions ($MtCO_2eq$)	431	567	542	511	952	598	367

Many ASEAN countries have shown an interest in reducing their dependency on fossil fuels and transitioning towards EVs. Despite these government plans, electricity will comprise only 5% of the sector's total energy consumption in 2050 in the PES. The biofuel blending rate within the ASEAN region differs country to country depending on the availability of resources. Increased biofuel blending targets set up by several countries will drive biofuel consumption to grow almost tenfold, reaching 1.6 EJ by mid-century. Indonesia has the highest biofuel blending rate, increasing from 19% in the base year to 79% by mid-century in the 1.5-S. Singapore has banned new diesel car sales from 2025, and the Singapore Green Plan 2030 requires that all cars and buses registered by 2040 run on cleaner energy. Indonesia has accelerated the EV target, aiming for 12 million EV cars and 13 million e-motorcycles by 2030. Looking at the burgeoning EV and battery storage industry in Indonesia, it is possible that development in the country will accelerate more quickly. Malaysia's Low Carbon Mobility Blueprint 2021-2030 envisions a 15% share of electric motorcycles and 20 000 electric cars by 2030.

Road transport continues to grow with population and economic growth.

Table 10 ASEAN vehicle stock growth (million units), by mode

	2018	2030	2050
Motorcycle	220	272	349
Car	53	82	165
Microbus	2.1	2.4	3.4
Bus	1	1.5	2.3
Small truck	7.6	11.8	25
Large truck	2.1	3.1	6.5
Total	**287**	**374**	**553**

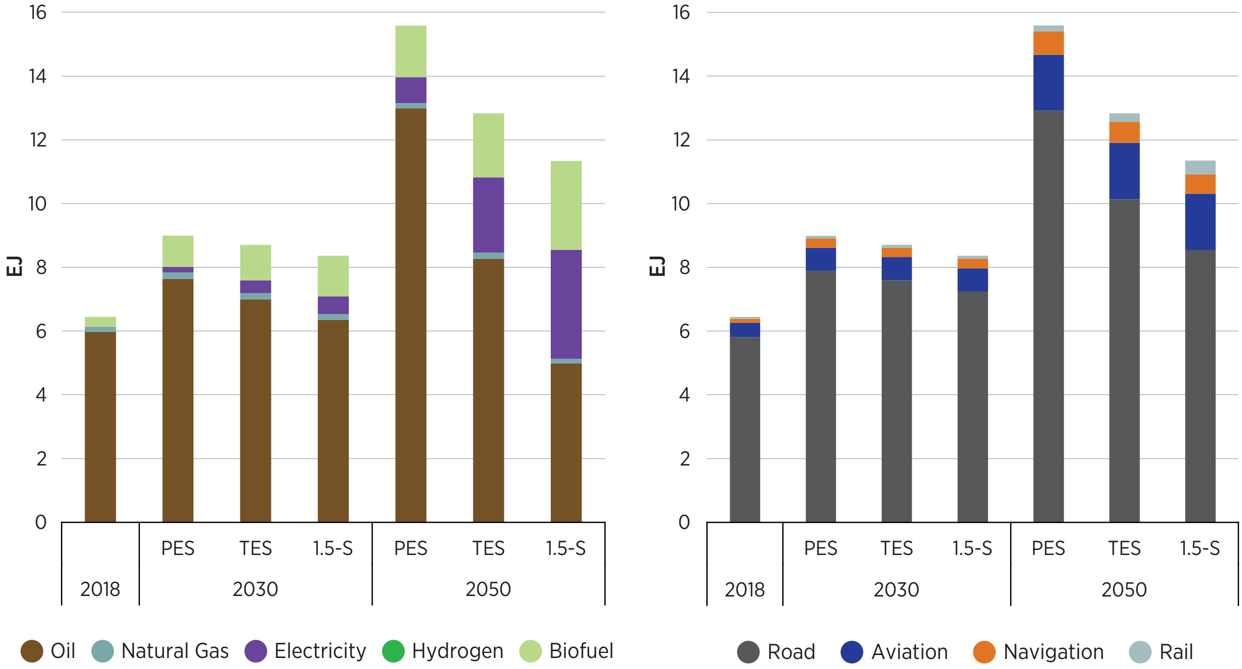
An accelerated transition towards EVs in IRENA's 1.5-S will see electricity's share grow to 30% of the sector's total energy consumption by 2050. Total EV stock in the 1.5-S reaches about 440 million, or four times more than the PES. Electric cars comprise around 25% while electric motorcycles make up almost 70% of the total EV population in the 1.5-S 2050. The number of electric cars and electric motorcycles in the 1.5-S by mid-century is six and four times over the PES, respectively.

Oil products continue to have a role in the sector, accounting for a 44% share, mostly consumed in heavy-duty freight, shipping and aviation. This translates to a more than 60% oil fuel reduction in the 1.5-S over the PES. The share of biofuel grows to one-quarter, because it is an important fuel for decarbonising heavy-duty road transport.

The result of a switch to electricity, and higher overall efficiency, means that in the 1.5-S the transport sector's energy demand will grow on average only 1.8% annually – lower than the PES at 2.8%. Total transport energy demand in the 1.5-S is one-quarter lower than the PES by mid-century, but still almost double the sector's energy demand in 2018.

The transport sector will see an aggressive transition towards EVs and biofuels.

Figure 22 Transport sector energy consumption, all scenarios, 2018-2050



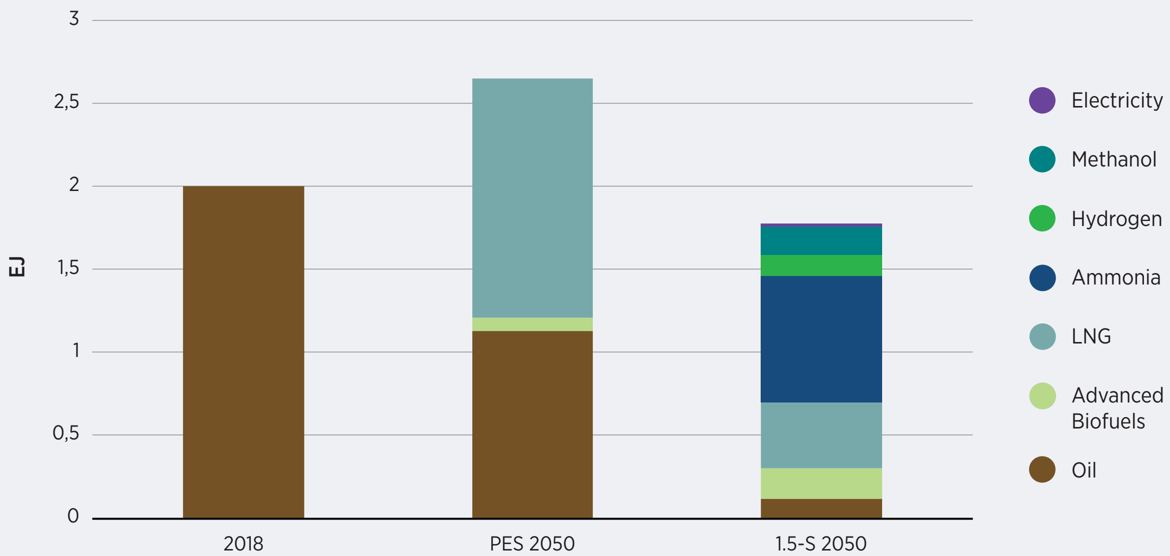
Box 4 Decarbonising international shipping and aviation in Southeast Asia

Maritime transport

Situated in one of the busiest trading routes, Southeast Asia currently captures almost a quarter of the bunkering fuel market for international shipping, while Singapore provides 21% of bunker fuel requirements globally (IEA, 2021). About 98% of the fuel is oil based, but there is increasing demand for low-carbon, very low sulphur fuel oil (VLSFO) and liquified natural gas (LNG) as the International Maritime Organization adopts mandatory measures to reduce the sector's GHG emissions.

International bunkering for shipping will need to shift from oil to a broader mix of fuels.

Figure 23 International shipping bunkering demand in ASEAN, by scenario, 2018-2050



Box 4 Decarbonising international shipping and aviation in Southeast Asia (continued)

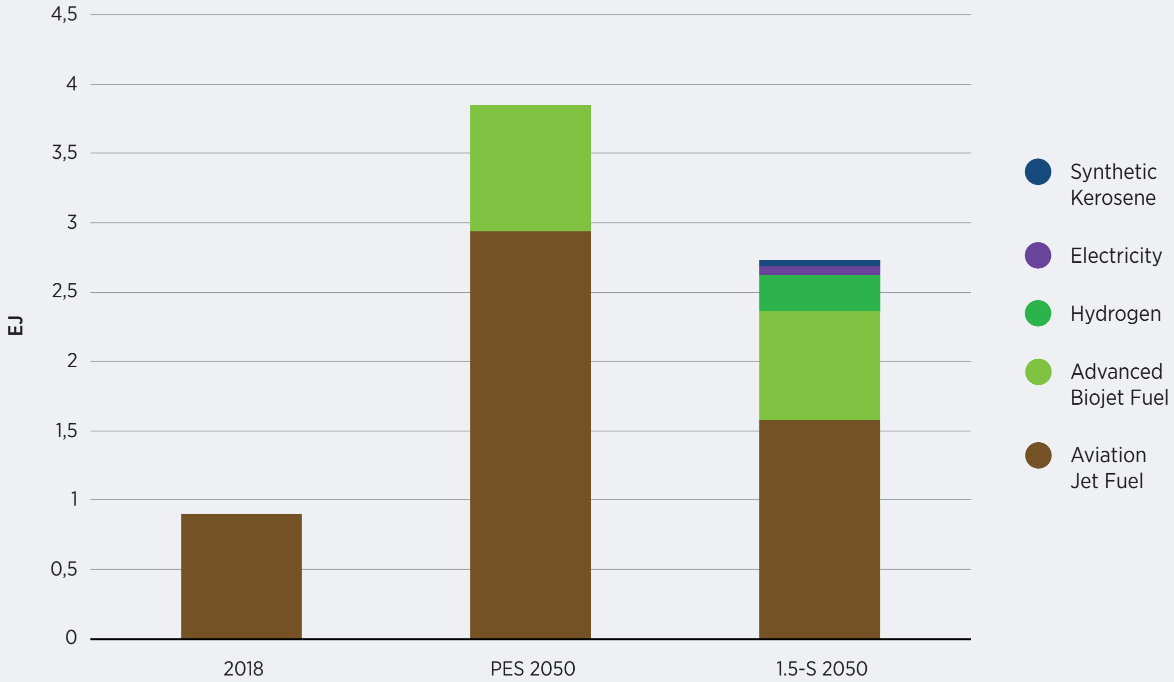
IRENA's *World Energy Transitions Outlook* (WETO) 1.5°C scenario outlines how, by 2050, 60% of all fuel needed for international shipping will be from hydrogen and its derivatives, including ammonia and methanol (IRENA, 2022b). According IRENA's analysis of the global supply chain for hydrogen, Southeast Asia has the potential to produce up to 64 EJ of cost-effective green hydrogen across the whole region. Therefore, there is opportunity for countries to capture part of the market share of providing low-carbon bunkering fuels from excess renewable-energy-based electricity (IRENA, 2022d).

Aviation

In addition to domestic demand, around 18% of all international aviation passengers either depart or arrive from a Southeast Asia country, where 10% of bunkering demand is fulfilled in the region (ICAO, 2021; IEA, 2021). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) scheme by the International Civil Aviation Organization obligates airlines to monitor and report emissions while aiming to offset GHG emissions through technological and operational improvements and sustainable aviation fuels (SAFs).

Fuels for international aviation will rise significantly across ASEAN.

Figure 24 International aviation bunkering demand in ASEAN, by scenario, 2018-2050



Currently, more than half of AMS have agreed to voluntarily participate in the CORSIA scheme from 2023. Recent initiatives in the region also indicate that SAFs are already being used in the region, with several airlines participating in pilot flights using blended SAFs. IRENA's WETO 1.5°C scenario proposes that around 47% of aviation fuel come from biokerosene and 27% from synthetic kerosene by 2050. While aviation energy demand within ASEAN is expected to grow threefold from 2018 to 2050, the demand for SAFs would still constitute 14% of the global demand in the 1.5-S.

POWER SECTOR

3

3. POWER SECTOR

Key highlights:

Electricity demand could grow by as much as fivefold compared to today's levels by 2050 in ASEAN in the 1.5-S resulting from the wide-scale electrification occurring across end-uses.

How power generation capacity is expanded to meet this demand will be instrumental in addressing national CO_2 emissions. If no action is taken, sectoral emissions could rise from 650 Mt/year today to over 2 000 Mt/year by 2050.

ASEAN has a vast wealth of renewable energy resources. Key among these is solar PV, which has an overall resource potential of about 15 terawatts peak (TWp). Integrated planning in distribution, transmission and generation capacity will be needed to determine how and where these resources are developed so that they can be effectively and meaningfully unlocked in a high renewables pathway.

To achieve a high renewables pathway, renewable energy projects need to be identified and prioritised in national and international expansion planning and be bankable. Existing power purchasing agreements for coal units in particular have the effect of disincentivising this process due to their flexibility, long-term PPA, and "take or pay" fuel contracts. Such issues hamper renewables expansion planning and are a barrier to renewables expansion and coal phaseout.

Note: PPA = Power Purchase Agreement.

OVERVIEW AND SCOPE

To be consistent with a climate-compatible world, the electricity sector will have to be thoroughly decarbonised by mid-century across the ASEAN region. Accomplishing this will require accelerating the deployment in power generation of all forms of renewable energy technologies: wind (onshore and offshore), solar PV, hydropower, biomass and geothermal energy, among others. Wind and solar PV will lead the transformation, supplying up to 20% of total electricity generation by 2030 (from just over 1% today) in ASEAN.

ASEAN's power sector is a key source of emissions and spans a vast region which is operationally integrated to varying degrees and in some regions through an electrical interconnection system. The large share of coal-fired generation means the power sector's 649 $MtCO_2$ of emissions in 2020 are responsible for the biggest share of energy sector emissions, with coal representing over 80% of the power sector's emissions. The expansion of coal generation over recent and coming years means that the emissions intensity of electricity has been and will continue to be on an increasing trend in the near term. The scale of ASEAN's emissions mean that it is a pivotal player in any global emissions reduction pathway.

To achieve decarbonisation goals in a climate-compatible pathway will require higher levels of electrification across the energy system combined with increased levels of renewables penetration. However, measures designed to achieve such goals must also have security of supply, affordability and environmental considerations at their heart. Historically, ASEAN has over-projected electricity growth, which is an important consideration in the context of such ambitious levels of electrification. The 1.5-S power sector analyses did consider the impacts of lower potential electrification levels on capacity expansion, but the systems were largely of a similar composition, which indicates that attaining a lower level would not inhibit or alter the technology mix needed at an overall high level, just its overall magnitude.

ASEAN has significant resources of both fossil fuels and renewables, but the vast majority of its renewable energy potential remains to be developed. To date, the key renewables in the power sector have been geothermal and hydropower. There has been very little development of wind and solar PV generation in most countries with the notable exception of Viet Nam, which had a combined installed capacity of approximately 21 GW by 2021 (IRENA, 2021a). Additionally, bioenergy also currently plays a minor role with nearly 9 GW installed by 2021 (IRENA, 2021a) of its approximate potential of 76 GW, which implies significant scope for growth. The renewable energy resource potential used in this study can be seen in Table 11.

ASEAN's renewable energy potential massively exceeds current deployment.

Table 11 ASEAN's renewable energy potential for power generation

	RENEWABLE ENERGY RESOURCES (GW)					
	PV	ONSHORE WIND	OFFSHORE WIND	BIOMASS	HYDRO	GEOTHERMAL
Brunei Darussalam	1.9	-	-	-	0.1	-
Indonesia	2 898	19.6	589	43.3	94.6	29.5
Cambodia	1 597	2.5	88.8	-	10	-
Lao PDR	983	11.9	-	1.2	26	0.1
Myanmar	5 310	2.4	-	1	40.4	-
Malaysia	337	-	53.3	4.2	29	-
Philippines	122.5	3.5	69.4	0.2	10.5	4
Singapore	0.3	0.1	-	-	-	-
Thailand	3 509	32.4	29.6	18	15	-
Viet Nam	844	31.1	322.1	8.6	35	0.3

Source: See text.

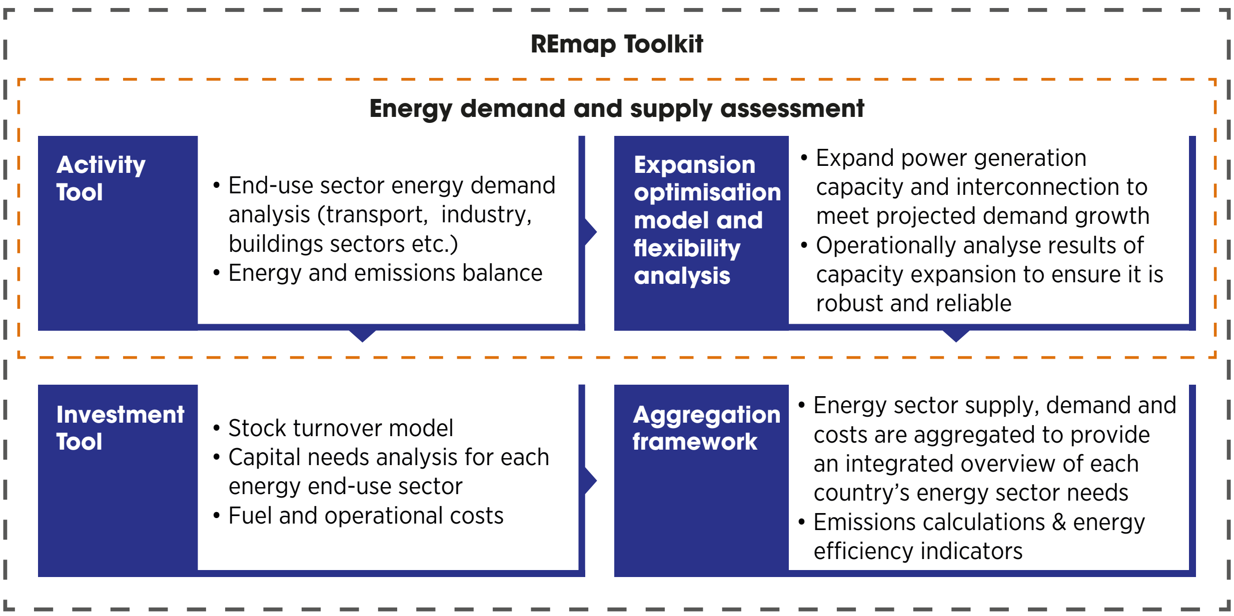
Renewable energy resource potentials used for bioenergy, hydropower and geothermal in this analysis were derived from a range of published reputable national and international studies (DGE *et al.*, 2021; Handayani *et al.*, 2022; IRENA, 2022e). Given the seasonality of hydropower, its generation pattern varies in each country across the year. Thus, the model was calibrated in this regard based on best available data which was either provided by national bodies or extracted from the PLEXOS World model (University College Cork, 2019).

However, to determine the solar and wind potentials, and respective resource hourly profiles, an analysis was performed using the same methodology as was applied in *Global hydrogen trade to meet the 1.5°C climate goal: Part III – Green hydrogen cost and potential* (IRENA, 2022j). This used a geographic information system search engine with extraction layers to determine these potentials and their hourly generation profiles for five different classes each respectively of resource quality (Amante and Eakins, 2009; Amatulli *et al.*, 2018; Friedl *et al.*, 2010; Gao, 2017; IUCN *et al.*, 2022; Maclaurin *et al.*, 2019; Service (C3S), 2017). Given the scale of the resources, in particular solar, such a representation was crucial in understanding the role that they can reasonably play in the long-term expansion of the ASEAN power system by capturing the opportunities and challenges they have in terms of renewable energy integration. It was also important in understand how wind power in ASEAN can be expanded, despite the large national potential in some countries the quality of this resource and its location may make it too costly to effectively harness.

The methodological approach applied across this study seeks to deliver an assessment that meets the growing energy demand across ASEAN member states whilst also delivering on several key regional goals in terms of emissions reductions, energy costs, energy security and energy access. This requires an integrated approach that spans the whole energy system of the region and captures the evolution of all energy end-use sectors such as transport, industry and buildings out to 2050 with high granularity (*e.g.* passenger transport, industrial process heat, building cooling and miscellaneous appliances etc.). This was achieved by using the approach outlined in Figure 25, in which the energy supply and demand assessment composed three separate modelling activities 1) Activity-level demand assessment; 2) capacity expansion of the power sector; and 3) operational flexibility analysis of the power system. This enabled the power system to be expanded based on the understanding gained of how energy demand will evolve and what levels of electrification of these energy demands can be achieved whilst maintaining reliable operation of the system. This in turn enabled a tailored capacity expansion to be developed to deliver emissions and energy cost reductions whilst bolstering energy security and access, largely through increased deployment of renewables across ASEAN in an operationally robust power system.

IRENA's REmap environment consists of many intercorrelated analyses.

Figure 25 REmap Toolkit overview



For the power sector the analysis consists of two key parts: a long-term capacity expansion analysis for all scenarios of energy demand resulting from the activity tool assessment with a view to capturing a broad range of possible power system developments out to 2050; and, an operational assessment of these scenarios for power system flexibility. In the case of this study, both the long-term expansion and short-term operational flexibility analyses were performed using an industry-standard modelling tool, PLEXOS.

The power system long-term expansion analysis was guided by two key questions:

1. What is the role of national and regional integration in unlocking the potential benefits of a joint energy transition strategy?
2. What is the role of various technologies in achieving a highly renewable and low-carbon power sector?

The answers to these questions depend on the energy demand scenarios considered and wide-ranging assumptions in the power system expansion modelling. Scenarios such as BES and PES were designed to best represent "business-as-usual" and best available national plans, respectively. While TES strives to deliver higher renewable and decarbonisation ambition than BES and PES, and both 1.5-S cases (a 90% and 100% renewable power generation case) expand on this with a focus on deeper decarbonisation in designing power system technology pathways that can deliver a climate compatible future for ASEAN. The rationale for this capacity expansion analysis is shown below in Table 12 and spans four pillars.

Many factors need to be considered for proper long-term power sector simulation.

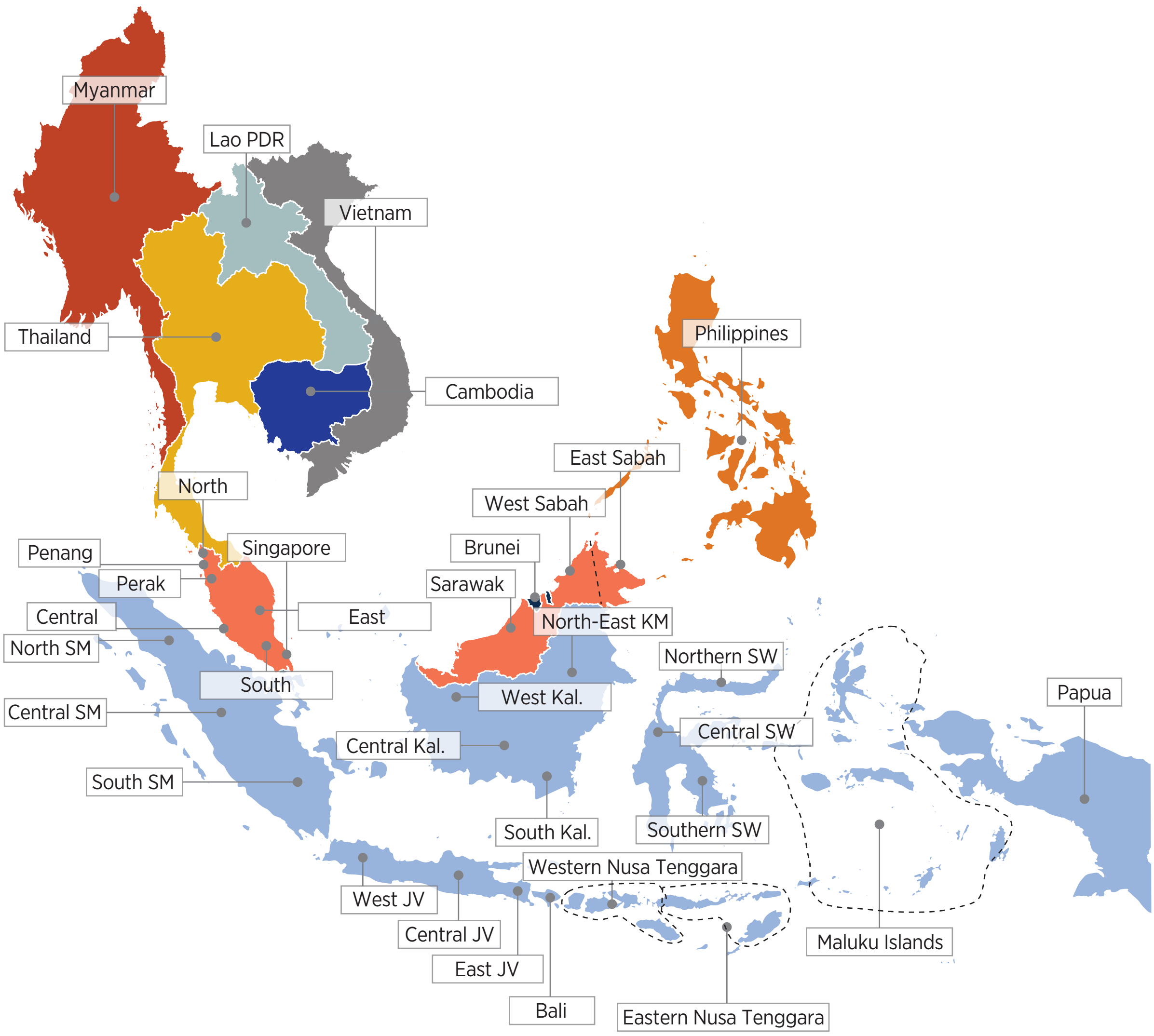
Table 12 Rationale for long-term power sector simulations

RELEVANT SCENARIOS		BES/PES	TES	1.5-S RE90	1.5-S RE100
	GUIDING QUESTIONS AND CONSIDERATIONS	Existing pipeline of renewable energy projects in each country	What is the implication of not expanding with fossil fuel? Is it technically feasible? Is it economical?	Between RE and CCS or nuclear - which is more competitive?	How feasible is it to push further toward 100% RE generation?
		Fossil fuel expansion based on national plans	Which countries are affected and why?	How challenging is it to deploy additional renewables and to deploy CCS or nuclear?	What are the key factors that affect the technical feasibility and what are the infrastructure needs?
		Limited exchange between market players – countries based on a conservative scenario in AIMS	Which technologies take the role of the fossil expansion?		What are the additional investment needs? Is it economic and is it operationally robust?
	MOTIVATION	To demonstrate what can be achieved under current plans with existing framework and endowment enabling environment for renewables (PES) or none at all (BES)	To analyse how regional and national systems are affected by an increase in renewable ambition and what are the technical and non-technical barriers that need to be overcome in achieving this	To demonstrate how a climate compatible and/or highly renewable future (90% RE in power generation) can be achieved whilst considering all technology options available such as nuclear and CCS technologies	To explore and analyse what a climate compatible 100% RE pathway means for the ASEAN region and how it can be realised while excluding all fossil and nuclear technologies

Note: CCS = carbon capture and storage; RE = renewable energy.

These scenarios for the power sector were considered in a 35-node model of ASEAN as shown in the following figure, with 18 nodes in Indonesia, nine in Malaysia and one node for each of the remaining AMS. Malaysia and Indonesia are represented in more detail than other ASEAN countries because they are also the focus of national reports.

Figure 26 ASEAN region representation with 35 nodes



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.
Note: North SM = North Sumatra-Aceh; Northern SW = Gorontalo, North Sulawesi; Central SM = West Sumatra, Jambi, Riau; Central SW = Central, West Sulawesi; South SM = South Sumatra, Lampung-Bengkulu, Bangka Beitung; Southern SW = South, Southeast Sulawesi; West JV = West Java, Jakarta, Banten; Central JV = Central Java-Yogyakarta; East JV = East Java.

POWER CAPACITY AND GENERATION

Key highlights:

The deployment of solar PV is a common feature across all scenarios due to the strength of the resource across ASEAN. By 2050 it could exceed 2 000 GW in the 1.5-S, but this would require a paradigm shift in system operation and a move toward a more distributed power system.

1.5-S will require making clean dispatchable technologies key to balancing resource variability. The costs and availability of these technologies are pivotal in terms of their cost-effective deployment in any highly ambitious decarbonisation scenario.

Regional interconnection within ASEAN has many benefits in achieving a lower-cost power system overall. By allowing for integrated energy supply planning and minimising of duplication of both energy and non-energy service provision, it reduces system costs in all scenarios regardless of ambition level. International line expansion in aggregate increases 100-fold by 2050 in both 1.5-S climate-compatible pathways given the crucial role it plays in unlocking the wide and diverse renewable potential of the region.

A 100% renewable power system is possible and feasible for ASEAN, but it does call for much greater scaling of renewable energy and international co-ordination for system operation, with costs only 5% higher than in the 90% renewable case.

Power capacity will need to grow at pace to ensure that electricity needs are met out to 2050. There are many possible trajectories for power system expansion, but action is needed to avoid fossil fuel lock-in investments in the near term, particularly given the prevalence of coal-fired generation. Solar PV is going to be a key technology in ASEAN's power sector capacity expansion in all the scenarios, regardless of ambition level, as shown in Figure 27. Regional expansion of interconnection will enable much of this regional integration of renewables.

Careful operations planning and ancillary service provision is needed to ensure effective integration of the technology, and this increases with renewables ambition. Solar PV in the BES, PES and TES will reach about 550 GW, 1 120 GW and 1 730 GW, respectively, representing the share of 47%, 65% and 68% of total installed capacity, respectively, by 2050 across the whole of ASEAN. The two 1.5-S cases, both the RE90 and RE100, will see the solar PV share of total installed capacity by 2050 at approximately 70%. Translated into average build rates over the study horizon, this corresponds to annual build rate of 64 GW to 73 GW per year for both the 1.5-S RE90 and RE100 cases, respectively.

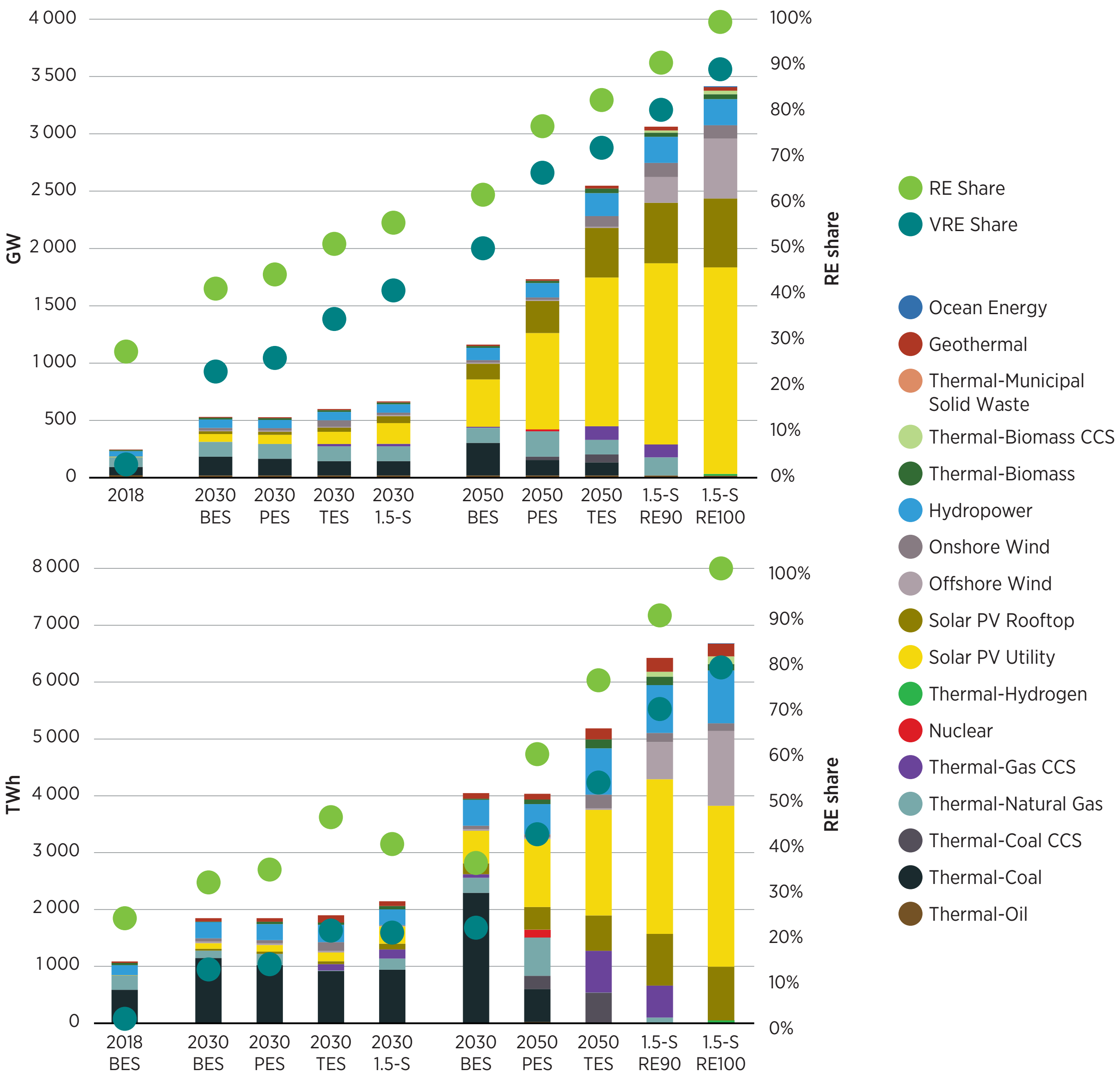
Other renewable energy sources will also play important roles in these highly ambitious scenarios. The BES and the PES will see both geothermal and hydropower capacity increase 3.5-fold and 2.5-fold by 2050 across ASEAN to meet electricity demand growth. The TES will see more geothermal and hydropower installed capacity, reaching 25 GW and 200 GW, or about a sevenfold and fourfold expansion from today's levels, respectively. Both 1.5-S cases reinforce these technology trends with both technologies reaching 32 GW and 227 GW by mid-century, increases of ninefold and fivefold, respectively, over today's levels.

Wind energy will also see increased importance especially in the most highly renewable scenarios, namely 1.5-S RE90 and RE100, mainly due to its differing generation profile which can complement the highly concentrated daily profile of solar PV generation. The BES, PES and TES will see the total installed wind energy reaching 31 GW in both earlier scenarios, and 103 GW in the TES, in which onshore wind dominates the installation. The trend in both the 1.5-S cases will see offshore wind being more dominant as a result of the more aggressive development of the technology and lack of land. Total installed wind energy in the 1.5-S RE90 and RE100 cases will reach 349 GW and 639 GW, respectively, of which offshore wind accounts for around 65% and more than 80%, respectively, by mid-century. This corresponds to an average annual build rate of under 1 GW per year in the BES and PES, rising to 3 GW per year in the TES and 10.5 GW per year and 19 GW per year in the 1.5-S RE90 and 1.5-S RE100 cases, respectively. The vast majority of this capacity is concentrated in a few countries, such as Viet Nam and the Philippines.

There is a maintained role for fossil fuels with and without carbon capture and storage (CCS) and non-renewable modes of generation capacity by 2050, with their combined capacity share of 38%, 23% and 18% in the BES, PES and TES. Their proportionally low share of capacity however belies their value in terms of power generation, where their ability to deliver power during periods of low VRE provides valuable system resilience. Additionally, given the range of uncertainties that exist with these technologies, this role needs to be carefully explored so that these are well understood in terms of their sensitivity to these uncertainties. The share of these technologies in the 1.5-S are all below 10%, and are 0% in the RE100 case.

Solar PV will play a fundamental role in ASEAN, regardless the scenarios.

Figure 27 ASEAN capacity expansion, by scenario, 2018, 2030, 2050



Note: RE = renewable energy; VRE = variable renewable energy.

The share of renewables in power generation in 2050 will reach 35%, 59% and 75% in the BES, PES and TES, respectively, increasing from 23% in 2018. Both 1.5-S cases see at least 90% of ASEAN's power generated from renewables by mid-century. Meanwhile, the share of variable renewable power generation reaches over 50% in the TES, and both the 1.5-S cases reach 69% and 78% in the RE90 and RE100 cases, respectively. Solar PV plays a key role in ASEAN's power generation in all the scenarios, especially in the 1.5-S, accounting for over 55% of generation. In the generation mix, the role of different power generation sources in meeting demand across the year becomes clear. This is to say that in power systems with high shares of solar PV and other renewables, the nature of renewable power sources implies that the operation of the system and their use across the year rely on the variability of the resources underpinning them. In these scenarios these attributes are mitigated to large extent by a vast expansion of battery storage capacity. However, this resource variability does also see the expansion of lower or zero emission technologies such as nuclear and fossil fuel technologies with CCS which can readily be dispatched regardless of short or long-term weather conditions, though entail significant uncertainty in deployment timelines and costs.

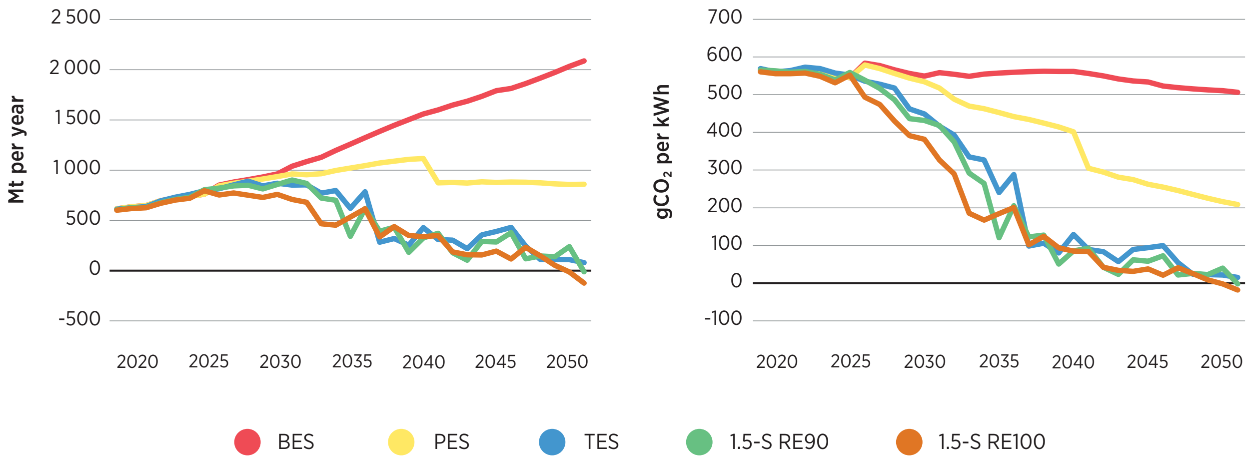
Proper policy and market design and implementation are needed to achieve the projected scenarios successfully as the role of fossil fuels is decreasing in all the scenarios and the energy and non-energy services that they provide will need to be substituted. In 2018, unabated coal represented about half of ASEAN's power generation but by 2050 coal (both abated and unabated) will have penetrations of 70%, 27% and 4% in the generation mix of the BES, PES and TES. ASEAN is projected to have no coal power generation by 2050 in all the 1.5-S cases, with a full retirement or conversion foreseen of all generation units.

The CO_2 emissions in each scenario paint a stark picture of the need for action across the region. Even with significant reductions in the use of coal generation and increases in solar PV generation in the PES, total emissions remain at about today's levels by 2050. Figure 28 makes clear the need to accelerate the expansion of solar PV further and the crucial need for clean dispatchable capacity across the region, which could take the form of batteries, hydropower, bioenergy, nuclear and CCS. In the PES, the expansion of clean generation capacity does not outpace demand growth, which leads to flatlining of emissions post-2040 despite large reductions in emissions intensity, in contrast to the TES and both the 1.5-S cases, which achieve near zero or negative emissions intensity.

Grid expansion

Power sector emissions fall significantly in the 1.5-S when the region's renewable energy potential is optimised.

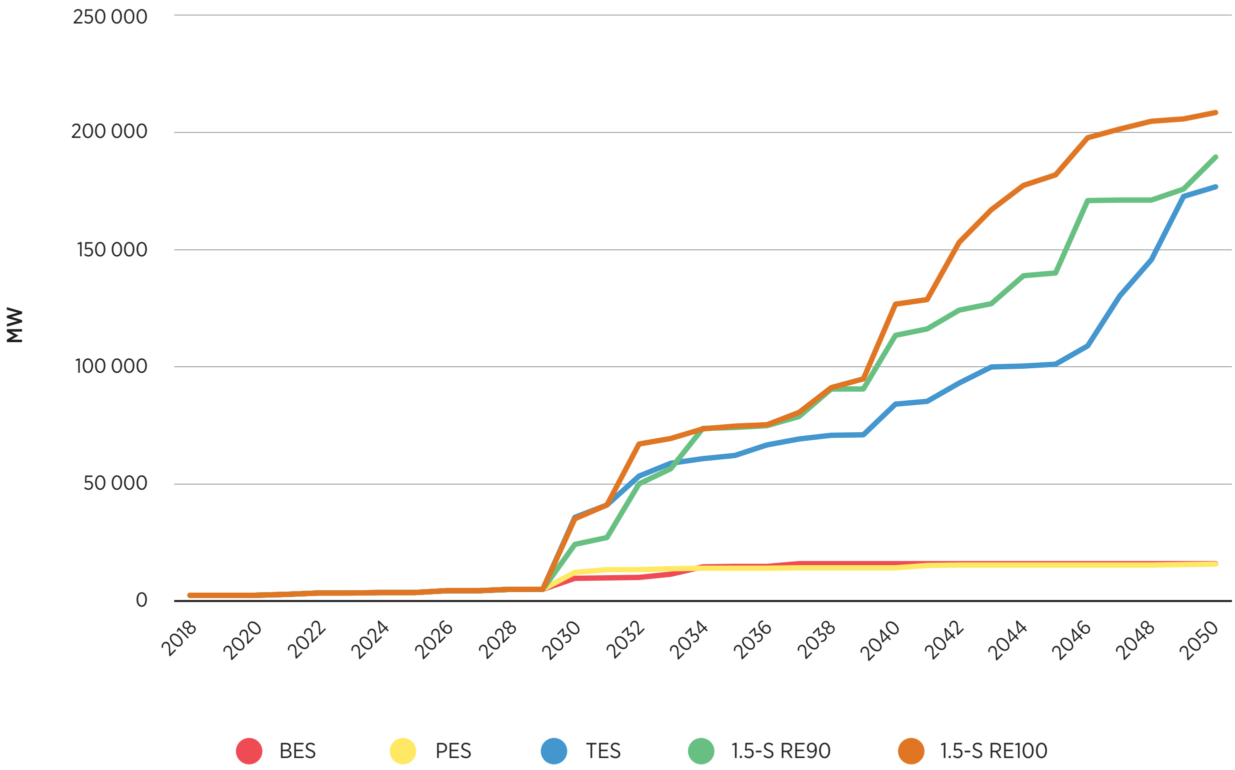
Figure 28 ASEAN power sector CO_2 emissions and emissions intensity



There are benefits to increased international transmission expansion in all scenarios, even in the BES and PES, where the expansion is limited. Transmission expansion allows for reduced duplication of energy and non-energy services provision in each country, allowing the sharing of different system generation sources which leads to cost savings as a result, regardless of renewables ambition. However, this transmission expansion becomes crucial in integrating renewables in the higher-ambition TES and in both the 1.5-S cases. This is shown in Figure 29, which shows the sum total of international line expansion for each scenario. While it does not show individual candidates (which are further discussed in the "Power flexibility" section), it demonstrates the level of regional power system integration needed and the economic benefits of these line expansions, given these were derived using cost optimisation modelling in a full regional model of the ASEAN power system. This is not only owing to VRE integration but to sharing of clean, dispatchable power sources like batteries, hydropower, bioenergy and geothermal across the region.

Transmission expansion needs to increase significantly in the energy transition scenarios, especially when RE100 is pursued.

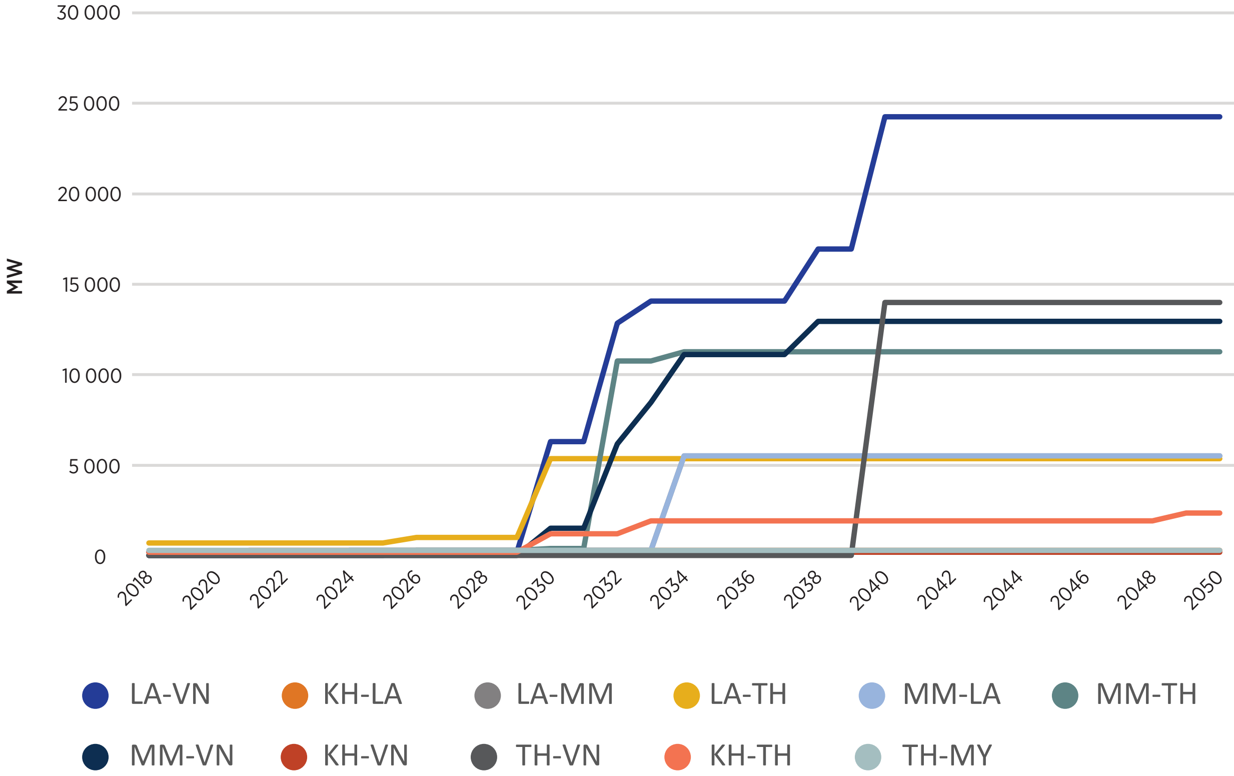
Figure 29 ASEAN transmission capacity expansion



To give an insight into what this implies at a national level, an interesting example to consider is that of countries along the Mekong River. In this area, a wealth of hydropower, solar power and wind power resources are not uniformly distributed. The role of hydropower in Lao PDR and Myanmar in helping to mitigate regional supply-demand fluctuations is crucial in understanding how national system characteristics can complement each other and facilitate power system flexibility and shared system services provision. This leads to a significant expansion of interconnector lines, as shown in Figure 30, between these countries, which exchange hydropower and solar and drive this expansion. Most notable are the expansion of lines between Lao PDR and both Viet Nam and Thailand, which will be 24 GW and 5 GW, respectively, by 2050, and Myanmar and both Viet Nam and Thailand, which reach 11 GW and 13 GW, respectively, by 2050 in the 1.5-S RE90.

The Mekong area will require international transmission line expansion.

Figure 30 International line expansion along the Mekong River in the 1.5-S RE90



Note: For the country code legend please see the beginning of the report.

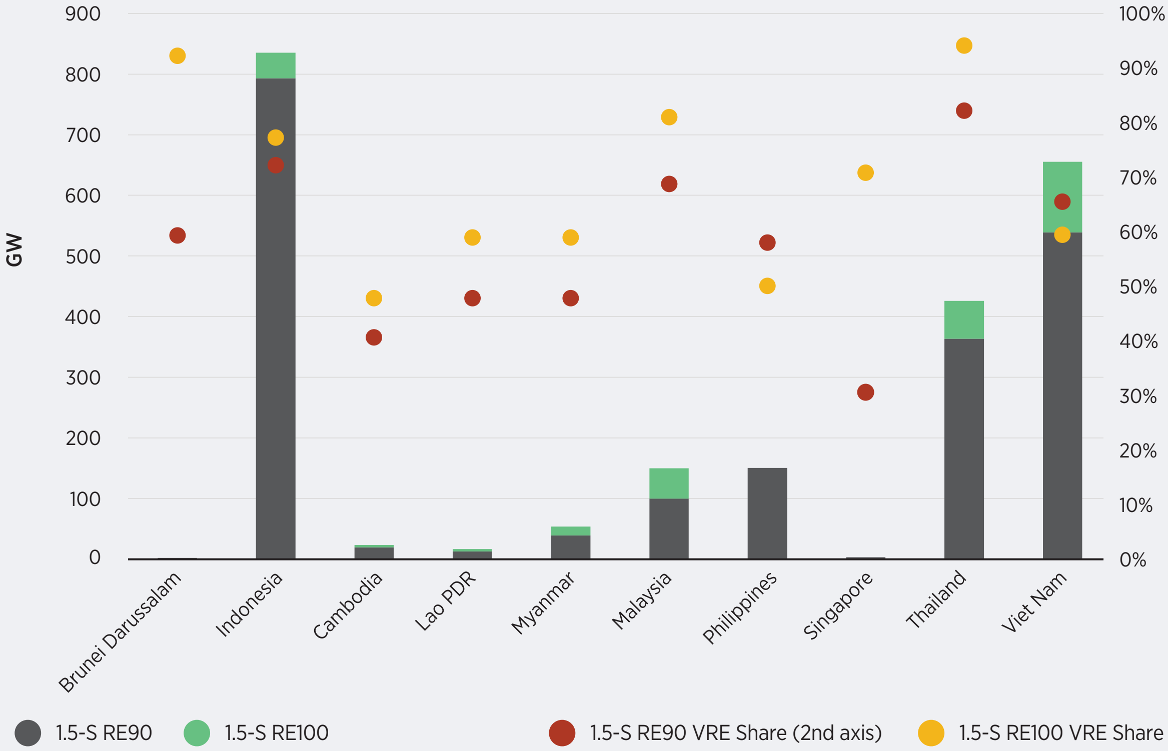
It is not only hydropower and solar power that drive this expansion, as evidenced by the near 15 GW line between Thailand and Viet Nam which as a high-voltage direct current (HVDC) line/s over water is a technically complex expansion candidate to implement. The offshore wind power potential in Viet Nam drives this line expansion with Thailand due to the complementarity of its generation profile and cost efficacy. This expansion of lines leads to significant grid integration across the region and, implicitly, closely integrated system operation along the Mekong River. While beneficial at a regional level, all international expansion of transmission lines would also need to be developed with close international collaboration which recognises the political complexity in developing these lines. This is pivotal in ensuring that their benefits and costs are fairly distributed which should span the entire life of the projects, all the way from the project development phase through to mutually beneficial operation in the long-term.

Box 5 Ambitious deployment of solar power in the 1.5-S

National plans in the region generally envisage a limited role for solar PV in the near term with a limited deployment overall in the planned horizon as can be seen in the BES and PES. The TES and 1.5-S see a vastly more substantial expansion along the study horizon, with increasing PV and other renewable deployment in the TES and 1.5-S. In terms of a national distribution of solar PV and its national share of the capacity mix, there is quite a difference among countries in the region, as shown in Figure 31. This presents a simultaneous opportunity and a challenge for the region. It is an opportunity to take advantage of one of the lowest cost sources of power available today and develop an indigenous industry to develop and roll out the technology. Such is the resource level in ASEAN and the technology cost projection that the region could become a world-leading player in the technology at the backbone of a decarbonised world. However, skills need to be developed and a supply chain prepared to meet such ambitious levels of deployment out to 2050, which is where the challenge lies. A long-term perspective is needed to enable such deployment in every sense, both technically and economically.

Box 5 Ambitious deployment of solar power in the 1.5-S (continued)

Figure 31 National expansion of solar generation capacity and total VRE share of capacity in the 1.5-S RE90 in 2050



Note: RE = renewable energy.

Even when considering average expansion rates, which neglect the S-shape deployment rate of technologies, this corresponds to very high levels that need to be rolled out over the long term, even in the 1.5-S RE90. In terms of annual deployment, this reaches average levels as shown below, which are quite ambitious between 2018 and 2050. For ASEAN as a whole, this corresponds to 64 GW per year, which is a significant share of the 206 GW per year envisaged in for Asia in IRENA's WETO 2022 out to the year 2050.

1.5-S RE90	Brunei	Indonesia	Cambodia	Lao PDR	Myanmar	Malaysia	Philippines	Singapore	Thailand	Viet Nam
Average annual Solar PV additions (GW per year)	0.07	24.18	0.63	0.40	1.23	3.11	4.93	0.16	11.15	17.86

Costs for renewable energy within countries in ASEAN

Renewable technologies have seen unprecedented cost reductions over the last decade. IRENA's latest *Renewable power generation costs in 2021* report (IRENA, 2022f) shows that cost reduction trends have continued for key renewable energy technologies, such as solar PV and wind. The report, and underlying database, present technology costs for selected technologies in some ASEAN countries. The two core sources of data for the cost and performance metrics are based on the IRENA Renewable Cost Database and the IRENA Auctions and Power Purchase Agreement databases. The IRENA Renewable Cost Database has grown to include project-level cost and performance data for over 1 900 GW of capacity from around 20 000 projects, either installed or in the pipeline for commissioning in the coming years.

Solar PV, which has seen more than an 80% reduction in cost over the last decade, shows a wide range in cost in ASEAN. The average investment costs (AIC) for solar PV ranges from the lowest at USD 690/kilowatt (kW) in Viet Nam with many others in ASEAN falling below USD 2 000/kW. Wind energy has largely been limited to projects in Viet Nam and Thailand, and average around USD 1 500-1 700/kW for onshore. Hydropower costs generally range from around USD 2 000 to USD 2 200/kW, with the exception of Viet Nam at USD 1 300/kW. Geothermal and biomass are the most capital-intensive technologies in the region, with costs ranging from USD 2 800 to over USD 5 000/kW.

The capacity factor of solar PV falls between 14% in Singapore to 17% in Cambodia, Thailand and Viet Nam. The other AMS have solar PV projects with the capacity factor at 16%. Wind projects in Viet Nam reach capacity factors of between 34% for onshore and 38% for offshore wind. Geothermal projects in Indonesia represent the highest capacity factor, reaching 84%, while biomass is slightly behind at on average close to 80%. The capacity factor of hydropower in the ASEAN region is 44%, 45% and 52% in Viet Nam, Lao PDR, and Indonesia, respectively.

However, AIC does not fully the capture cost of producing electricity. The LCOE of a given technology is the ratio of lifetime costs to lifetime electricity generation, both of which are discounted back to a common year using a discount rate that reflects the average cost of capital. The cost and performance metrics include total installed costs (including cost breakdowns, when available), capacity factors, operational costs (such as fuel) and maintenance costs (O&M) and the levelised cost of electricity (LCOE).

The LCOE for solar ranges is lowest at USD 0.046/kWh in Viet Nam, with many others falling in the USD 0.05-0.075/kWh range. The LCOE of onshore wind is USD 0.048/kWh and for offshore, USD 0.076/kWh. Hydro represents the lowest LCOE in the region with a cost of USD 0.036/kWh. Geothermal and biomass generally fall around USD 0.08/kWh.

These metrics allow a perspective on the evolution of the costs of renewable power generation technologies. IRENA's costing work analysis shows what the underlying drivers are in terms of costs and cost reductions. Although LCOE is a useful metric for a first-order comparison of the competitiveness of projects, it is a static indicator that does not consider interactions between generators in the market. The LCOE does not consider either that the profile of a technology's generation may mean that its value is higher or lower than the average market price it might receive.

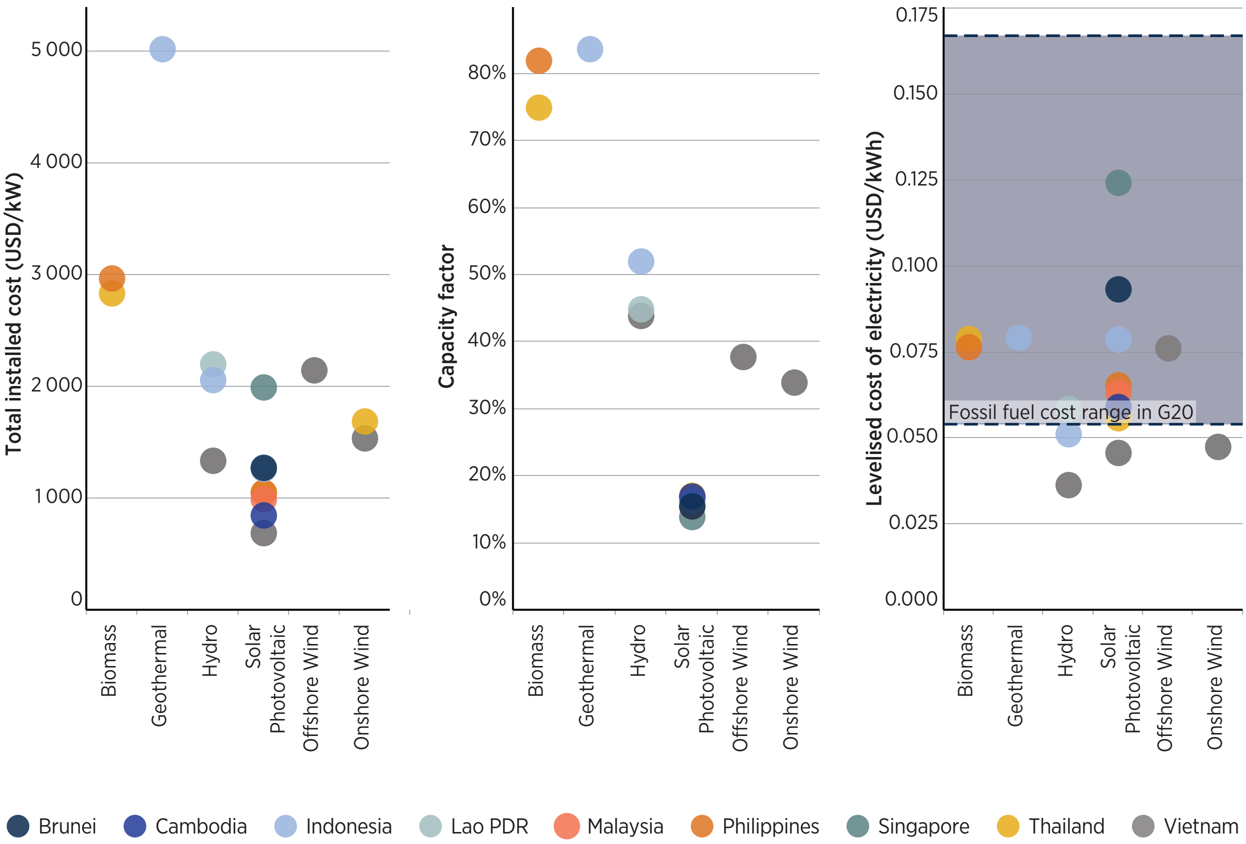
However, the global trend is changing as it is also in the ASEAN region. LCOEs from renewables are getting cheaper. Renewables such as wind and solar have experienced massive deployment globally, which has contributed to lowering the cost of equipment. Because equipment cost makes up a high share of capital cost, the LCOE of renewables is also expected to come down in ASEAN as capacity installations grow. On the other hand, fossil fuel thermal plants have experienced an increase in investment cost due to stricter emission and environmental standards, and rising global fossil fuel prices are driving up their generation cost (IESR, 2019).

The shift to renewable power and electrification is a trend that has been reflected in recent years. The competitiveness of renewables continued to improve in 2021. Data from the IRENA Renewable Cost Database and analysis of recent power sector trends affirm their essential role in the journey towards an affordable and technically feasible net-zero future. The period 2010 to 2021 witnessed a seismic shift in the balance of competitiveness between renewables and incumbent fossil fuel and nuclear options. The global weighted average LCOE of newly commissioned utility-scale solar PV projects declined by 88% between 2010 and 2021, that of onshore wind and concentrated solar power (CSP) by 68%, and offshore wind by 60% (IRENA, 2022f).

Costs in ASEAN countries span a wide range, while deployment in 2021 was modest, meaning cost trends can also be volatile. Having noted these caveats, Figure 32 shows the total installed costs, capacity factors and LCOE for projects commissioned in ASEAN countries in 2021. Viet Nam has achieved some of the most competitive cost structures in the region, with costs for hydropower, utility-scale solar PV and onshore wind below USD 0.05/kWh.

Renewable power technology costs continue their rapid decline.

Figure 32 Total installed costs, capacity factors and cost of electricity by country, 2021



Source: IRENA Renewable Cost Database
Note: Data are the weighted-average (by capacity) for projects in the database, which are a subset of total projects commissioned in 2021.

IRENA surveyed the finance sector, utilities, developers and bank professionals in 2021 on the cost of finance for renewable power generation projects (IRENA, 2022f). This survey concluded that financing costs (the weighted-average cost of capital [WACC]) for solar PV, onshore wind and offshore wind were higher than in more established renewable energy markets in Malaysia and Viet Nam. These survey data were used to calibrate a benchmark model of WACC, with results for ASEAN countries for utility-scale solar in the range of 4.5% (for Thailand and Singapore) to 6% (for Indonesia and Viet Nam) to a high of 7.5% (for Cambodia and Lao PDR). Wind WACC had similar ranges, with the largest market in Viet Nam, averaging 5.1% for onshore wind and 7.4% for offshore wind. In some of these markets, as these technologies become more mainstream and polices become supportive, financing costs will come down. Reducing the WACC will also in turn increase the competitiveness of these technologies and lower costs for procuring electricity from solar PV and wind.

The power system modelling relies on the Indonesian technology catalogue for a majority of its technology parameters and costs for the modelling of the ASEAN power sector. The catalogue envisages a continuation of these trends and is based on a range of reputable national and regional sources (DGE *et al.*, 2021). The capital cost projections envisage significant reductions in the capital costs of renewable energy technologies such as solar PV and onshore wind, which will drop to USD 410/kW and USD 1 080/kW, respectively, by 2050. All these costs were mostly derived from the technology catalogue by DGE *et al.* (2021), but the Annual Technology Baseline produced by NREL (Vimmerstedt *et al.*, 2021) was also consulted in addition to the technology catalogue of the US Energy Information Administration (Nalley and LaRose, 2022) and that of the Joint Research Centre of the European Commission (EC JRC, 2017), which were consulted in a sensitivity assessment of technology costs and their impact on modelling results.

Box 6 Phasing out coal

The ASEAN region is home to the youngest coal power plants in the world. The average plant age of the ASEAN coal fleet is 11.8 years (ACE, 2022b). Coal contributes to about two-thirds of the emissions from the power sector across ASEAN.

Coal power plant lifetime is measured in many decades, with many operating for 40 to 50 years or longer. Therefore, partial or complete shutdowns in the near term will result in stranded assets for many plant owners, investors and the utility companies who signed construction and operation contracts. In some countries, such as Indonesia, shutting a large portion of coal power generation will require large-scale deployment of alternative generation sources, such as renewables, and investments in complementary infrastructure, such as grids and storage.

In the near term, it seems likely that some coal power plants will continue to operate. There are several pathways that could be taken to address emissions from these coal plants as the region shifts to low and zero-carbon sources such as renewables. One is the deployment of biomass co-firing, or carbon capture utilisation and storage, and high-efficiency low-emissions technologies. But these remain stop-gap measures in the short- to medium-term. In the longer term, these coal plants will need to be retired as the region moves towards net-zero emissions by mid-century.

In the 1.5-S, while many coal plants are phased out in the period from now through the 2030s, coal power is entirely phased out between 2040 and 2050. Importantly, no new coal plants should be built except those that are already in planning and construction.

Countries have already expressed their commitment to phasing down coal but require further regulatory frameworks and roadmaps that allow a smoother transition. This implies that the coal phase-down will need at least three phases:

1. strengthening the grid to enable higher renewable energy penetration
2. enabling financial mechanisms that can encourage early retirement of existing coal-fired power plants
3. continuous implementation and improvement in integration of clean energy sources and novel operational practices.

Strategies for strengthening the grid include the investment in expanding integrated grid infrastructure and capacity to accommodate renewable resource-rich locations. Enabling policies and financial mechanisms that promote the use of smart grid technologies, market models that promote higher storage adoption, and financial mechanisms that would support AMS interconnection through the ASEAN Power Grid all need to be part of the solution.

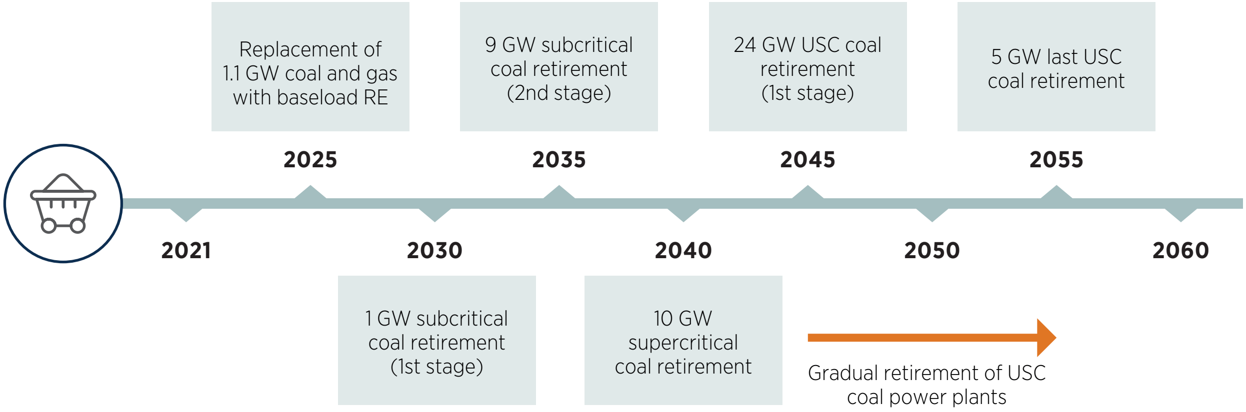
Meanwhile, enabling financial mechanisms could include implementation of stricter emission standards and carbon pricing schemes, alignment with the global market mechanism set by the Glasgow Climate Pact, agreed by countries during the COP26 in Glasgow (UNFCCC, 2021), and provision of support that enables coal plant operators to recycle the capital from closing their plants through conversion and/or replacement with renewables to earn returns on their investment.

The political landscapes, resource availability, power market setups, and regulations provide different starting positions for a coal phase-down in each country, with further important factors including social considerations related to job security and energy affordability. However, there are also commonalities that can be shared across countries. These include the strategies to ensure coal phaseout target achievement, to establish a just workforce transition, and to maximise the socio-economic benefits of the energy transition.

In the ASEAN region, the phaseout of coal is imperative to accomplish net-zero targets. This is not an easy task to accomplish. However, Indonesia has signed up to a global pledge to phase out coal. The roadmap to phase out coal is depicted in Figure 33.

Indonesia's state-owned utility company aims to be carbon neutral by 2060.

Figure 33 Timeline from PLN to retirement coal power plants to carbon neutral



Note: USC = ultra super-critical; RE = renewable energy.
Source: (PLN, 2021).

Box 7 Clean dispatchable supply from renewable sources

Clean dispatchable power has been, and will continue to be, a crucial element in the generation mix of ASEAN. Most notably from geothermal and hydropower which can deliver power on-demand to balance supply-demand variability and provide a whole host of non-energy services to help provide secure and stable system operation.

To advance both generation sources internationally, the International Renewable Energy Agency (IRENA) has co-ordinated the Global Geothermal Alliance and the Collaborative Framework on Hydropower to serve as platforms for dialogue, co-operation and co-ordinated action between policy makers and stakeholders worldwide. This knowledge was used to look deeper into the power sector in ASEAN and develop future pathways for power system for this report.

In terms of the power generation mix, in 2020 it was composed mostly of fossil fuel which represented little over 70% of power generation capacity and nearly 80% of power generation. Geothermal and hydropower combined make up the vast majority of renewable power in the ASEAN region with the remainder made up of solar PV, wind and bioenergy. Geothermal and hydropower contributed around a 20% share of generation capacity and power generation but this understates the crucial role they perform and can perform going forward. Geothermal is not weather-dependent and can operate at very high capacity factors. Beyond electricity and ancillary services related to the grid operation, geothermal can also provide heat to industry and buildings. All of these characteristics make it particularly dependable across the entire year, due to its lack of seasonality, and make it a crucial component of the power system. Particularly because it can mitigate periods of low renewable supply from other renewables and supply interruptions and price volatility from non-renewable sources.

Whereas geothermal tends to operate as a baseload power plant, hydropower is capable of both operating at constant rates and swiftly power ramping to accommodate variable renewables and, overall, contribute to the supply-demand energy balance. Besides, hydropower can be equipped with reservoirs that can act as storage buffers which can give room to variable renewables by allowing upstream resevoirs to save unused energy for later use. These characteristics also see pumped hydro storage facilities often reinforce the benefits of these storage capabilities by allowing it to store energy sourced from other modes of generation by pumping water up to upstream reservoirs. It should be noted, however, that hydropower's flexibility sometimes has project specific limitations related to the multiple uses of water (*e.g.* mandatory max/min outflow rates due to environmental protection measures and other localised considerations) and may present socio-environmental impacts due to the displacement of water flows. However, they also can have positive impacts in improved management of water availability and flooding control.

Geothermal and hydropower are generally considered mature technologies in that their deployment and operational integration are well known. Enhanced Geothermal Systems (EGS) are still in the demonstration stage and could provide nearly unlimited amounts of energy, but challenges still remain in its commercial development (IRENA, 2017).

Box 7 Clean dispatchable supply from renewable sources (continued)

The comparative technological maturity of geothermal and hydropower as a whole (though potential for further innovation remains) stands in contrast to staggering transformation of variable renewable technologies such as solar PV and wind, which have seen rapid declines in cost in recent years because of technology learning gained through mass deployment across many regions of the world. For ASEAN, both solar PV and wind hold much promise – most notably solar PV given the sheer scale of the resource available in all ASEAN countries which place it among the lowest cost power sources available. This alone sees them feature strongly in long-term power capacity expansion pathways for the region purely on a cost basis, regardless of decarbonisation ambition considered which reach between 2100 GW and 2400 GW for the ASEAN in IRENA's 1.5°C climate compatible pathway by 2050. Their modularity can see them deployed in an array of circumstances but also implies a more distributed power system in these pathways. Combined with increased electrification of end-use sectors which would also be widely distributed (particularly notable in high decarbonisation scenarios) indicates a paradigm shift in system operation being needed to operate such a power system.

A challenge in achieving this in national generation mixes stems in increased variability of supply and demand, which geothermal and hydropower are well positioned to mitigate through the application of flexible operational practices.

As a very active volcanic region, geothermal potential is widely spread across Southeast Asia. So it is no wonder that Indonesia and the Philippines currently rank second and third respectively in geothermal installed capacity globally, and the former has one of the highest potentials in the world. Hydropower resources are prominent across countries like Myanmar, Viet Nam, and regions such as Sarawak (Malaysia) and Kalimantan (Indonesia). So how and where projects are deployed using these resources will be crucial, given that they are not necessarily located near the largest demand centers in the ASEAN region, as shown in Table 13, and to maximise their system impact, they need to deliver power to where it is consumed. For example, some select countries along the Mekong River such as Cambodia, Lao PDR and Myanmar have hydropower potential that substantially exceeds their potential peak demand in a climate compatible pathway by 2050. This implies that such hydropower projects would need to be developed in a regional context with regional expansion of interconnection so facilitate power flow to the large demand centres such as those in Thailand, Viet Nam and other countries. Regionally integrated planning and operation of the power sector with a view to deeper regional integration is a powerful tool in harnessing these resources going forward that would be propelled by increased system interconnection. That also entails coordinated operation and alignment in regulation and electricity markets.

Table 13 Peak load (GW) in 2018 and by 2050 in global 1.5°C compatible pathway and hydro and geothermal power resource distribution across ASEAN (GW)

	APPROXIMATE PEAK ELECTRICITY DEMAND IN 2018	PEAK ELECTRICITY DEMAND BY 2050 IN GLOBAL 1.5 °C COMPATIBLE PATHWAY	HYDRO POTENTIAL	GEOTHERMAL POTENTIAL
Brunei Darussalam	0.7	4.2	0.1	-
Indonesia	35.9	261	94.6	29.5
Cambodia	0.9	6.0	10.0	-
Lao PDR	0.9	6.6	26.0	0.1
Myanmar	2.3	17.2	40.4	-
Malaysia	24.1	62.9	29.0	-
Philippines	12.3	89.5	10.5	4.0
Singapore	6.9	17.9	-	-
Thailand	27.7	116.2	15.0	-
Viet Nam	21.3	126.4	35.0	0.3

Source: (DGE *et al.*, 2021; Handayani *et al.*, 2022) and IRENA analysis.

Box 7 Clean dispatchable supply from renewable sources (continued)

However, the benefits of regional integration both nationally and internationally go far beyond this given that it is key to unlocking the lowest cost power system for ASEAN as a whole. It is an enabler of reduced duplication of efforts at national level to provide the same necessary system services which could reinforce regional energy security whilst reinforcing mutual reliance.

POWER FLEXIBILITY

Key highlights:

The integration of national power systems helps to utilise the best solar resources from countries like Indonesia and Viet Nam and deliver this energy to the main load centres. A scenario with limited interconnectors makes the decarbonisation more expensive and adds an upper boundary to the integration of VRE.

Hydropower resources with reservoirs have an important role to play in balancing supply and demand, particularly during the night. Nevertheless, battery facilities will become operational as of 2030-35, reach large-scale cost-effectiveness from 2040 onwards and become the backbone of the future system. There will be a steep growth of storage resources, mostly batteries, and the respective market must be ready when the time comes. There will be battery projects before this period to eventually solve local network issues, and overall experimentation.

On average, over 50 GW of spinning reserve capacity must be available every moment in the entire region in 2050. Available batteries and hydropower are sufficient for the provision of frequency-response reserves that are equal to 10% of the demand load at every time step, and sparse potential shortages would be seen whether reserves were set at 15% of the load. Yet, high-capacity transmission lines may impose challenges to stability in case of tripping of a line in 2050.

Given the need for sizeable power assets, caution is needed to plan and operate the system by 2050. In the case of transmission lines, opting for more circuits of lower capacity rather than a few larger ones – and the adoption of fast-frequency reserves for small and medium grids in the medium term, and large grids in the long term – can help address potential issues. Nonetheless, the combination of high VRE generation and low demand or synchronous generations may limit power exchange at certain moments – not because of the line capacity but because of voltage stability. Lastly, the system should be designed to cope with less synchronous machines in the future, when grid-forming inverters are likely to assume the leading role.

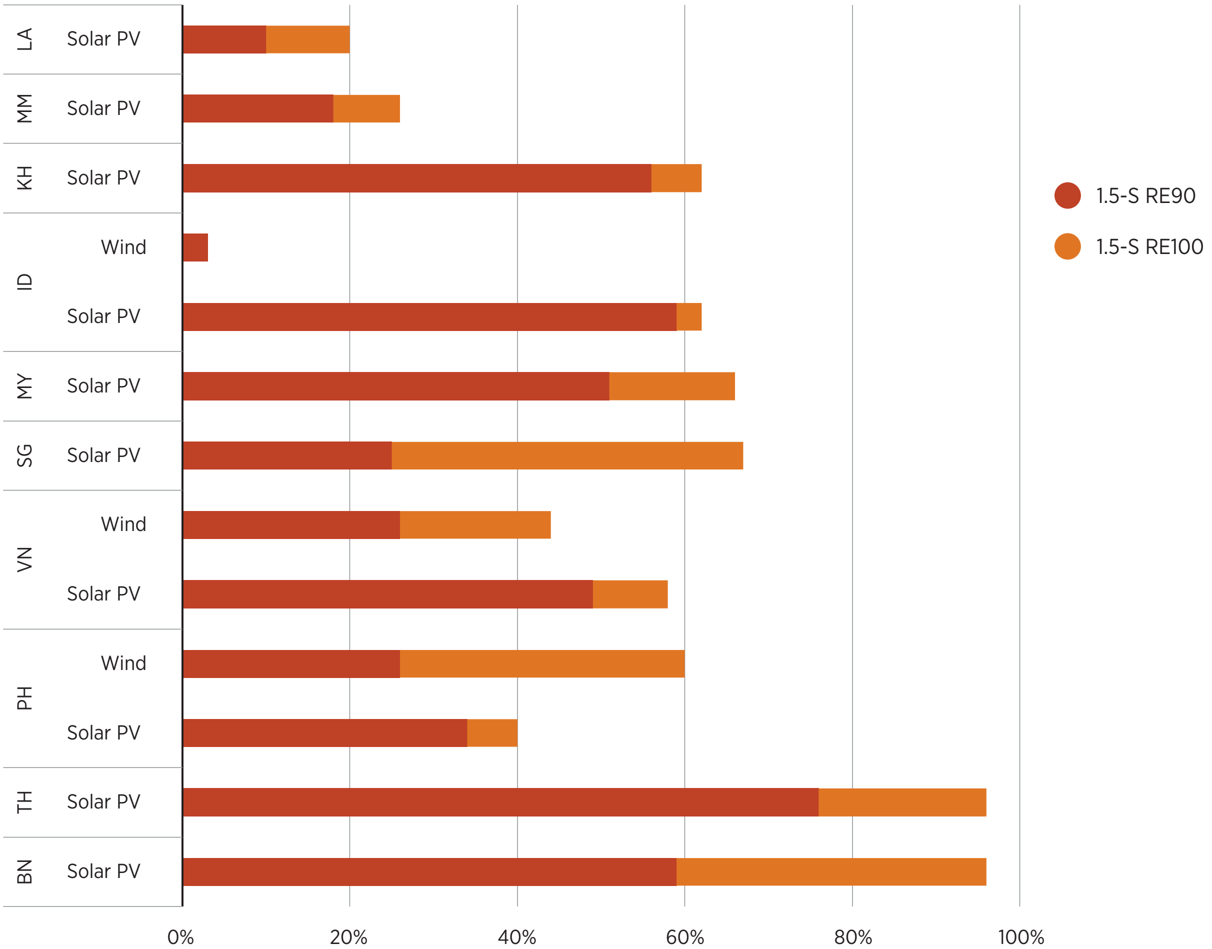
The full potential of renewables requires open markets and the alignment of regulations between national transmission system operators (TSOs). The former ensures that the least-cost merit order based on short-run marginal cost is followed across the region, and for regulation and eventually even ancillary services. That also means giving no privileges to domestic resources and setting up an integrated ASEAN market for generators and transmission rights. Common regulations secure reliability across the region by setting norms for the operation and provision of services (energy, regulation, reserves), the amount to be procured at each time scale, and the practices followed by TSOs. An independent regulator and market authority might be providential whether that is the defined pathway for the region.

Solar and wind generation's share in the ASEAN region will achieve 20% by 2030 and 69% by 2050 under the decarbonised energy scenario compliant with the Paris Agreement. This is 66% more ambitious than the share based on current plans. If the region decides to go to 100% renewable power supply (1.5-S RE100), VRE generation increases to 78%, almost two times the current aspirations. Solar resources comprise 56-58% of the aforementioned scenarios, while wind goes from 13% to 22%.

Flexibility requirements are subject to the existence of more or less of either of the resources, in addition to other renewables like hydropower and the broader national and regional power assets from neighbouring countries. For example, countries like Brunei generate 96% of power from the sun under the 1.5-S RE100 case. Nearly all country generation (excluding cross-border exchange) is subject to daily solar profiles. Others, like Lao PDR, have hydropower resources making up the bulk of the national generation; thus, VRE participation is modest at 10-20% by 2050. Therefore, the country might face some challenges in the future, while it can provide flexibility abroad.

Power system flexibility requirements are subject to the total VRE share and the predominant VRE resource (solar and/or wind).

Figure 34 Solar and wind VRE share in ASEAN countries in the 1.5-S RE90 and 1.5-S RE100 by 2050



Generally, there is a need for 1) accommodating the solar and wind generation to the demand (*e.g.* storage solutions); 2) operating the non-VRE generating portion of the system flexibly, based on the net load; and 3) adjusting demand to the availability of energy in the system (*e.g.* smart charging of EVs).

Additionally, power generation from renewables is constrained based on the location of resources. For instance, the island of Java, home to 68% of demand in Indonesia, possesses only 4% of the solar potential. That necessarily will mean transporting massive quantities of electricity from the best-quality renewable spots to where it is most needed, as pointed out in the previous section.

Balancing supply and demand at all times is crucial for a system's reliable operation, since even a small mismatch can disturb power system frequency and possibly affect the reliability of system operations.[1] Put simply, power system flexibility refers to a power system's ability to respond to both expected and unexpected changes in demand and supply. Given that supply must equal demand across all timescales, flexibility is generally the ability of system assets to modulate either the production or uptake of electricity according to its availability and price across all time scales.

A series of flexibility options have been considered to help integrate VRE in Indonesia. They assume that there will be a price or time-based signal to consumers, or a call from TSOs under a given framework, to increase or decrease consumption according to electricity availability at a given time. Wholesale markets that also include the participation of small and medium consumers through aggregators, demand response programmes at industrial facilities, time-of-use rates, among others, are useful for this purpose.

Flexibility options considered for this study are:

- smart charging of EVs (opposed to charging when most convenient from the user perspective – *i.e.* when arriving at home)
- flexible production of green hydrogen
- storage assets to support both arbitrage and the provision of spinning reserves
- expansion of the transmission grid across islands.

The ASEAN power grid is an enabler of the region's decarbonisation

The ASEAN Power Grid (APG) is an initiative to deploy a regional power interconnection regarding physical infrastructure, procedures, and enabler mechanisms for power trade. From initial cross-border bilaterals, the plan is to expand to sub-regional and then to an integrated Southeast Asia power grid. The ASEAN Centre for Energy (ACE) and ASEAN Power Utilities/Authorities (HAPUA) have discussed the way forward through a series of ASEAN Interconnection Masterplan Studies (AIMS). There have also been dialogues connecting the region with Australia and ongoing initiatives with Eastern and Southern Asia like the GMS and the Bay of Bengal initiative.

The region-wide transmission of electricity maximises the use of renewables and needed flexible assets over ASEAN. It also helps meet the rising electricity demand and improve energy access at the lowest possible price. For instance, the 230 MW line connecting West Kalimantan (Indonesia) and Sarawak (Malaysia) has displaced between 50-130 MW of fuel oil-based generators in the former, instead supplied by hydropower resources from the latter, resulting overall in cheaper electricity supply (ADB, 2015; IEA, 2019). However, not only the physical interconnection must be in place, but also a multilateral market and centralised dispatch the make the best use of resources when and where needed.

[1] *Power systems are designed to operate under nearly constant frequency. Frequency deviations beyond acceptable limits and time periods can damage generators and electromechanical equipment and thus create a chain reaction of loss of load and/or generation that can lead to a blackout.*

To date, power exchange has been mostly realised on a bilateral basis. Nevertheless, initiatives like the LTMS-PIP[2] have served as experimentation for multilateral trading by enabling power transactions (and sharing of hydropower resources) from Lao PDR to Malaysia and Singapore, leveraging Thailand's existing network. The GMS[3] also provides a framework for bilateral exchange, which envisions a multilateral market in the long term. Standard draft grid codes have been discussed with this aim. Yet, technical and regulatory challenges still need to be overcome, including creating the Regional Power Coordination Center (RPCC) to oversee cross-border transactions and coordinate regional planning (GMS, 2022). Plans also include establishing a synchronous grid between Lao PDR, Myanmar, Thailand and China's southern provinces.

A regional centralised and liberalised market with gate closure as close as possible to the physical delivery would probably be the most resource-efficient option, thus maximising the renewables uptake and the overall accessibility to available flexible assets. The overall objective would be harmonising the market into a single price coupling solution, for each delivery period across all buyers and sellers under a same bidding zone (*e.g.* a country region or subregion). The market solution, including prices, can be defined by a price coupling algorithm run by a central coupling operator, and eventually cross-checked in parallel by other relevant entities as seen in the European Market (Meeus, 2020). That could also facilitate an eventual market for regulation and ancillary services and should be ideally implicitly coupled with interconnector transmission rights.[4] However, such a framework will require complex collaboration under political, technical, and institutional spheres. Nevertheless, there are midway solutions that might better fit a given country's context, including subregional configurations, until or whether a regional framework is not achieved (IEA, 2019).[5]

For this study, the ASEAN system operation is run across a given year at hourly time steps, following the expansion optimisation. Generating electricity and cross-border exchange minimises total system operating costs at each step. Thus, the marginal generation is set at the lowest available short-run marginal cost. The overall participation of renewables varies by scenario and country. In any case, the variability of solar and wind is supported by hydro, geothermal and biomass power plants. Energy balance is enhanced by storage facilities and the tailoring of demand-side activities like the production of green hydrogen and the smart charging of EVs. That is reflected in the regional exchange of power, where each ASEAN country has a unique role to play in the proper functioning of the system.

Solar is the flagship resource for ASEAN's decarbonisation; thus, its potential is massively deployed, while all other power assets that make up the system, to more or less extent, are tailored to its availability. It means that solar (and wind) energy is transported to demand centres, and devices like storage are optimised to displace generation to when power is most needed, while flexible demand is released when prices are at lower levels.

Viet Nam, Thailand, Sumatra, Nusa Tenggara (Indonesia) and the Philippines are the solar hotspots. Viet Nam and the Philippines are also home to good wind. The electricity is most needed in Viet Nam, Java-Bali (Indonesia), Thailand and the Philippines. Only Java-Bali will import more than 1 000 TWh by 2050 in the case of a 100% renewable energy scenario. This is almost three times the overall electricity demand of the United Kingdom in 2021, or one and half times that of Brazil.

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2 The Lao PDR, Thailand, Malaysia and Singapore Power Integration Project (LTMS PIP) enables power exchange, including between those countries that do not share borders through so-called transit countries (e.g. Thailand and Malaysia).

3 The Greater Mekong Subregion (GMS) collaboration is formed by Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam, along with southern provinces of China. As an activity-based program that includes energy cooperation, the group has been discussing creating a multilateral power market following ongoing bilateral transactions.

4 Beyond cross-border interconnectors, domestic transmission networks must be ready to deal with results from the eventual cross-region market model optimisation, which means reinforcements and expansion may be required. Otherwise, internal bottlenecks may limit the flow of active power, and further market splitting can eventually be applied.

5 The Philippines and Singapore have ongoing wholesale markets, and Malaysia is on the way. Therefore, a potential regional market must integrate or be complementary to existing ones.

The places with the best solar resources and overgeneration, like Viet Nam, Sumatra and Nusa Tenggara, feed power hungry regions/countries like Java-Bali, Peninsular Malaysia and Thailand.

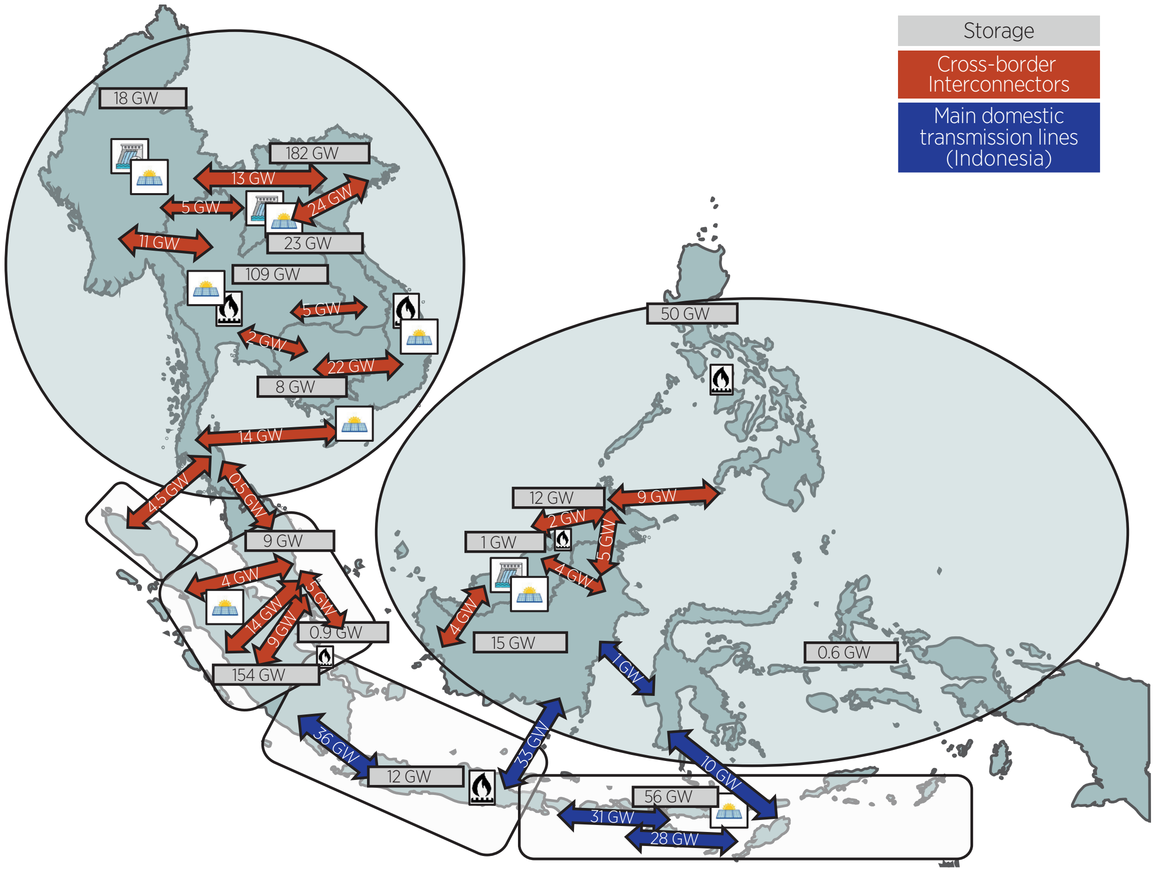
Figure 35 Energy exchange at the dispatch level across the ASEAN region in 2050 under the 1.5-S and 1.5-S RE100

The ASEAN power grid must be reliable and capable of dealing with significant amounts of electricity with minimum interruption (expected and unexpected). For example, the sudden interruption of a 10 GW+ interconnector can collapse the system, leading to blackouts. For comparison, Brazil's and China's most extensive existing transmission lines in capacity (and length) can transport 7-8 GW along 2 000-2 500 km. Existing subsea cables have achieved over 2 GW.

By 2050, the required lines in ASEAN are likely to reach three to five times this value. It may mean having two or more lines (circuits) in parallel, irrespective of future technological breakthroughs. That also minimises the possibility of collapsing the system due to the tripping of very high-capacity transmission lines. Nonetheless, the combination of high VRE generation and low demand or synchronous generations may limit power exchange at certain moments – not because of the line capacity but because of voltage stability. Therefore, devices like synchronous and static VAR[6] compensators may be required to improve the system strength. Although voltage control is a local problem, co-operation and sharing of information between TSOs are needed to ensure cross-border stability with standard control methods.

Caution is required in the planning, commissioning and operation of the assets that comprise transmission capacities of 10-30 GW between two regions or countries.

Figure 36 Transmission lines and batteries in 2050, 1.5-S RE90



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Flexibility exchange from importing to exporting-oriented regions

A country's balance between supply and demand is thoroughly and constantly adjusted, taking advantage of the available domestic system assets. The price of electricity at the operation step results from the system's short-run marginal cost of generating an additional unit of electricity. The most expensive unit in operation typically sets that. It can be very low or zero at moments of high generation from solar and wind, which has no or minimal marginal cost. Provided markets are set for that, from the demand side, electricity consumption can tailor to the availability of energy in the system. That means there is an attempt to use the least-cost generation resources and consume electricity at the least-cost moments. As the system optimisation occurs

[6] *Volt-Ampere Reactive*

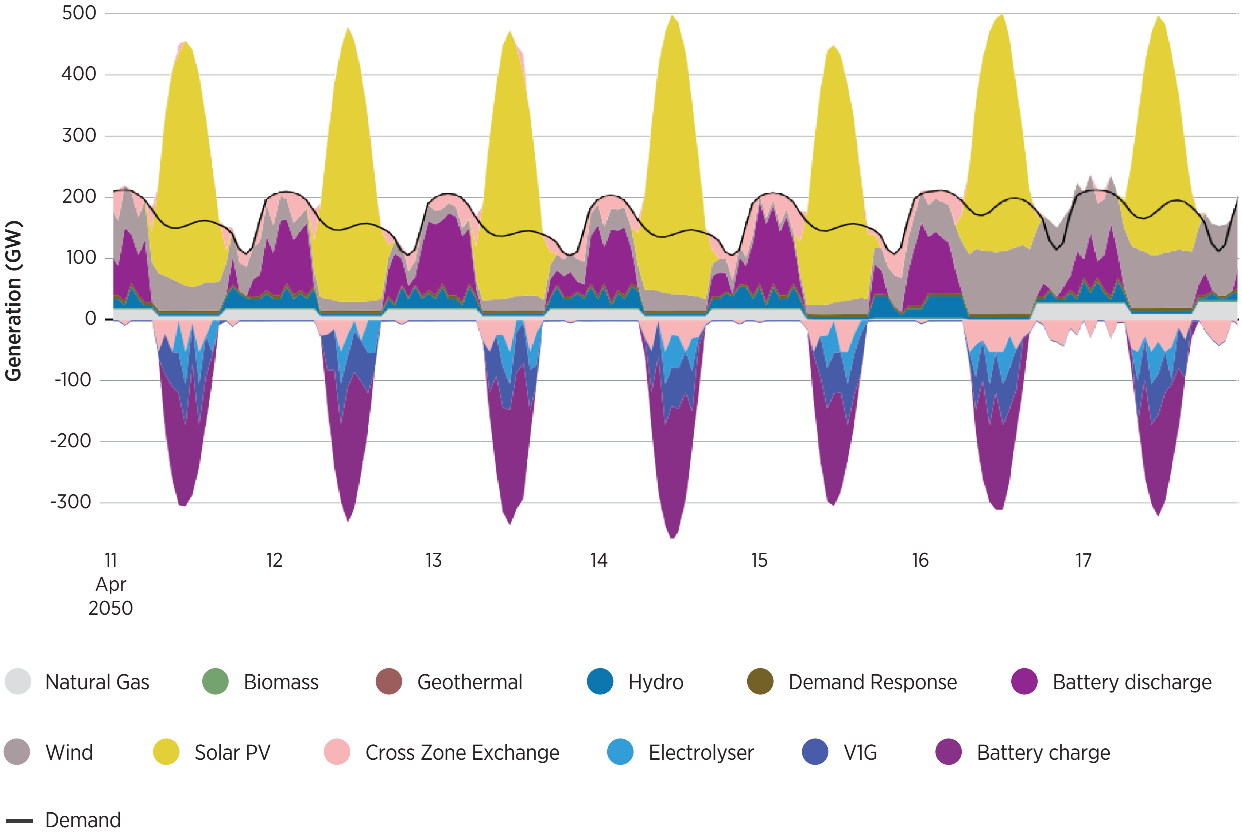
from the regional perspective, the same dynamic defines cross-border power exchange, from low-cost to high-cost regions. Regional grids enable the sharing of flexible resources and operating reserves where markets and regulations are appropriately set.

For instance, cross-border support is noticed in moments of overgeneration in Denmark (low price), when power is exported mainly to hydropower-dominated Norway and Sweden. In a way, electricity is stored in hydropower reservoirs. In practice, hydropower units decrease power generation to give room to the imported wind energy while maintaining water levels, or even increasing them, that would otherwise be used. Energy can then be exported back when needed. A similar context with batteries has not been seen given the still relatively few projects in the field, but it should follow a similar pattern.

In 2050, short-to-medium-term storage facilities will cycle daily to absorb the massive generation of solar spots in ASEAN for later use, while flexible consumption will align with the solar generation. At the same time, interconnectors make way for solar to go where it is most needed. Figure 37 illustrates the week with the highest VRE generation in Viet Nam, where 200 gigawatt hours (GWh) of solar energy is produced daily above the assumed inflexible demand.[7] Storage devices increase demand-load in such moments, and flexible end-uses like green hydrogen production and charging of EVs[8] are concentrated during the daytime.

The use of short-term storage like batteries is vital in balancing daily supply and demand. The further displacement of the demand (e.g. EVs charging, electrolysers, others) to moments of solar generation helps alleviate the need for additional storage and transmission.

Figure 37 2050 week with max VRE generation in Viet Nam - 1.5-S RE90



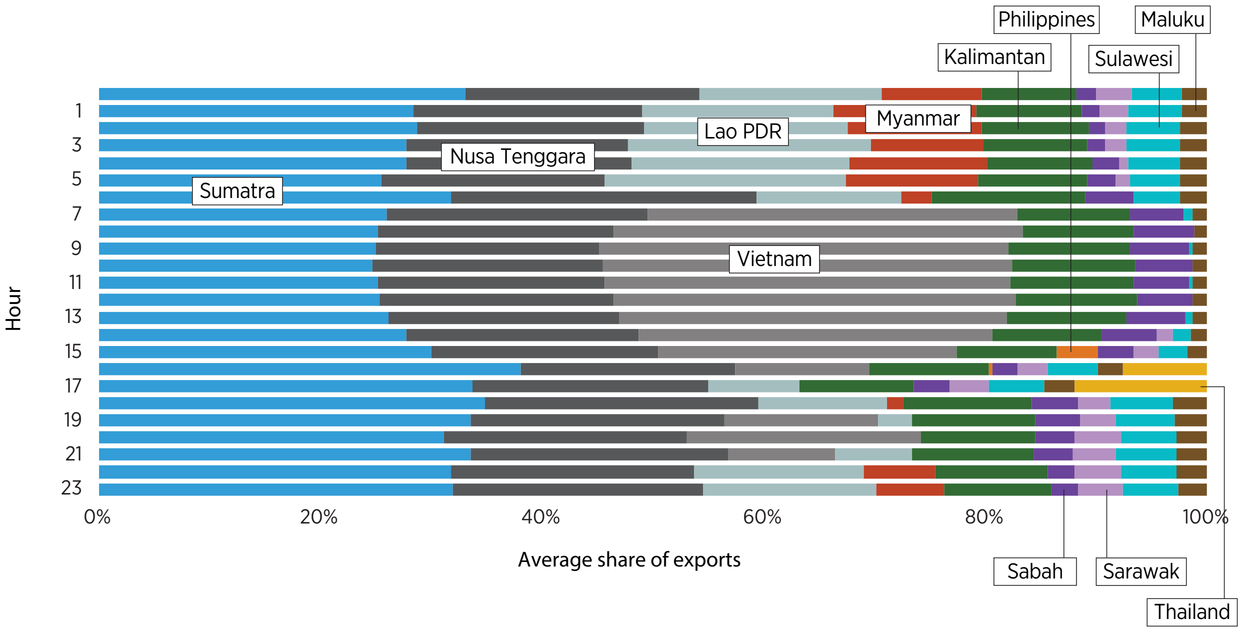
[7] *The entire country's demand minus the flexible part of hydrogen production, smart EV charging and allowed demand response.*

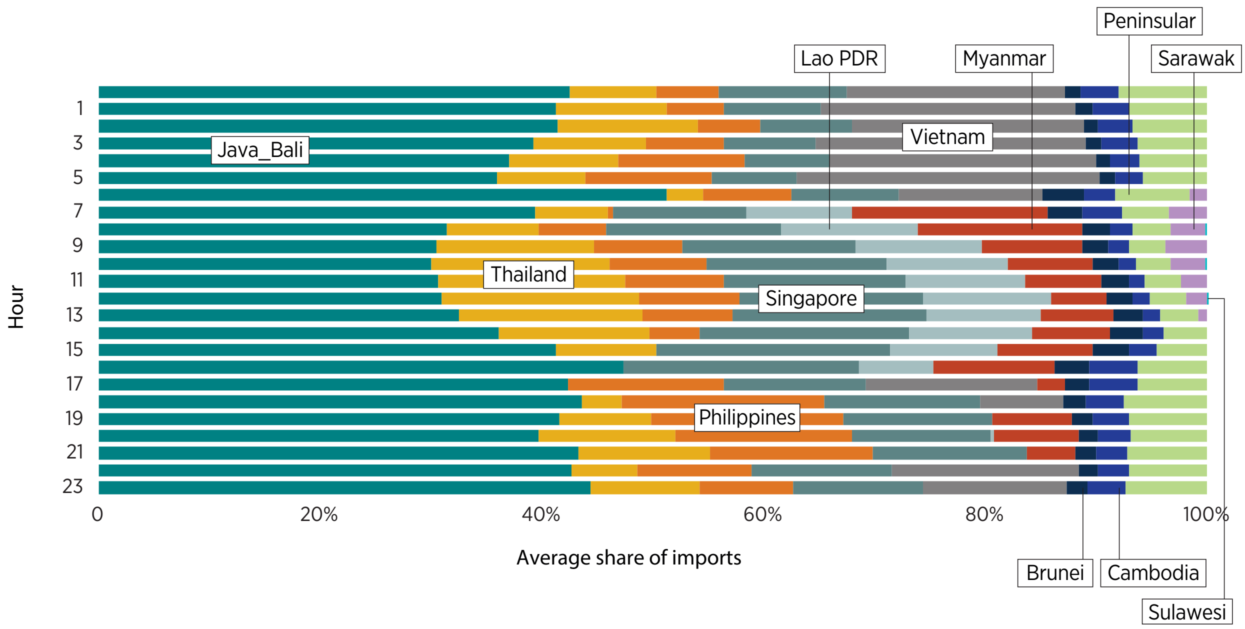
[8] *The production of green hydrogen and the charging of EVs were assumed to be 90% flexible and 10% inflexible. That entails the use of hydrogen storage (included in the model), and the required EV charging infrastructure for steep spikes of loads. The inflexible part of both of them follows a flat demand curve along the day. Eligible flexible demand is deemed as 3% of the load.*

To illustrate, Viet Nam is responsible for roughly 50% of the Mekong region's solar generation and 100% of that from wind. VRE provides 74% of that region's total electricity generation, which is expected to be partially exported. However, the country's 180 GW of battery charging capacity (with an average eight hours of storage) is insufficient to export energy at nightfall, which occasionally happens during nights of solid wind (depicted on days 16-17 April). To overcome that, existing hydropower units with reservoirs from Lao and Myanmar provide electricity during the night by importing and storing solar generation during the day from Viet Nam (lower part of Figure 38) to be later exported (upper part of Figure 38). In practice, hydropower units decrease power to give room to the imported electricity while maintaining water levels that would otherwise be used. Supporting the system with these existing reservoirs is more cost-effective than building additional storage, which is just one of many regional interactions highlighting the importance of countries with low total yearly power exchange, as depicted in Figure 35.

Hydropower in regions/countries like Lao PDR, Myanmar and Sarawak plays the role of importing solar generation to export it through the night.

Figure 38 Map of the average hourly profile of exports and imports across the region by 2050, 1.5-S RE90





Electricity storage shift generation to meet the peak load and the night

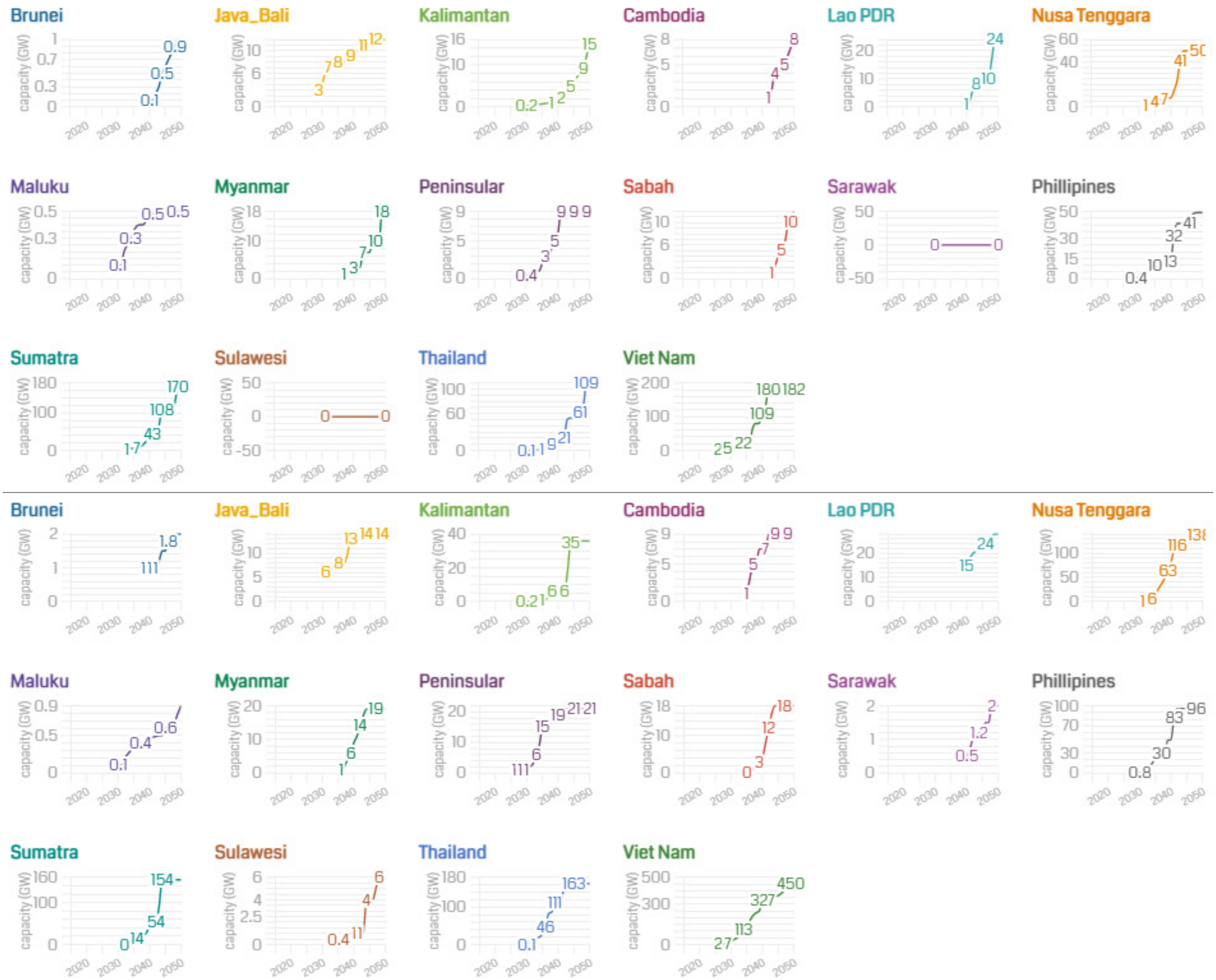
There is a wide range of commercial storage technologies, most of which are likely to have a role in providing the different services for the energy transition (IRENA, 2020). However, for the sake of simplicity, this study considers two technologies as flexibility candidates: batteries and pumped storage. In addition, it should be noted that hydropower with reservoirs has embedded storage capabilities[9] as the energy potential from waterfalls from reservoirs can be managed driven by the availability of variable renewables.

As expected, results show a clear correlation between storage needs and the expansion of renewables in countries across scenarios. Short-term storage like batteries is vital in balancing daily supply and demand. However, long-term storage needs are reduced given the low variation of solar resource availability across the year.

Beyond that, storage may also postpone or alleviate the need for transmission projects. As such, battery requirements will reach 667 GW by 2050 in the 1.5-S RE90 scenario (Figure 39). Cost-effectiveness is first achieved in Viet Nam in 2030, comes to other countries a few years later and speeds up from 2040 onwards. The last mile towards 100% renewables is challenging, requiring an additional 50% capacity, getting to over 1 000 GW.

Battery storage is cost-effective in a few countries from 2030, achieving large-scale maturity from 2040 in the ASEAN region.

Figure 39 Battery capacity development across the period, 1.5-S RE90 (upper) and 1.5-S RE100 (lower)

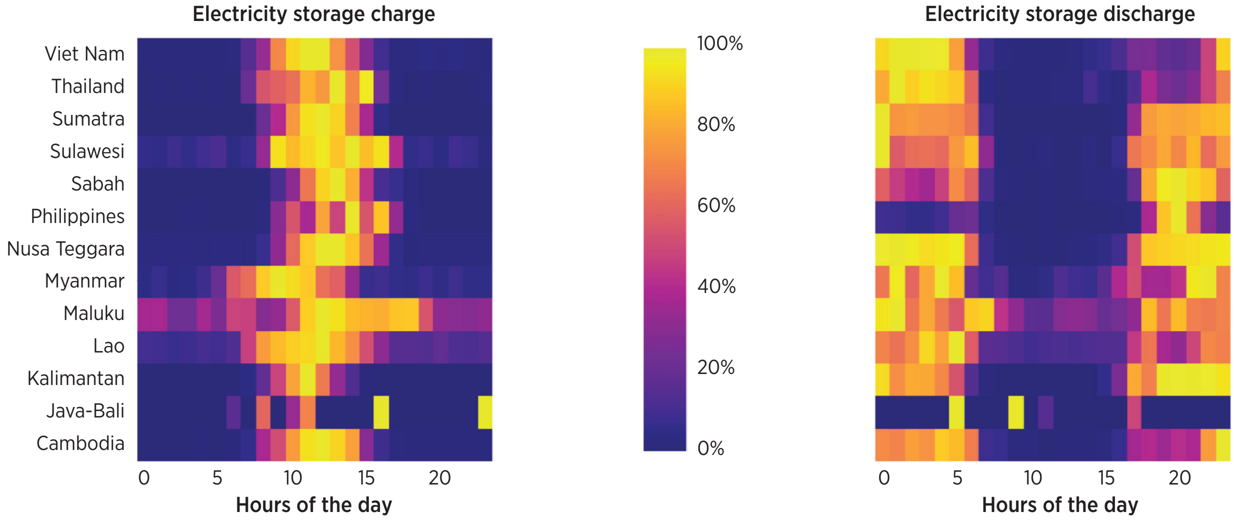


[9] *Hydropower with reservoirs may have socio-environmental impacts. Upstream flooding and the reduction of downstream water flows can destroy wildlife habitats and impact small-scale fishery, farming land and others, raising costs that are outside the scope of this study.*

The storage charging and discharging hourly profile follows the availability of solar energy (Figure 40). That is essentially the case across the region under the 1.5-S RE90 case, except for Java-Bali, where solar capacity is relatively low and batteries have the principal role of proving operating reserves rather than energy. The Maluku Islands have significant participation of wind; thus, charging activities also happen during the night (upper chart). Similar behaviour is seen in Viet Nam and the Philippines, under the 1.5-S RE100 case (lower chart), where domestic wind thrives at 44% and 60%, respectively. Again, market and forecasts will be essential to give the right price signals to ensure the battery behaviour that is more beneficial to the system.

Understanding when batteries charge and discharge has important implications for system operation.

Figure 40 Battery charge/discharge daily average profiles as a percentage of peak power, 1.5-S RE90

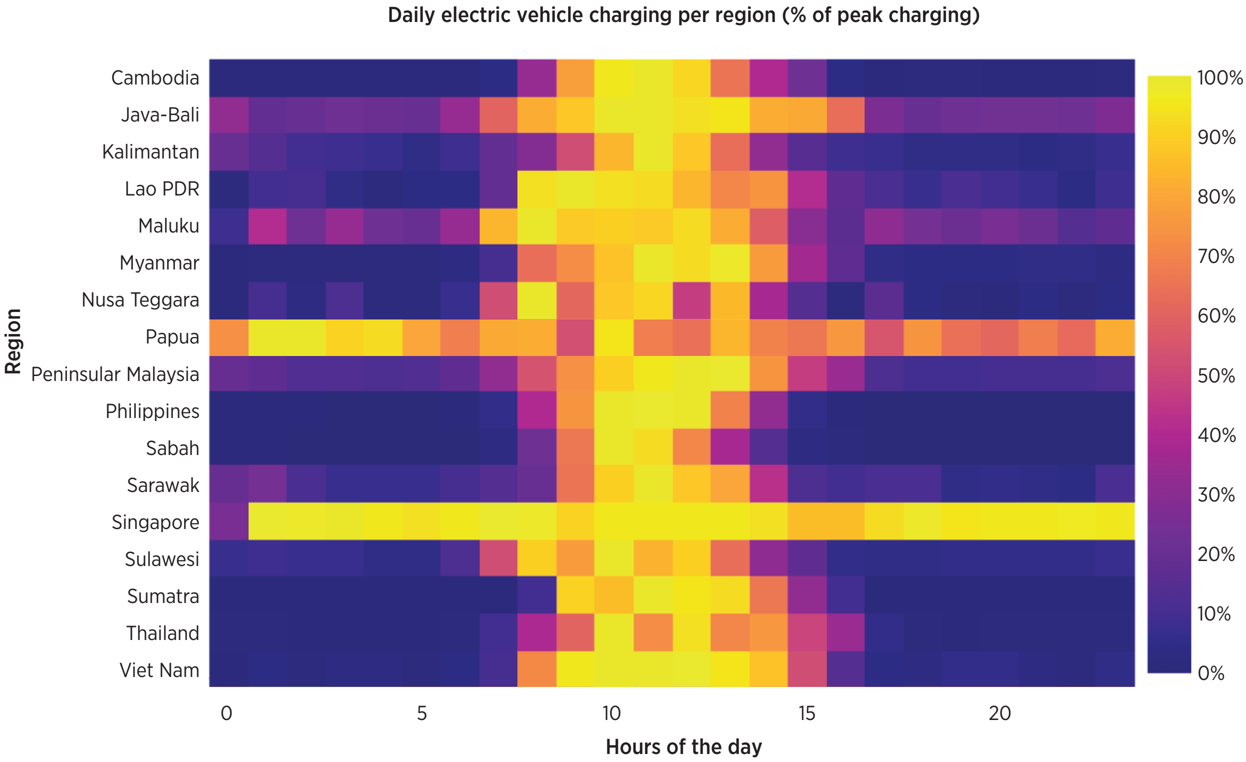


Similarly, EV charging and electrolyser operation follow the availability of energy. The countries' EV fleet presented in section 4 was deemed 90% flexible, so they can charge whenever electricity prices are at lower levels. The remaining 10% is inflexible (*e.g.* onsite hydrogen production without storage, non-responsive EV charging behaviour), represented by a continuous flat curve along the day (Figure 41). Demand displacement potential is naturally higher in densely urbanised and industrialised areas where the EV fleet and hydrogen production[10] are higher.

[10] *The study assumed that green hydrogen production occurs where the demand is located. Forthcoming work will assess potential exchange routes in the region and exports to non-ASEAN countries (see also the Hydrogen section in chapter 4).*

Charging EVs when variable renewable generation is at its peak is a key enabling solution for flexibility.

Figure 41 Average hourly charging profile of EVs



System reserves in the power sector

Spinning reserves are the amount of unused generation capacity at online power assets kept on standby for the causality of power shortages or frequency drops. In practice, reserve providers must operate below their rated value to quickly ramp up power when needed. Reserves requirements are typically defined based on the largest power asset (generator, transmission line and other assets). This is the "n-1 criteria" that is the standard in Indonesia. In renewable-dominated systems, the installed capacity of generation units tends to decrease with distributed and smaller-scale assets rather than large, centralised power plants. From this perspective, reserve requirements tend to reduce. However, the increasing number of high-capacity transmission lines tends to raise needs.

Reserves were set at 10% of the load for all region-grids, except for Java-Bali, where a 15% load risk was considered.[11] Reserves can be shared within a region (*e.g.* Sumatra's Southern Mid-Center provinces), but not across macro-regions or countries (Sumatra, Java, or Cambodia and Thailand). The exception is the Java-Bali grid, given the existing synchronous grid there. The sharing of reserves between other macro-regions would probably make provision more efficient, which would also entail grid synchronisation of the respective areas.

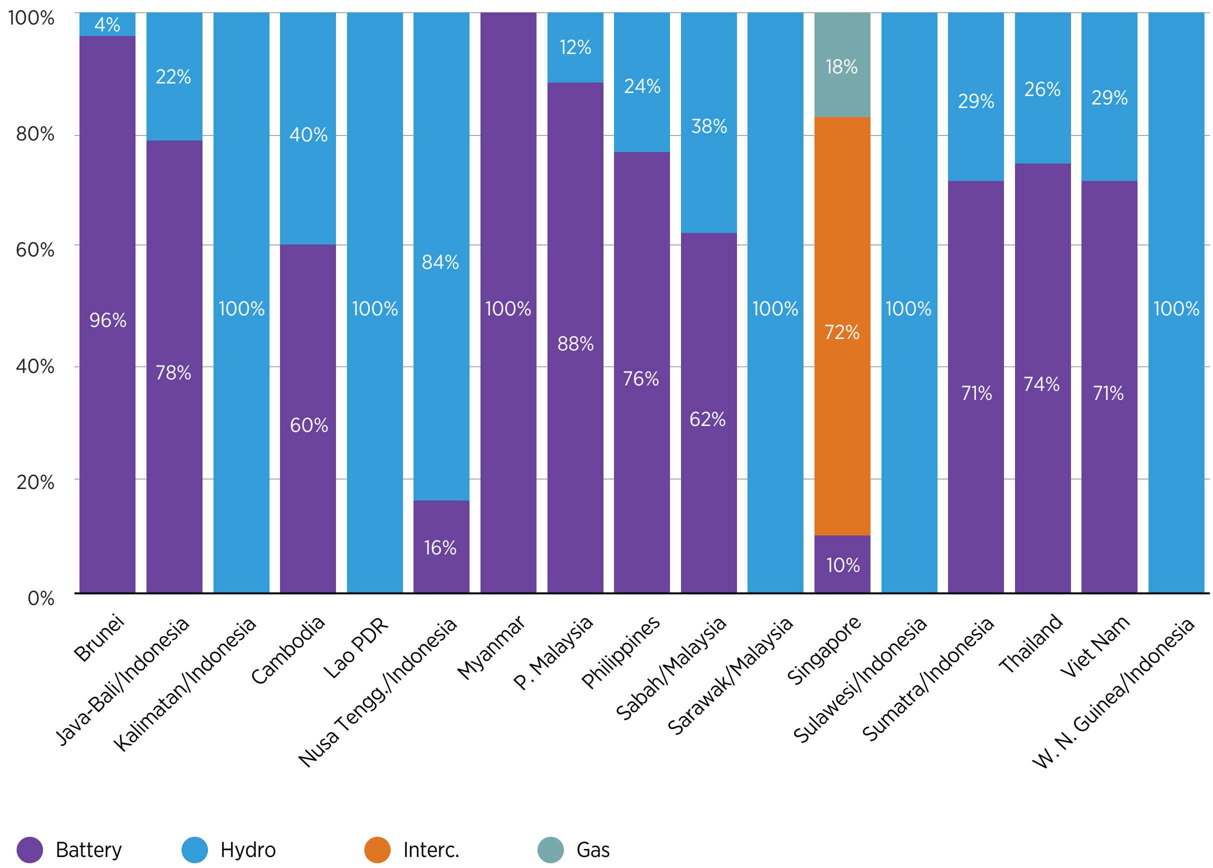
Only hydropower and storage assets were allowed to provide assets by 2050 (upward/downward), to avoid having non-renewable assets locked in for this purpose. Whether power electronics are designed to do so, battery technologies can deliver a response on a millisecond scale, which is faster than any traditional generator. Solar and wind were set to provide downward reserves only (curtailment), though operation adjustments could also allow the technologies to offer an upward response.

11 *Considered grids are Brunei, Cambodia, Indonesia (Java-Bali, Kalimantan, Sumatra, Eastern Nusa Tenggara, Sulawesi, Maluku, and Papua), Lao PDR, Malaysia (Peninsular, Sarawak and Sabah), Myanmar, the Philippines, Singapore, Thailand and Viet Nam. Eastern Nusa Tenggara and Maluku in Indonesia are island-regions, made up of several small-isolated systems, so requirements are a proxy exercise.*

On average, over 50 GW of reserve capacity must be available every moment in the entire region. Provision is a function of the resources available in a given area. For instance, reserves are guaranteed by spinning hydropower resources in Myanmar, while batteries mainly back Eastern Nusa Tenggara in the wake of the tremendous solar development. Almost 70% of reserves are battery-based, with the remaining met by hydropower. The exception is Singapore, where there is a need for natural gas resources in the 1.5 RE90 case.

The provision of reserves is made from the most available renewable-based resource in each region.

Figure 42 Operating reserves provision in 2050, 1.5-S RE90



A sensitivity scenario analysis was undertaken where spinning reserves are set at 5-20% of demand for the Java-Bali grid, given the region's enormous demand, the magnitude of resources and the phaseout of a significant number of thermal units. Although the 15% reserves case raises shortage, only the highest risk level (20% of load) was deemed critical (Table 14).

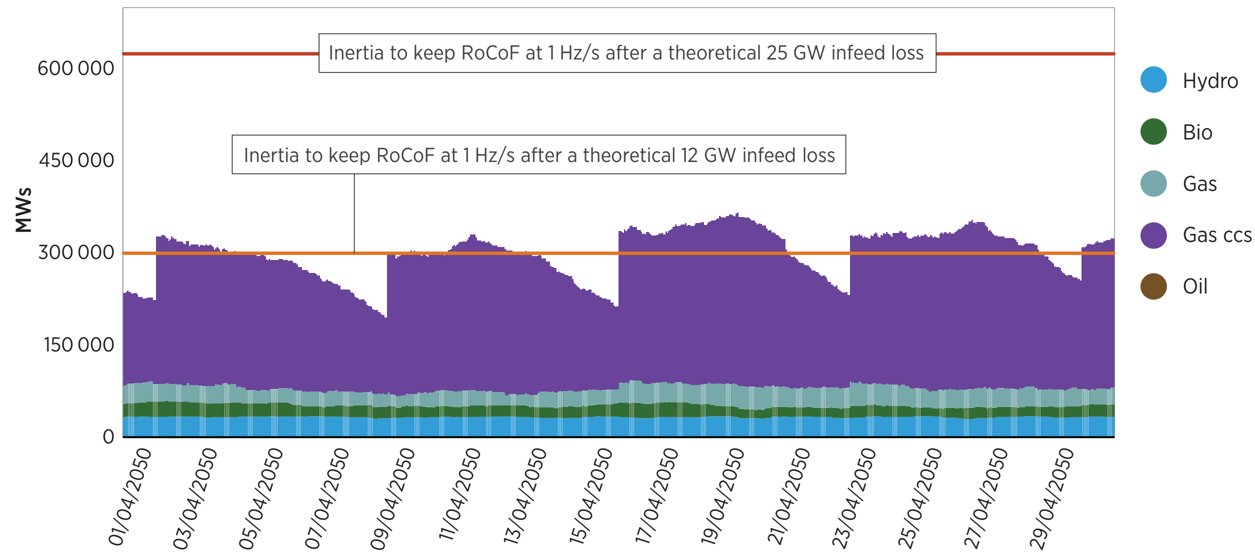
Table 14 Sensitivity scenarios on operating reserves

	STATUS		
	SHORTAGE (GWh)	HOURS (hrs)	GWh/hr
5%	No	No	-
10%	No	No	-
15%	190	138	1.37
20%	49 390	5 443	9.07

The large transmission assets connecting the Java-Bali grid can bring operation challenges in case of the tripping of a line, namely with Sumatra (36 GW), Kalimantan (33 GW) and Nusa Tenggara (31 GW). These may provide 24%, 22% and 20% of its average load at total capacity, or 70% in case of simultaneous imports. Even though this is not likely to happen, and each of the lines themselves should be composed of two or more independent smaller circuits, that should be adequately explored in grid integration studies. There will be a need to rethink how imbalances are noticed and reserves are activated. There will be less and less synchronous inertia, which is the ability to oppose changes in frequency after a failure, inherently provided by synchronous generators like thermal plants and hydropower. The amount of reserves and agility needed in today's power systems is a function of inertia conditions. Figure 43 shows inertia provision in the Java-Bali grid in 2050 at around 300 MWs on average. At least two times this value is needed to maintain the Rate of Change of Frequency (RoCoF) at 1 Hertz per second (Hz/s), and more than four times to keep it at 0.5 Hz/s,[12] in case of tripping two of the abovementioned lines together, considering each as a single asset. Therefore, the future system will likely need faster-frequency response resources like batteries and a different way to signal imbalances. The good news is that grid-forming inverters are on the verge of addressing this issue, allowing operation at very low or even zero-inertia conditions.

Moving from synchronous machines to inverter-dominated systems reduces the system inertia, requiring innovative approaches.

Figure 43 Inertia contribution by synchronous machines in the Java-Bali grid in April 2050 - 1.5-S RE90



[12] *Considering grid frequency of 50 Hz.*

TECHNOLOGY VIEWS

4

4. TECHNOLOGY VIEWS

This section goes into greater depth on some of the key topics and technologies that are crucial for the transition in the ASEAN region. Many of these solutions are cross-sectoral, and they are discussed here in a wider context. However, many findings related to these solutions are also contained in chapters 2 and 3.

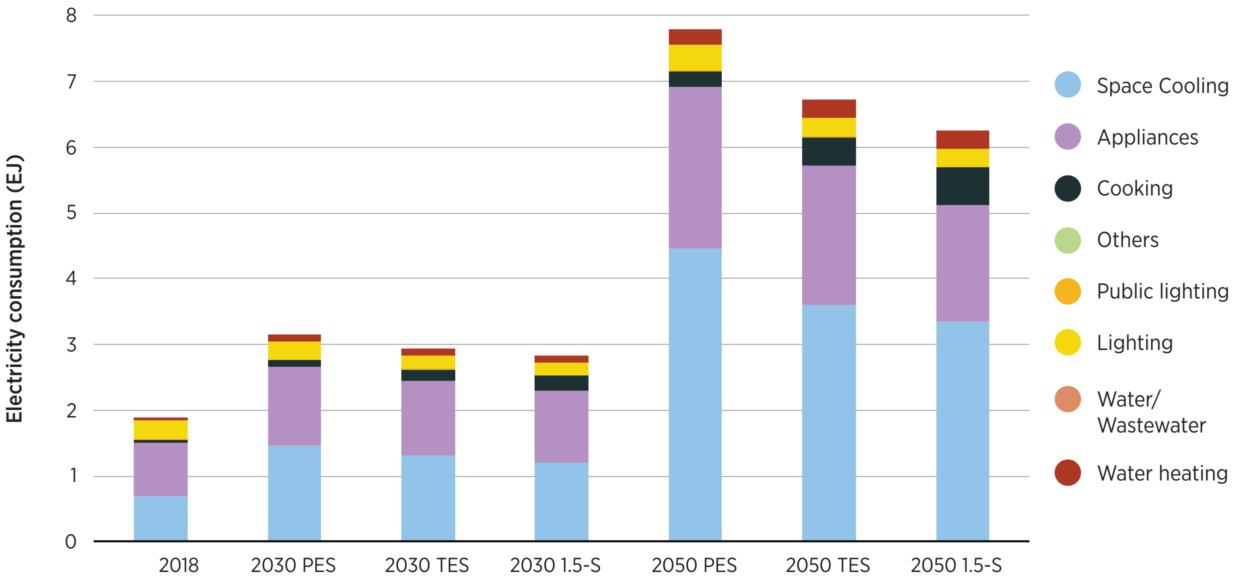
ELECTRIFICATION IN BUILDINGS, INDUSTRY AND TRANSPORT

The share of electricity in energy consumption in the building sector increases from 46% in 2018 to 78% in the PES 2050 and 85% in the 1.5-S 2050. This is primarily due to an increase in the use of electricity for space cooling, appliances and cooking.

In both residential and commercial buildings, space cooling is the most electricity demanding service, increasing from about 36% in 2018 to 57% in the PES 2050 and 53% in the 1.5-S 2050. This can be associated with the increased use of air conditioners and fans within the ASEAN states to meet the residential space cooling needs over the years. Although electricity demand remained consistent for appliances across all scenarios in each year, there is a significant increase in electricity demand for cooking from 2.5% in 2018 to 9.1% in the 1.5-S 2050. This is mainly due to the decrease in the use of traditional cookstoves and wider adoption of efficient electric cookstoves.

Electricity demand in the building sector is dominated by space cooling.

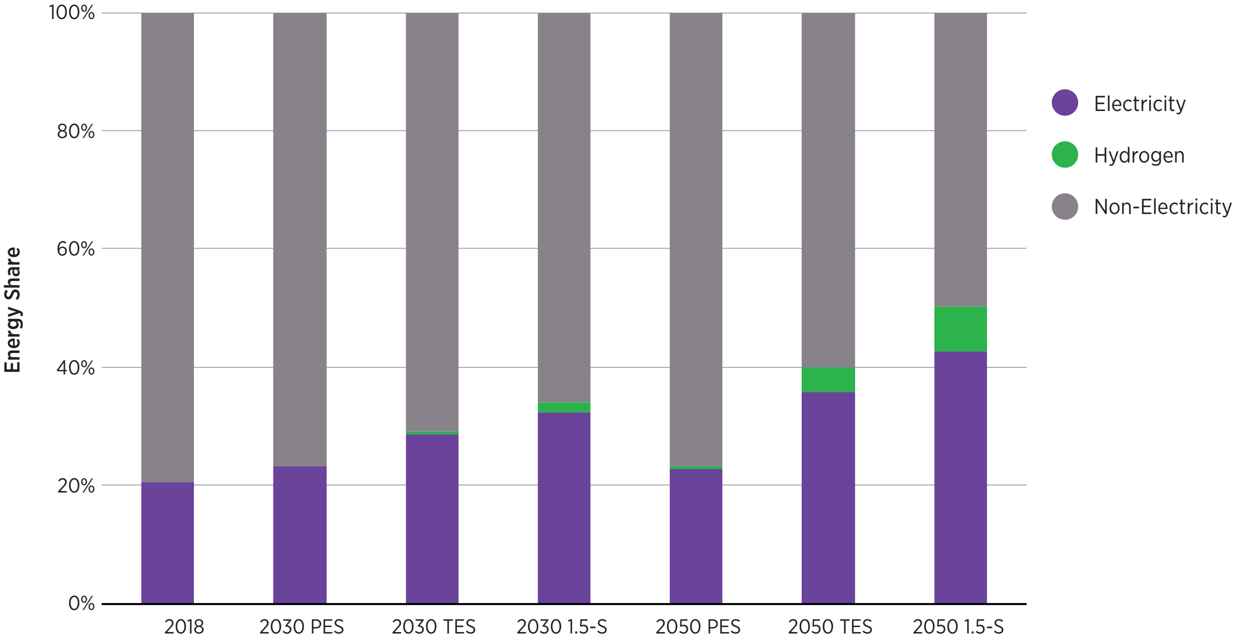
Figure 44 Building sector electricity demand, by scenario, 2018, 2030, 2050



In industry, electricity is used across a wide range of applications, from running machinery and appliances to motors, process heat, fans and cooling systems. Around one-quarter of the sector's energy demand comes from electricity, and this share will decline to 22% in the PES in 2050, largely due to the growth of heavy and medium industry, which utilises more fuels. In the 1.5-S, measures to directly electrify process heating are the main drivers in increasing the electricity share to 45% of sector energy. Additionally, the emergence of green hydrogen also comes into play for certain industrial subsectors.

Electrification and hydrogen will be key to the energy transition in industrial process heat.

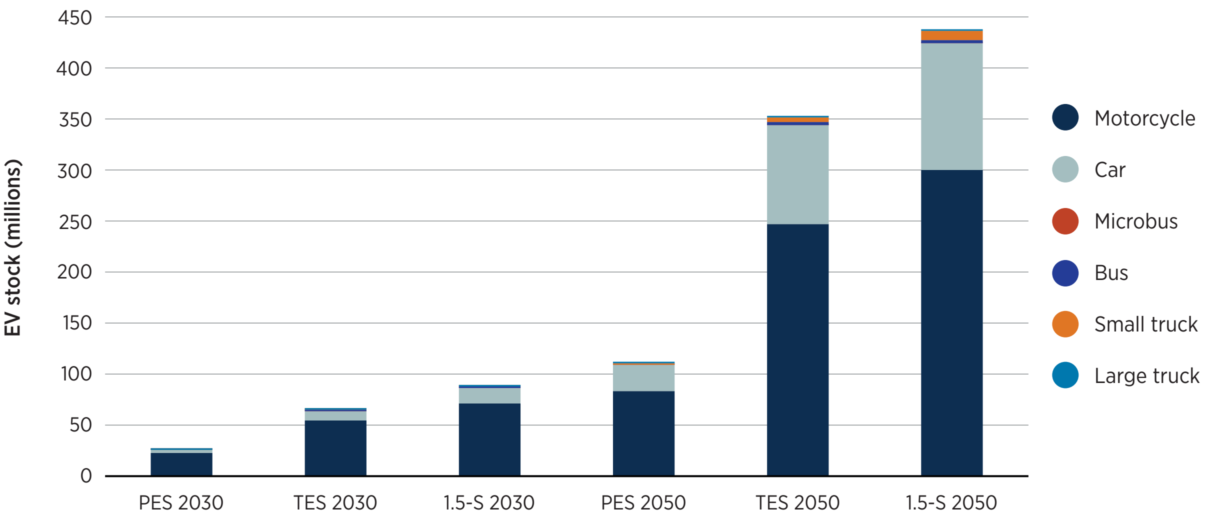
Figure 45 Share of industry energy demand by carrier group, by scenario, 2018, 2030, 2050



The electrification of road transport is the single most important shift in transport that will occur over the coming decades. Shifting to EVs must coincide with a shift to renewable power and other low-carbon sources of electricity supply. Under the PES, the share of EVs in the region reaches about one-fifth by 2050. In the 1.5-S, the share of EVs in the region grows, resulting in only about 20% of total road vehicles running on internal combustion engines. For these vehicles, biofuel covers a little over one-third of fuel consumption in 2050. Electric two-wheelers and electric cars in the 1.5-S will reach 86% and 75%, respectively, of 2050's total fleet share. Almost 70% of the total bus fleet in the 1.5-S by 2050 will run on electricity, while less than 25% of the truck fleet will be electrified. Oil products continue to have a role in the transport sector, accounting for a 44% share, mostly consumed in heavy-duty freight, shipping and aviation, despite an increasing biofuel share reaching 25% of total transport energy demand by 2050 under the 1.5-S.

EVs will need to grow substantially to reduce reliance on fossil fuel and decarbonise the transport sector.

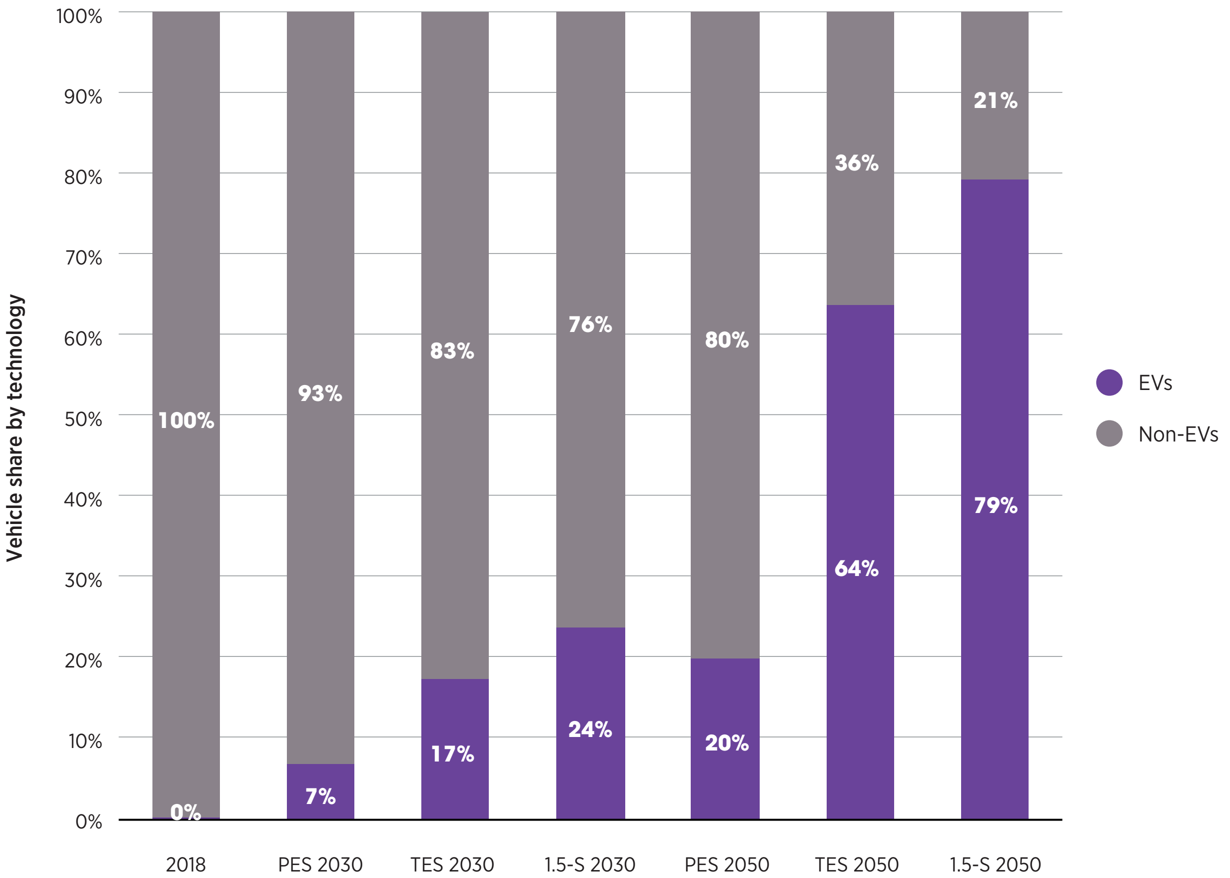
Figure 46 EV stock, by scenario, 2018, 2030, 2050



Note: "Car" includes jeeps, vans and SUVs; "motorcycle" includes three-wheelers.

Only about one-fifth of ASEAN's vehicles are not running on electricity by 2050 under the 1.5-S, most of those are heavy freight vehicles.

Figure 47 Vehicle share by technology, by scenario, 2018, 2030, 2050

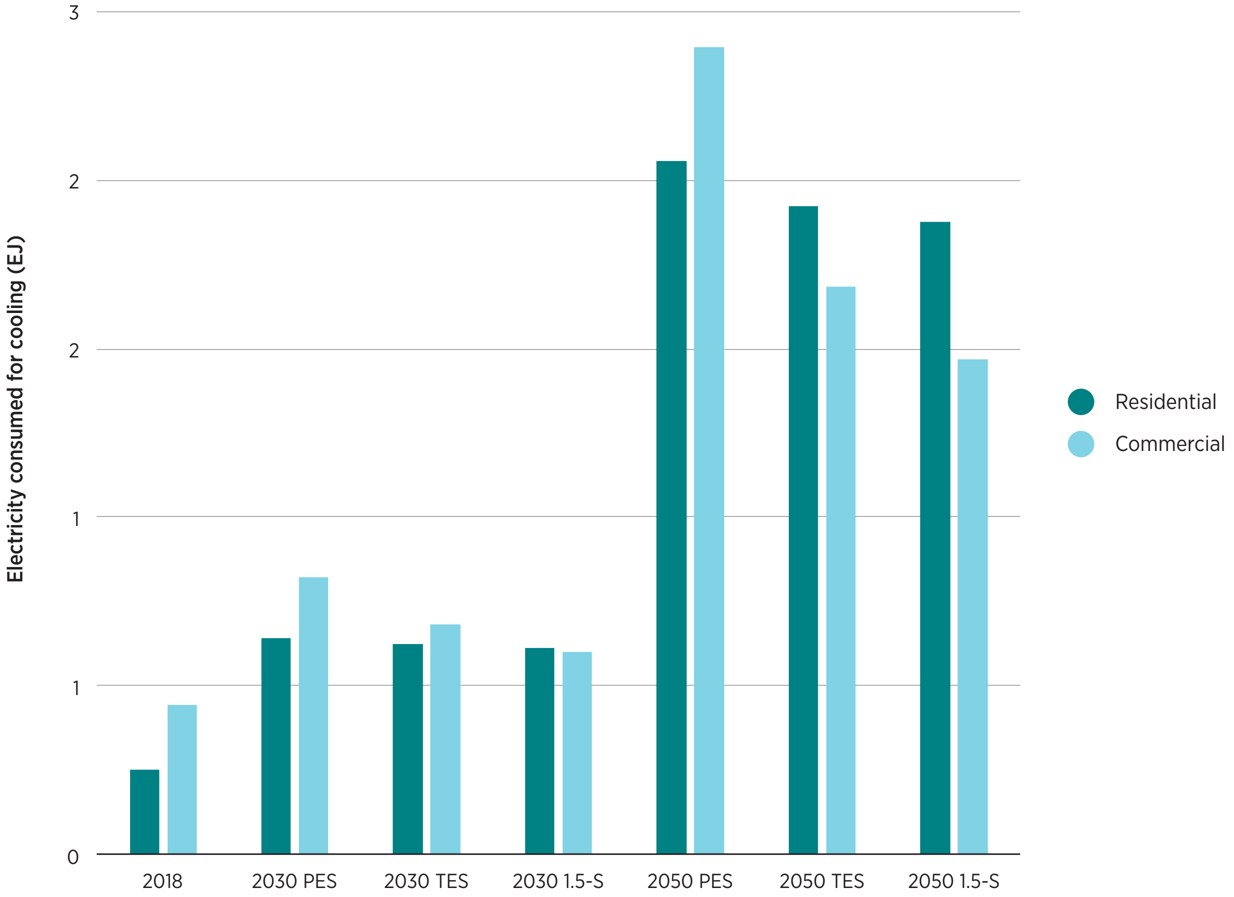


ENERGY CONSERVATION AND EFFICIENCY IN RESIDENTIAL AIR CONDITIONING

Space cooling is the main driver for the building sector's energy demand in the future. In the ASEAN region, the share of space cooling energy demand in the building sector increases from 17% in 2018 to 46% in 2050, equal to about 4.5 EJ (~1.3 TWh). This increasing energy demand is due to the growth in equipment penetration and ownership, the number of households and the region's economy. Under the PES, residential space cooling energy consumption is projected to grow more than eightfold in the study period, with commercial space cooling growing more than fivefold. With the current minimum energy performance standard (MEPS), the overall expected energy savings in residential space cooling is only about 10% in the 1.5-S over the PES. The stock of residential air conditioning grows 5% annually in the region, reaching total stock of more than 120 million units – about 3 million unit sales annually to 2050. This shows the importance of more stringent policies to improve the space cooling MEPS across the region as soon as possible. Commercial sector space cooling shows more promising energy demand reduction, levered by mode developed building codes and efficient chiller technologies, which allows about 40% demand reduction from the activities in the 1.5-S by 2050 over the PES. The use of natural refrigerant should also be considered as one of the efforts in reducing the global warming effect from the space cooling activities.

Space cooling demand rises significantly in the building sector, growing almost fivefold.

Figure 48 Space cooling energy demand in buildings, by scenario, 2018-2050



ENERGY SOLUTIONS FOR ISLANDS IN THE SOUTHEAST ASIAN REGION: MINI-GRIDS AND STAND-ALONE ENERGY SYSTEMS

Southeast Asia is a vast region that consists of mainland Southeast Asia and a string of archipelagos to the south and east of the mainland, also known as insular Southeast Asia. The archipelagic geography of the insular Southeast Asia region comprises many remote and small island communities, and the smallest and most remote remain without access to electricity or are electrified mainly by diesel generators.

Rural electrification through the extension of the existing electricity grid infrastructure to these remote locations is often unviable – leaving mini-grids and stand-alone energy systems, especially those incorporating renewable energy, as an ideal solution. The archipelagic nature of the ASEAN region makes providing electricity in many isolated islands and remote communities a challenge. Diesel mini-grids are mainly used to provide limited electricity supply in these areas. This entails covering the high cost of delivering these services as well.

To accelerate the deployment of renewables for off-grid electrification, a holistic energy access strategy must be backed by dedicated policies and regulations designed for decentralised renewable energy solutions. A stable regulatory framework is necessary to attract private investment in all areas of the sector where public funding falls short. The framework must be aligned with the objective of universal energy access (*i.e.* leaving no one behind) and provide adequate guidance and incentives to reach the very last household, firm or public facility through the most optimum solution, and to ensure permanence of supply through both default and last-resort providers (GCEEP, 2020).

According to IRENA's WETO, significant progress has been made over the past decade in developing policy and regulatory frameworks to guide investments in energy access. Dedicated policies and regulations for decentralised renewables, particularly mini-grids and standalone solar systems, complemented by regional programmes and donor-led initiatives, have driven recent growth in deployment. Yet large gaps remain, and some of the countries in the insular Southeast Asia do not yet have dedicated policies, while others need adaptations to support the dynamic nature of their electrification processes in remote islands (IRENA, 2022b).

In the specific case of standalone systems, fiscal incentives, such as exemptions from import duties and value added taxes, are often needed to incentivise market development and make solutions more affordable. Scaling up renewable energy mini-grids requires dedicated policies and regulations to address licensing and permitting requirements (including quality standards), tariff-setting, the implications of the arrival of the main grid and the distinctive aspects of mini-grid public financing.

Legal and licensing provisions provide the legal basis for mini-grids to generate, distribute and retail electricity in a given area. Largely administrative, they can involve transaction costs that may be significant for mini-grid projects. Dedicated mini-grid regulations are increasingly simplifying licensing requirements.

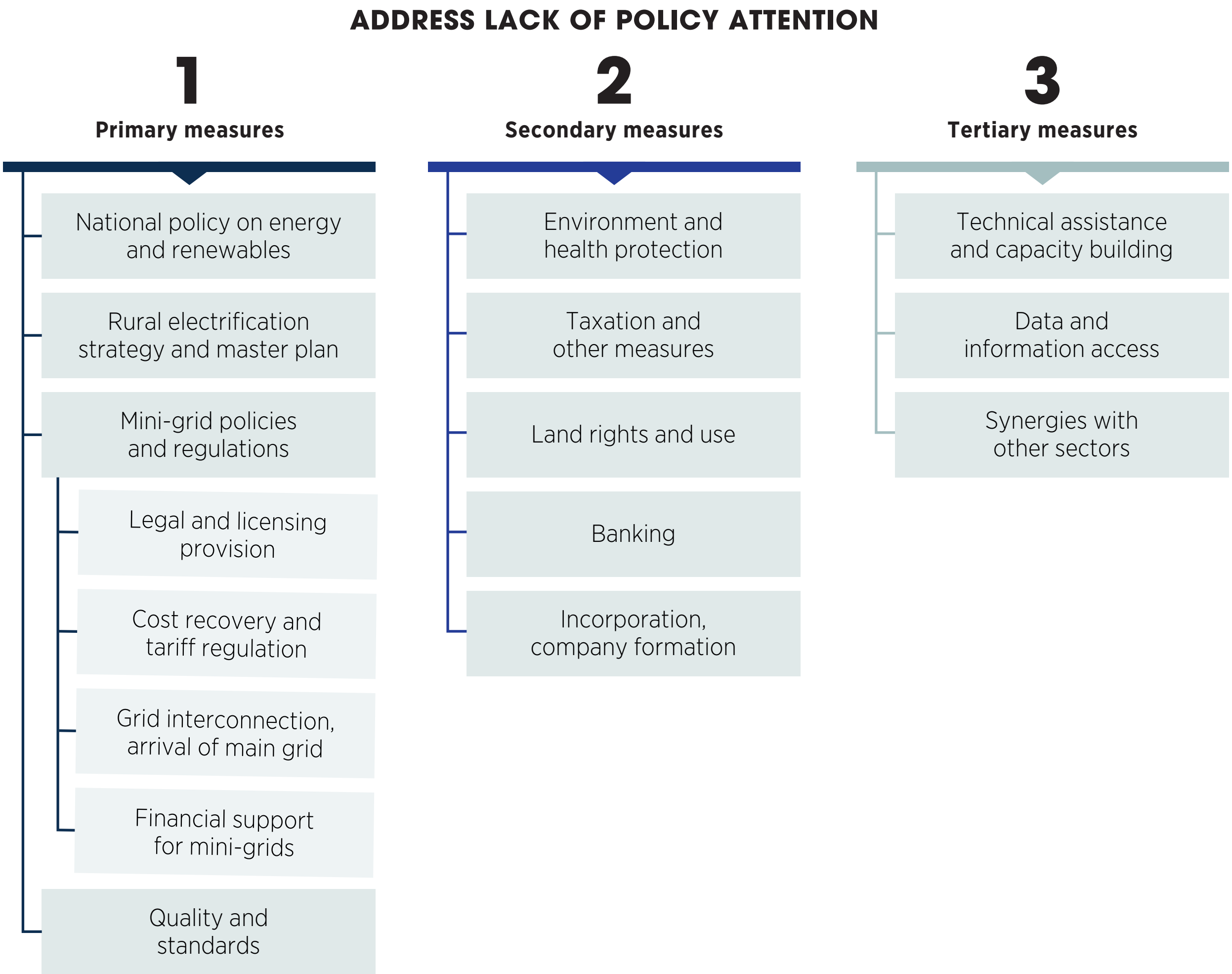
Tariff regulation is central to the viability of any mini-grid and is often shaped by local political economy considerations. Given the higher cost of supply in off-grid areas, the tariff setting process must balance cost recovery with consumers' ability to pay. Early mini-grid regulations used a "willing buyer, willing seller" approach to set tariffs for mini-grids of pre-defined system sizes. However, this comes with the risk of communities withdrawing consent during the operational phase. A cost-of-service approach to tariff setting is recommended that takes financial support (*e.g.* capital expenditure subsidies) into consideration. To support scale, portfolio-level tariff approvals are also recommended as they allow developers to cross-subsidise their portfolios. Where national uniform tariffs are applicable or regulators determine retail tariffs, adequate subsidy mechanisms are needed to bridge the gap between the cost of service and tariff revenue.

The arrival of the main grid is a major risk for isolated mini-grids. However, for remote islands this is not always the case. But in some cases mini-grid regulations, including those in Indonesia, Kenya, Nigeria and the United Republic of Tanzania, have attempted to address this risk through integrated planning and earmarking options for operators. These generally include compensation (based on a pre-defined depreciation schedule and business value estimation) and conversion to the status of small power producers or distributors. In each case, the regulatory guidance must be clear, transparent and reliable, given the significant risk of stranded assets.

Finally, it is important to underline that measures for mini-grid and stand-alone solutions for distributed generation entail a package of actions. These can be categorised in primary measures that directly affect project development and operation, where national regulatory frameworks must tackle measures that are needed to sustain these projects (IRENA, 2018). The implementation of secondary and tertiary measures usually rests with institutions outside the energy sector. Secondary measures include policies related to land rights and use, banking and company formation. Tertiary measures cover access to local statistics, technical assistance and capacity building, *e.g.* to support local enterprise development for mini-grids and stand-alone energy solutions.

Mini-grids as stand-alone solutions for distributed generation are particularly important for islands and isolated communities.

Figure 49 Overview of measures to scale up renewable energy mini-grids



Source: (IRENA, 2018).

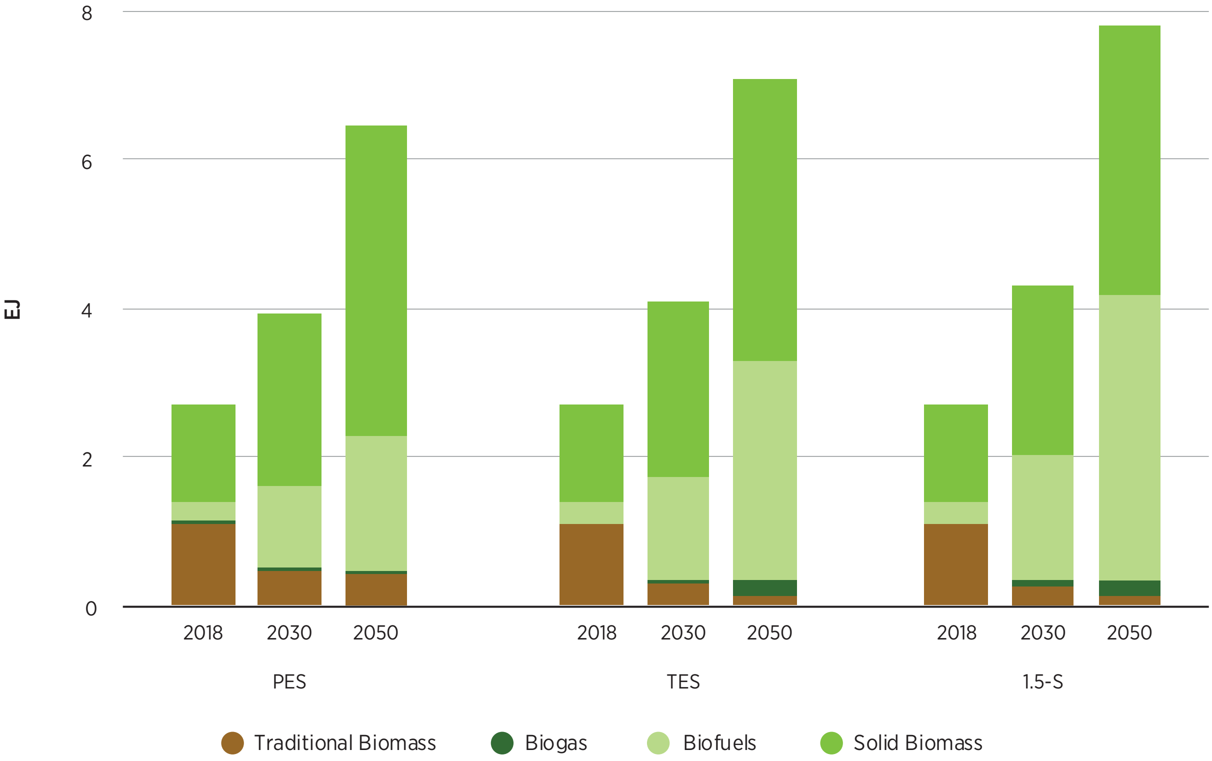
BIOENERGY

Sustainable bioenergy potential and availability in Southeast Asia

According to WETO, bioenergy today makes up over 50% of renewable energy use. Achieving the net-zero goal will not be possible with renewable electricity and energy efficiency alone. Bioenergy would represent 25% of TPES by 2050 in IRENA's 1.5°C Scenario. That would require just over 150 EJ of biomass primary supply, or around a threefold increase over 2019 levels – a challenging scale-up effort.

Bioenergy, in the form of modern biomass, will have an increasing role in ASEAN's decarbonisation effort.

Figure 50 Share of bioenergy in TFEC in ASEAN, by scenario



In ASEAN the scale-up is similar. In absolute terms, the increase will be from around 2.7 EJ (primary) to 7.6 EJ by 2050 in the 1.5-S. In 2018, around 14% of final energy came from bioenergy sources, with a little under half from traditional sources of bioenergy. By 2050 in the 1.5-S, the share will increase to 19%, with all traditional uses of bioenergy replaced with modern bioenergy. However, due to an increase in overall energy demand, total consumption will triple.

The supply of biomass feedstocks will need to expand if it is to meet the need for its use as energy. Global and regional estimates suggest, however, that biomass could reach the needed resource levels through a prudent and sustainable expansion in bioenergy. This expansion can be achieved with policies that promote a wider use of biomass sources, coupled with strong, evidence-based sustainability governance procedures and regulations.

In the ASEAN region, all renewable energy sources have a role to play in the energy transition. However, when it comes to the potential for sustainable bioenergy to serve Southeast Asia's energy demand, a recent study from IRENA identified 13 sustainable bioenergy pathways (see Table 15) that will enable bioenergy to compete economically with fossil fuels in the region's energy markets (IRENA, 2022e).

The analysis demonstrates an abundance of untapped bioenergy in Southeast Asia, with at least 7.1 EJ of selected feedstock per year by 2050 in the five countries studied. It also identifies immediate opportunities for adopting bioenergy in Southeast Asia's energy markets, demonstrating the potential for the selected sustainable biomass to economically meet 2.8 EJ of the energy demand.

The economic costs and benefits of an energy market transition to sustainable biomass were appraised for the 13 potential pathways, revealing potential benefits of USD 144 billion of net present value of socio-economic benefits in 2050, creating over 452 000 new resilient jobs and saving around 442 $MtCO_2eq$ of GHG emissions per year.

Bioenergy can be utilised in several ways in the energy transition scenario.

Table 15 Summary of 13 potential pathways for Indonesia, Malaysia, Myanmar, Thailand and Viet Nam

TYPE OF FEEDSTOCK		TYPE OF PROCESS	TOTAL APPLICABLE POTENTIAL BIOENERGY EQUILIBRIUM IN 2050 (PJ)
	Agricultural residues from major crops, rubber and acacia	Direct combustion for industrial heat generation	696
		Direct combustion for combined heat and power generation	1 065
	Palm oil mill effluent and cassava pulp	Anaerobic digestion to generate biogas for both heat boilers and combined heat and power (CHP) plants	32
	Agricultural residues from major crops, rubber and teak	Direct combustion for industrial heat generation	8
		Direct combustion for combined heat and power generation	449
	Cassava pulp	Anaerobic digestion to generate biogas for both heat boilers and CHP plants	6
	Sugarcane molasses and cassava starch and chips to bioethanol	Fermentation and blend to produce bioethanol	98
	Agricultural residues from major crops, rubber and eucalyptus	Direct combustion for industrial heat generation	188
		Direct combustion for combined heat and power generation	145
	Cassava pulp	Anaerobic digestion to generate biogas for both heat boilers and CHP plants	4
	Sugarcane molasses to bioethanol	Fermentation and blend to produce bioethanol	4
	Acacia and rubber	Direct combustion in CHP for heat and power generation	106
	Woody residues	Direct combustion for industrial heat generation	17

Source: (IRENA, 2022e).

Sustainable bioenergy pathways must link demand in energy markets with secure bioenergy supplies. There are four key market "push and pull" factors that decision makers must consider in this regard: availability, sustainability, accessibility and market.

The high productivity of Southeast Asia's agriculture sector generates considerable volumes of under-utilised residues. Table 15 provides estimated energy values for underutilised feedstocks in the study's selected countries of Indonesia, Malaysia, Myanmar, Thailand and Viet Nam. These ASEAN member countries were chosen as target countries due to their large agricultural industries and subsequent potential in terms of untapped biomass feedstock.

Private financiers of renewable energy projects often cite security of bioenergy supply as one of the biggest obstacles to investing in bioenergy projects. Various factors determine the total available volumes of bioenergy, including biomass scalability and seasonality. One way that governments can mitigate the seasonality of biomass outputs is by forming a central collection agency to map the collection of residuals from various agricultural practices and crops throughout the year and distribute them systematically according to demand.

Sustainable bioenergy

The use of bioenergy can bring GHG reductions along with other contributions to sustainable development objectives in the ASEAN region. However, the production and use of bioenergy must be managed with care, mainly because sustainability concerns about production and consumption are relevant topics in the bioenergy industry in the region.

The potential impacts of non-sustainable biomass in the ASEAN region include competition for land, emissions caused by land-use change, deforestation, biodiversity loss, competition with food production, lack of management of biowaste and air pollution. These impacts pose risks to investors and also discourage policy makers from making bioenergy a major pillar of their strategies for reaching 1.5°C targets. This is also interlinked with the assessment and estimates of biomass potentials and availability.

Appropriate solutions and measures to ensure sustainability of bioenergy in the region are available, but in some cases are not fully implemented. In several cases, the solutions are highly context-specific and correspond to locations along the region, including social conditions and local political and regulatory capacities. In the following section, some general considerations are outlined to promote further sustainable bioenergy production in the ASEAN region.

Sustainability-based target setting and long-term planning

Bioenergy target setting should emerge from a sound understanding of sustainability where the targets apply. This includes spatial and temporal characteristics of different options – the types and availability of feedstocks, supply chains and end uses – in all environmental, social and economic aspects. A long-term strategy for bioenergy development in the region should build upon a sound understanding of sustainability. Such a strategy can provide a consistent policy signal to guide policy makers and build confidence among investors and project developers.

Cross-sectoral co-ordination for bioenergy

Bioenergy policy making requires strong cross-sectoral and cross-country collaboration among relevant institutions, including environment, agriculture, forestry, industry and energy departments at various governance levels (from international to local) to align broader plans with those of the energy sector. Complex institutional structures and misalignment in dealing with sustainability issues across multiple policy domains have been a key barrier in many countries. A concept of "bio-economy" can be introduced to cover all bio-based sectors upstream and downstream and from land use to end use (Fritsche *et al.*, 2020). It intends to link agriculture, forestry, energy and industrial development, as they have similar supply chains, technologies and, most important, sustainability.

Sustainability regulations and certificates

National and regional regulatory frameworks help to ensure the sustainability of bioenergy. They can set conditions and requirements as part of the permitting process for projects and monitor the post-project performance to ensure compliance. Regulatory frameworks should define the criteria for sustainability requirements based on local context, with certification bodies conducting sustainability audits on the bioenergy products or projects.

The regulatory framework can be integrated with financial incentives. For example, in the Netherlands, the Ministry of Economic Affairs and Climate Policies provides subsidies to biomass projects through the Stimulation of Sustainable Energy Production (SDE++) scheme. Projects receiving subsidies must meet comprehensive sustainability criteria, including requirements related to GHG emission saving, soil management, land-use change, sustainable forest management and others (NEA, 2022).

Some widely known international platforms to promote sustainable bioenergy include Food and Agriculture Organization and the Global Bioenergy Partnership (GBEP). The 24 sustainability indicators agreed by GBEP have been applied or tested by more than a dozen countries, including bioenergy production powerhouses like Argentina, Brazil, Indonesia, Viet Nam and others, to help national and local stakeholders monitor and develop sustainable bioenergy policies (GBEP, 2020)

Voluntary certification schemes can demonstrate compliance with sustainability regulations. For example, numerous schemes are employed or tailored for the Renewable Energy Directive of the European Union (RED) sustainability criteria so companies and producers can prove that their bioenergy meets these criteria with evidence, especially in tracing the feedstock origins. An independent voluntary certification body usually establishes a set of practicable indicators on sustainability and then audits the supply chain. Bioenergy certification schemes are often aligned with systems pioneered by other bio-based industries. Most are built upon existing schemes in agriculture and forestry.

There are many certification bodies and schemes. Some schemes are established as roundtables or multistakeholder initiatives, including the Roundtable on Sustainable Biofuels, Roundtable on Sustainable Palm Oil and Roundtable on Sustainable Soy. Some schemes are supported by industries, such as Bonsucro, an international scheme established for the sugarcane industry, or government, such as International Sustainability and Carbon Certification, which is supported indirectly by the German government, and the RenovaBio Programme developed by the Brazilian government. Some schemes are specific to forestry management, including the Programme for the Endorsement of Forest Certification, the Sustainable Forest Initiative, the Forest Stewardship Council and the Sustainable Biomass Program (IRENA, 2022c).

For the ASEAN region, a set of environmental and social criteria that companies must comply with to produce Certified Sustainable Palm Oil should continue to be enforced. When these criteria are properly applied, they can help to minimise the negative impact of palm oil cultivation on the environment and communities in palm oil-producing regions.

The growth in the international bioenergy trade has triggered the development of governance of bioenergy through instruments like certification, for example, the Green Gold Label, Roundtable of Sustainable Palm Oil, and Roundtable on Sustainable Biomaterials and the Sustainable Biomass Programme. These form polycentric, transnational regimes that involve a range of actors. These transnational sustainability regimes may increase the costs of bioenergy, but they also represent an important way to ensure sustainability, which is key to accomplish climate targets in the region along with sustainable development.

Fomenting biomass markets

In the ASEAN region it is important to identify accessible biomass feedstocks in the short term to demonstrate the viability of this source for energy markets, before even moving on to address political, legal, social and environmental concerns. Infrastructure construction to increase biomass accessibility in the medium and long terms will directly impact the scalability of feedstock and deliver socio-economic benefits.

Volumes of accessible bioenergy resources will grow over time with increased market awareness, improved logistics chains, technology enhancements and mounting private financing appetite. Private financiers of renewable energy projects typically have a negative view of bioenergy supply, but this is due to outdated perceptions on issues that now have a range of commercially proven technical solutions. There is, therefore, an urgent need to build awareness among decision makers of commercially proven technical solutions.

Based on a number of lessons from successful projects in established markets, decision makers in Southeast Asia should seek to:

- Explore how agricultural and industrial sectors can collaborate to establish supply and logistics networks for creating secure and sustainable biomass supplies.
- Determine which fuel enrichment technologies would be appropriate for the sustainable bioenergy resources available and would meet the specifications of local energy markets.
- Identify knowledge and technology gaps that require further research and development (R&D) and pilot projects to test the "first-of-a-kind" risks of deploying such technologies in Southeast Asia's markets.
- Form ministerial-level collaboration to unlock further opportunities and ensure the smooth execution of bioenergy strategies in each country.

Decision makers can also accelerate the adoption of sustainable biomass by addressing negative sentiment among private financiers. This can be achieved by demonstrating the commercial successes achieved in markets that have advanced the deployment of sustainable bioenergy. At the same time, decision makers can facilitate transitions in the energy markets by regulating the requirement for industrial, commercial and domestic users to progressively reduce fossil fuel reliance; seek greater efficiency in facilities, plants and equipment; and progressively increase the proportion of sustainable bioenergy. To foment this, the following can be promoted:

- Influence energy market dynamics by increasing taxation on fossil fuels while reducing the tax burdens on sustainable biomass.
- Give tax incentives for R&D and investments in new facilities, plants and equipment that are fuelled by sustainable bioenergy.
- Provide feed-in-tariffs to incentivise private sector participation in the market (which is proven in Southeast Asia and elsewhere). However, careful design needs to be considered to ensure the right level of incentive while not adding too much burden to the energy off-takers or government fiscal support.

HYDROGEN

Hydrogen uses in ASEAN

In the PES, zero-carbon hydrogen demand sees limited use within the region. In the 1.5-S case, zero-carbon hydrogen demand is expected to grow significantly to 1.5 EJ or 11 Mt by 2050. Zero-carbon hydrogen is either considered green, produced from electrolysis using carbon-free electricity, or blue, produced generally from natural gas utilising CCS to capture the significant CO_2 emissions produced during production. IRENA's study on global hydrogen trade to meet the 1.5°c climate goal (IRENA, 2022g) discusses in more detail the economics and green hydrogen production in the future.

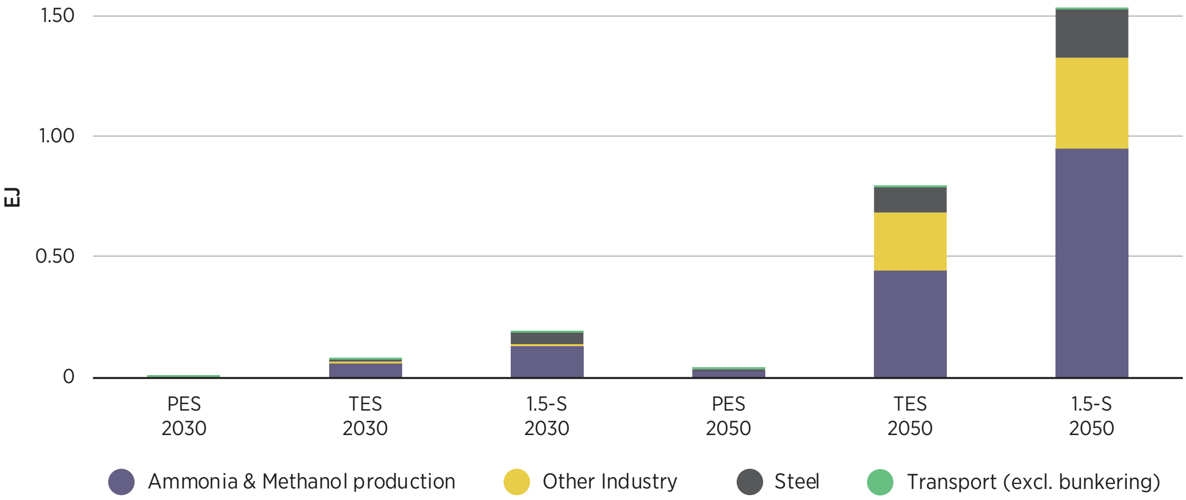
Hydrogen can be used directly, or it can be used as a feedstock used to produce derivates. Overall, most of the use of the fuel is expected to be in the industry sector – for example, in the production of iron and steel – and also as feedstock for the production of ammonia and methanol, which are key fuels required to decarbonise international shipping. The majority of the demand is expected to come from Indonesia, Malaysia, Thailand and Viet Nam, where there will be a stronger base for hydrogen production.

In the 1.5-S case, the expectation is that two-thirds of the hydrogen demand will be green hydrogen sourced from renewable electricity from 2030 onwards. The additional electricity demand in the sector is expected to be 40 TWh in 2030 and 340 TWh in 2050.

However, the ASEAN region as a whole has further technical potential to become a hydrogen hub. It is estimated that between 6 EJ and 60 EJ of low-cost green hydrogen (less than USD 2/kilogramme [kg]), can be produced in the region (IRENA, 2022g).

Green hydrogen will play a role mainly in the industrial sector and to some extent in long-haul transport.

Figure 51 Hydrogen consumption by subsector and scenario



ASEAN hydrogen strategies

Worldwide, the advent of green hydrogen as a feasible, cost-effective solution to decarbonise the hard-to-abate and hard-to-electrify sectors has spurred political and industrial activity to transform it from a niche to a mainstream option.

In particular, in Europe, East Asia, Latin America and Oceania, policy makers and industrial stakeholders have kickstarted several national and international initiatives (IRENA, 2020). While policies to support local hydrogen production and consumption are still not largely adopted, countries are already forging bilateral deals that could pave the way for new hydrogen trade relations (IRENA, 2022d, 2022h).

In this regard, the ASEAN region is not progressing at the same pace. Countries in the region do not have proper strategies, and only a few mention hydrogen in their policies and targets (see Table 16). Most of the projects planned in the region are export-oriented, missing the opportunity to use hydrogen production for the decarbonisation of local consumption first. This export-oriented focus could be affected by the import-oriented strategies of Japan and the Republic of Korea.

The Japanese and Korean strategies are characterised by a technology-neutral approach to hydrogen production that does not account for the carbon emission factors of production and transport of hydrogen. Instead, the strategies stress the importance of hydrogen use in fuel cells in stationary and mobile applications and ammonia-based power production. This is in contrast with the strategies in Europe focusing on carbon emission reduction and hard-to-abate sectors.

Japan's government, in particular, has been working on international hydrogen trading since the 1990s, when it allocated USD 41.5 million (JPY 4.5 billion [Japanese yen]) to this goal. This country had the first-in-their-kind blue and grey hydrogen (hydrogen production that is not carbon neutral) and products shipments from pilot or demonstration projects in Australia, Brunei and Saudi Arabia (IRENA, 2021b).

However, without a strong focus on green hydrogen from the onset, the ASEAN region risks being cut out from the export market. Australia and the Gulf Cooperation Council (GCC) region hold the promise to become major exporters of green hydrogen, with prices around USD 1.5/kg, below current grey hydrogen prices (IRENA, 2022h). Moreover, current import-oriented countries in East Asia have the opportunity to update their rules, introducing carbon emission limits to hydrogen production similar to those of European countries, making the business case for blue hydrogen less strong.

To improve the business case for green hydrogen in the region, governments would have to assess the national hydrogen uses and include them in their decarbonisation efforts. Developing some local production would help drive acceptance of this new energy carrier. Import-oriented countries in the region should consider carbon footprints in their policy making to avoid giving a lifeline to unabated fossil-based solutions (IRENA & WEF, 2021).

AMS should initiate hydrogen development programmes sooner rather than later.

Table 16 Hydrogen projects in ASEAN

COUNTRY	MAIN ACTIVITIES IN THE COUNTRY
Brunei Darussalam	• Japan's Advanced Hydrogen Energy Chain Association for Technology Development has launched a demonstration project for a supply chain of by-product hydrogen shipped using liquid organic hydrogen carriers between Brunei and Japan. The first shipment was completed in April 2020.
Cambodia	• Cambodia's Long-Term Strategy for Carbon Neutrality announced some hydrogen-related measures, including studies and allocation of budget for R&D.
Indonesia	• Pertamina is looking to invest USD 11 billion to help accelerate its clean energy transition, including hydrogen developments. • Mitsubishi is planning a brownfield blue ammonia project, converting an existing 338 tonne per day hydrogen production plant to serve an ammonia plant in central Sulawesi.
Malaysia	• Sarawak Energy has developed a pilot hydrogen electrolysis plant and refuelling station and hydrogen-fuelled buses. Sarawak also plans a fuel cell light rail transit system by 2024. • H2biscus is a project developed by Korean and Malaysian companies for the production of green and blue products – hydrogen, ammonia and methanol – for export to the Korean market. • Petronas and Eneos of Japan are developing feasibility studies for the production of blue and green hydrogen production and the transport of 50 kilotonnes (kt)/year of hydrogen in toluene.
Singapore	• Multiple memoranda of understanding are being signed by Singapore with governments worldwide (Australia, Chile, and New Zealand) to collaborate on hydrogen technologies.
Thailand	• Under the Alternative Energy Development Plan, hydrogen is included as part of the "Alternative Fuels" category with a set target goal of 10 kt of oil equivalent (3.5 kt of hydrogen) consumed by 2036. • The Energy Regulatory Commission has included hydrogen in the definition of "renewable energy" to be purchased by the Provincial or Metropolitan Electricity Authorities and the Electricity Generating Authority of Thailand.
Viet Nam	• Germany's TGS Green Hydrogen is planning a green hydrogen production plant (24 kt/year hydrogen, 150 kt/year ammonia) in the Mekong Delta province with a total investment of USD 847.8 million. • Hydrogen is mentioned in Viet Nam's Power Development Plan 8 as a technology to be developed.

Sources: See references in text.

Hydrogen supply in a global context

The ASEAN region could satisfy the burgeoning Asian hydrogen market. In 2020, the hydrogen demand in Asia was over 40% of the global hydrogen demand. By 2050, the net demand could increase nearly six times to reach almost 190 MtH_2/yr. China, India and Japan are expected to be the largest markets in this region. ASEAN countries and Australia are well placed to satisfy this large market.

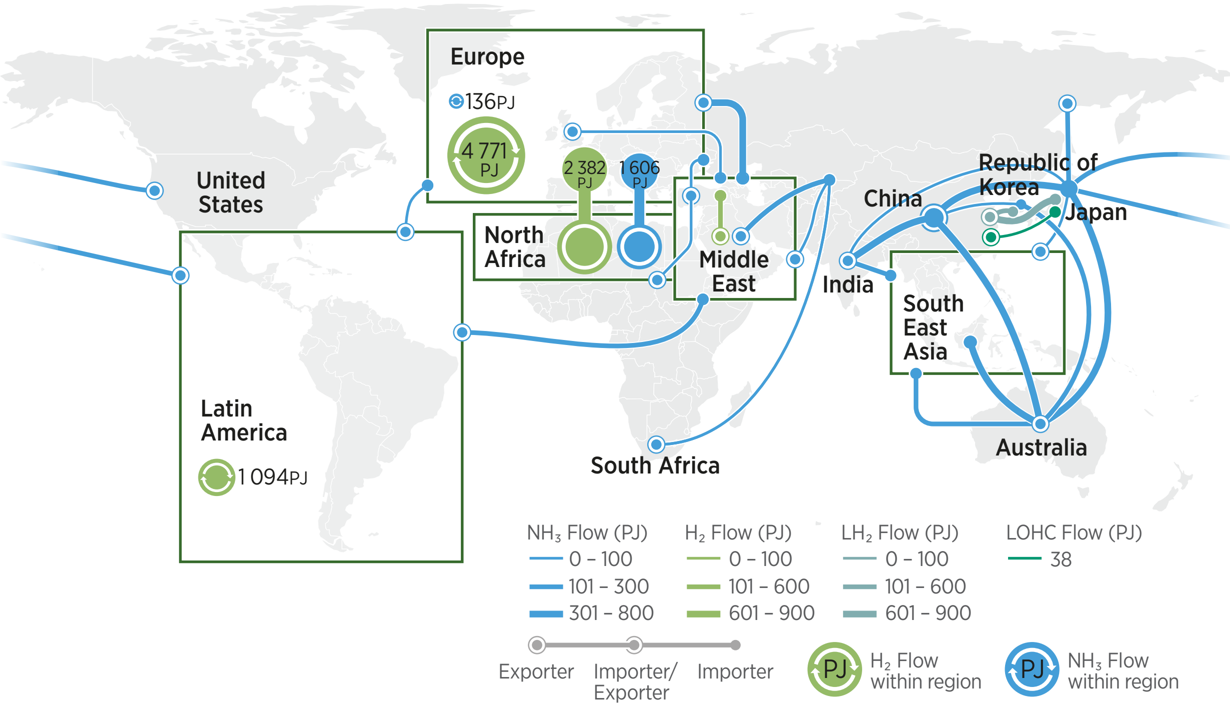
IRENA's recent report *Global Hydrogen Trade to Meet the 1.5°C Climate Goal – part 1* outlines a perspective of the hydrogen trade by mid-century based on the scenarios from IRENA's WETO report (IRENA, 2022b). Given the wide global scope of the report, some restrictions in granularity had to be made; therefore, G20 countries are represented individually while non-G20 countries are aggregated under their respective macro-regions. That means Indonesia's potential is represented separately from all other ASEAN members. Although that approach produces limitations, it still brings valuable insights into the region's role based on assumptions.

However, a forthcoming report focusing on the ASEAN region will go into more detail on hydrogen supply in the region.

IRENA's WETO shows how clean hydrogen will need to be scaled up significantly, and sourcing green hydrogen, which is expected to make up two-thirds of supply, will depend on matching sources of low-cost production with demand centres. The analysis shows that hydrogen will likely be exported through pipelines, as liquified hydrogen, or embedded in ammonia. Pipelines are cost-effective for regional trade, such as eventually across ASEAN or between ASEAN and southern Chinese provinces. Ammonia is the most attractive carrier to cover long-distance transport given the existing infrastructure and an expanding market as fuel for shipping and power generation. That would avoid having to crack ammonia back to hydrogen, which is costly and overall challenging (equals 13-34% of the energy contained in the hydrogen) (IRENA, 2022i). Nevertheless, the study put all options side by side, considering production, conversion plants, transports, reconversion (where needed) and final carrier use. For instance, some of the ammonia to be transacted may be consumed as ammonia itself, avoiding the ammonia cracking stage, which is still costly and overall challenging.

Hydrogen will be increasingly traded globally.

Figure 52 Global hydrogen trade flows in 2050 under IRENA's Global Hydrogen Trade to Meet the 1.5°C Climate Goal report



Source: IRENA (2022g).

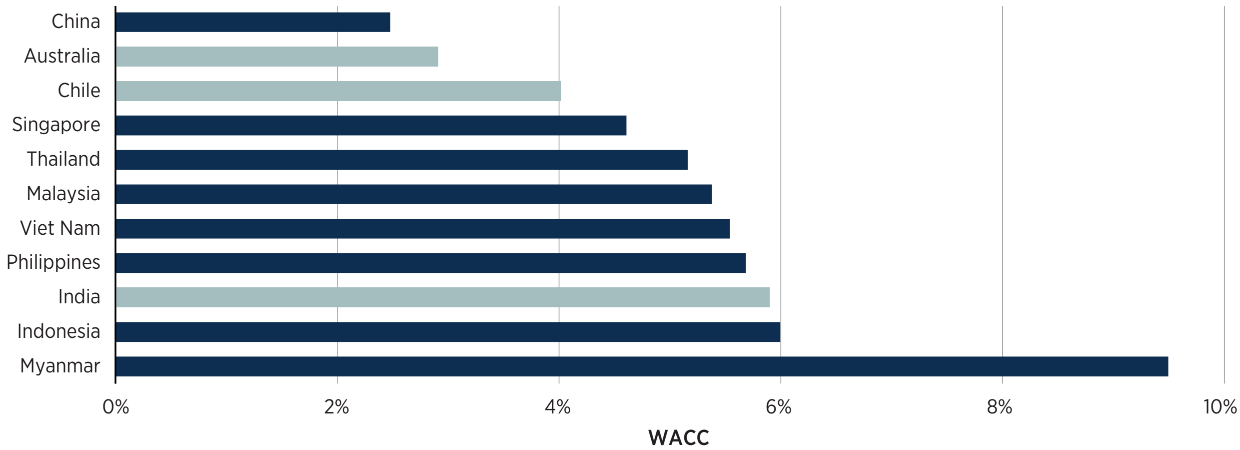
Looking at the Asian region supply more broadly, Australia has vast land of 7 million square kilometres for renewable production, which, combined with a low cost of capital, enables the production of green hydrogen competitive with fossil fuels-based. So, the Australian case relies on the country's capability of producing renewable electricity at very low costs, which makes the bulk of hydrogen total costs. Compared to ASEAN, that might be enough to compensate for the extra distance from demand centres like China and Japan.

A factor favouring ASEAN supply could be that hydrogen pipelines could connect neighbouring countries to China, the expected largest hydrogen demand at the global level. That pathway only requires compression and would prevent the energy losses associated with the conversion/reconversion of hydrogen carriers, which can sum up to 30-40% (IRENA 2022i). However, the uncertainty remains as to which China will produce hydrogen domestically, given its vast renewable potential. Even though resources are far from the demand centres, it could develop the infrastructure to reduce reliance on imports.

The cost of capital for solar and wind projects in Australia ranges from around 2.9-3.7%, which is significantly below that of ASEAN (Figure 53). In combination with relatively low investment costs, Australia has the potential to produce about 378 EJ/yr of green hydrogen below USD 1.5/kg. For illustration, that is higher than Japan and China's primary energy supplies (PES) in 2020 at 16 EJ and 126 EJ, respectively (blue/red vertical lines in the figure). The average difference in the production cost between Australia and ASEAN is around USD 0.5/kg of hydrogen (Figure 54), which can be narrowed if capital costs, and investment costs of renewables are to be reduced.

The cost of capital related to solar and wind new projects is significantly higher in ASEAN countries than in other potential world hydrogen exporters like Australia and Chile.

Figure 53 Average cost of capital (WACC) of solar and wind projects in ASEAN and selected countries

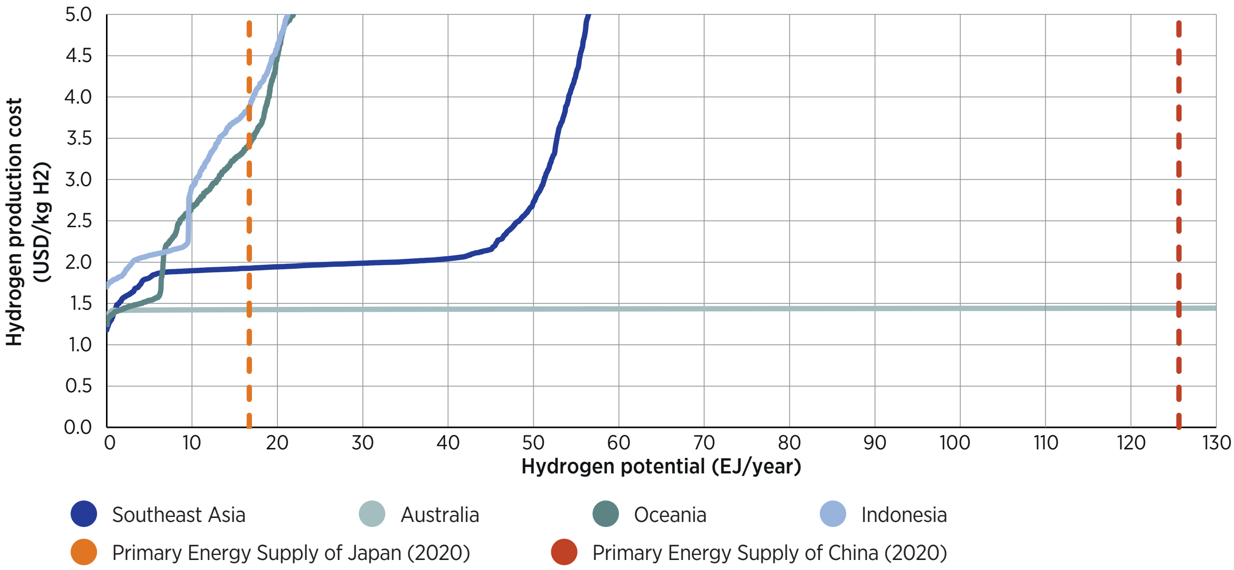


Source: (IRENA, 2022f).

Changes in transport costs naturally impact costs at the destination – which could be advantageous to increasing production within ASEAN – and exports, given the proximity to those main potential importers in Asia. For instance, increases in shipping costs would see a reduction in the largest exporters, Australia, Chile and North Africa, by 30%, 15% and almost 50%, respectively (IRENA, 2022i). This means that Australia exports less to China and Southeast Asia. As a result, the major importers produce more hydrogen domestically.

Production costs rise considerably in some countries as volume increases.

Figure 54 Hydrogen cost curve potential based on 2030 values



ENERGY INTENSITY AND CONSUMPTION

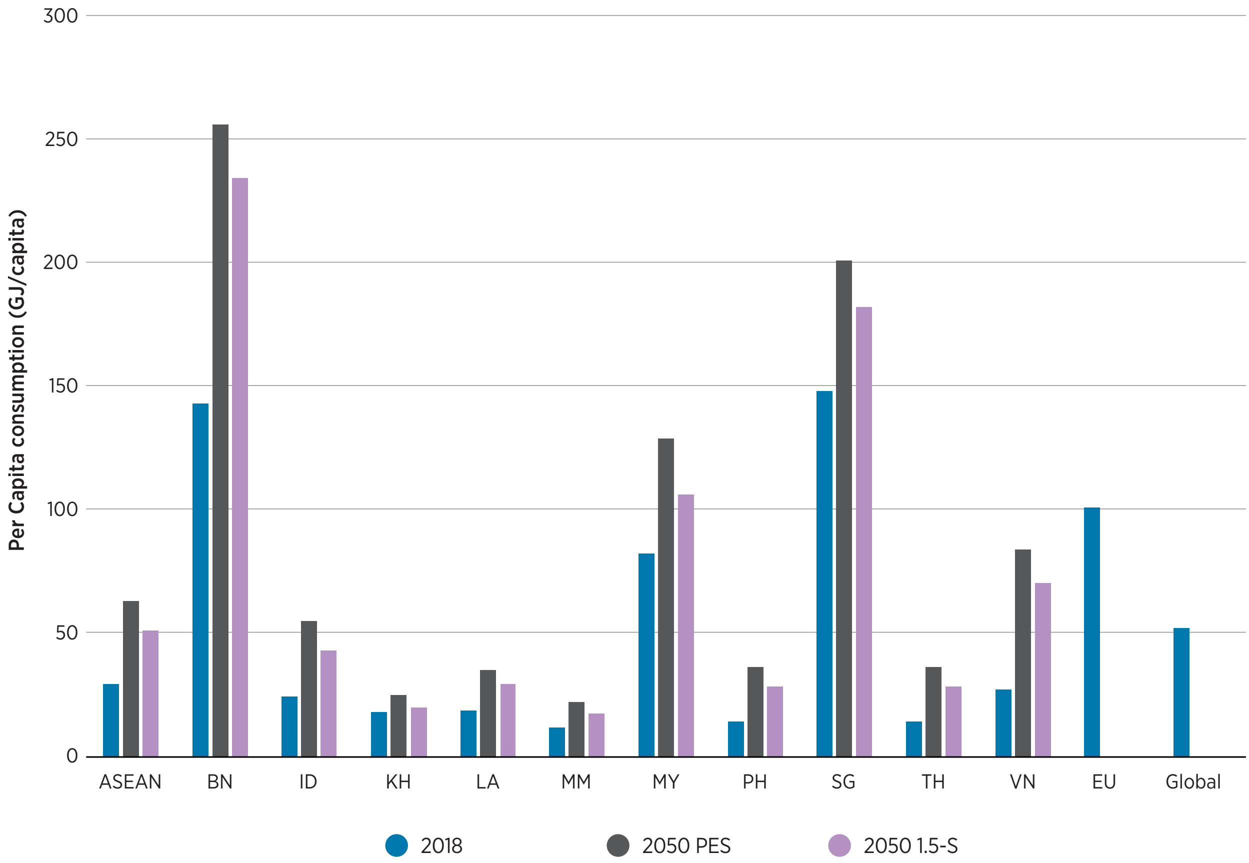
According to the latest *Tracking SDG7: The energy progress report*, Southeast Asia was one of two regions that surpassed Sustainable Development Goal (SDG) 7.3 on energy intensity improvement. Between 2010 and 2019, average annual energy intensity improved by 2.7% as a result of substantial improvement in energy efficiency and rapid economic growth (IEA, IRENA, UNSD, World Bank, WHO, 2022).

In the TES and 1.5-S in 2030, energy intensity measured by the percentage drop in the ratio of total energy supply per unit of GDP improves steadily. This can be attributed to a rise in energy efficiency, economic expansion and a decline in the final energy consumption. Energy intensity improved from 7.9 megajoules (MJ) per USD (2015) constant in 2018 to 5.1 MJ/2015 USD in the PES 2050. This value further decreased by 26% to 3.9 MJ/2015 USD in the 1.5-S 2050 within the ASEAN region.

Across the region, primary energy intensity varies among the countries. Indonesia had an average energy intensity of 7.9 MJ/2015 USD in 2018 that will reduce to 4.3 MJ/2015 USD in the 1.5-S 2050 owing to concentrated efforts to increase energy efficiency in the industrial sector and a reduction in final energy consumption across all sectors. The variations in the energy intensity within the region are also affected by the GDP structure and societal quality of life.

Per capita consumption varies greatly across the ASEAN region.

Figure 55 Final energy consumption per capita in ASEAN



Source: IRENA analysis, (UNSTAT, 2020).

Southeast Asia's final per capita energy consumption decreases slightly from 63 GJ in the PES 2050 to roughly 51 GJ in the 1.5-S 2050. The final energy consumption in the region in the 1.5-S 2050 decreased as a result of increased electrification and renewable energy shares.

Globally, per capita consumption was around 80 GJ in 2018, a level similar to South Africa. However, this global average increased significantly due to industrialised economies and China. Comparing base year per capita consumption in the ASEAN region with developing countries, it is clear that South Africa has almost triple the value of ASEAN's per capita consumption, while India and Colombia have values in close range with the region. This variation reflects the effect that energy access, GDP structure and an increase in energy services and societal quality of life have on both per capita consumption and energy intensity rather than energy efficiency.

CO_2 REMOVAL

In ASEAN, some energy-related CO_2 emissions remain in 2050 from fossil fuel use and industrial processes, as is the case in IRENA's global scenario in WETO. In the quest to reach net-zero emissions, there will thus be a need for both CCS technologies and CO_2 removal measures and technologies that, combined with long-term storage, can remove CO_2 from the atmosphere, resulting in negative emissions.

As of early 2021, 24 commercial fossil fuel-based CCS facilities were in operation globally with an installed capacity to capture about 0.04 Gt/year of energy- and process-related CO_2 emissions. Three operational commercial facilities use bioenergy with carbon capture and storage (BECCS) and seven commercial plants are in development. The current capture capacity of operational commercial BECCS plants is very small at 1.13 Mt/year (IRENA, 2022b).

In WETO, with the 1.5-S, the use of CCS in industry and CCS for fossil fuel-based hydrogen production would expand from 0.04 Gt/year of captured CO_2 today to 3.4 Gt/year of CO_2 in 2050. There are nearly 30 CCS projects under development, adding 0.06 Gt/year of CO_2 capture potential; however, current levels fall short of what is needed in a 1.5°C-consistent pathway – *i.e.* between 1 Gt/year and 2 Gt/year of CO_2 captured by 2030 (IRENA, 2022b).

CO_2 removal measures and technologies include nature-based measures such as reforestation as well as BECCS, direct carbon capture and storage (DACCS), and some other approaches that are currently experimental. In IRENA's 1.5°C Scenario, the potential for CO_2 capture per year from processes that use biomass – and to which CCS could be applied in principle – is about 10 Gt per annum by 2050. However, the scenario assumes around 5 Gt per annum will be required globally in the 1.5-S. The scenario describes how this could include a combination of removal measures, from BECCS to DACCS, reforestation and other measures. This reaches across multiple sectors such as power, heat, chemicals, biorefineries, cement, pulp and paper, and sugar production and possibly also iron and steel production (IRENA, 2022b). In ASEAN, residual energy-related CO_2 emissions will amount to around 0.7 Gt of energy-related CO_2. Therefore, of the 5 Gt ASEAN will require around 14% of that total to achieve net-zero emissions.

CRITICAL MATERIALS FOR THE ENERGY TRANSITION AND ASEAN

A material is classified as critical when it has economic importance associated with a product, when the risk associated with the supply of the material is at stake, or the availability of viable substitutes of the material is scarce. Critical materials in the energy transition play a vital role, especially when it comes to manufacturing key technologies such as solar panels, wind turbines and batteries, which require nickel, copper, lithium, and rare earth elements (REEs).[13] The importance of a critical material varies according to its usages and properties.

[13] *The 17 rare earth elements are: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), scandium (Sc) and yttrium (Y). From these REEs the most relevant are: neodymium, praseodymium, dysprosium and terbium, which are key to the production of the permanent magnets used in EVs and wind turbines. Neodymium is the most important in volume terms. Yttrium and scandium are used for certain types of hydrogen electrolysers, while europium, terbium and yttrium are used in energy-efficient fluorescent lighting. Conventional energy also relies on REEs, for example to produce car exhaust catalysts. However, the mix of energy-relevant REEs that are needed going forward differs from that of the past.*

Some examples of their uses are:

- Copper for electric wiring plays a key role throughout power production, transportation and use. Electricity demand will increase substantially, and this will raise copper demand. Although the copper resource is adequate, the quality of copper ore resources is decreasing.
- Nickel demand may increase substantially due to its widespread use in battery cathodes. Lithium-ion batteries typically compose between 30-80% nickel. Already, producers are considering alternative battery chemistries (notably lithium-iron-phosphate cathodes), but the product performance is inferior. However, such alternatives can reduce the growth in nickel demand substantially.
- Lithium is a critical component of lightweight batteries for vehicles. As battery use dominates total lithium use, the foreseen rapid growth of battery manufacturing will require a rapid upscaling of lithium production. Electric cars accounted for around 4% of global car sales in 2020; this share may grow fivefold to tenfold in this decade, and lithium production needs to grow accordingly.
- Neodymium and dysprosium play a key role in permanent magnets, which are widely used in high performance electric motors (including EVs) and in generators (wind turbines). The key challenge is that mining and processing of these materials is dominated by one country, whereas the supply of other critical materials is more diversified.
- Cobalt supply is critical for batteries. Demand may double between 2020 and 2030, and vehicle batteries may account for 60% of total cobalt demand in 2030. However, battery design innovations can reduce this dependency substantially.
- Today, around a tenth of all silver is used for solar PV modules. This share may rise further as demand for solar PV grows. To some extent, this can be balanced by more material-efficient cell design.
- Demand for other minerals and metals will grow but seems less critical. Such minerals and metals include aluminium, chromium, graphite, indium, iron, lead, manganese, molybdenum, titanium, vanadium and zinc. For some of these, the resource is abundant; for others, alternatives exist, such as substitution of materials and changes in product design that provide similar technical performance.

When it comes to critical materials, especially nickel and RREs, selected countries in the ASEAN region play a key role: Indonesia and Philippines for nickel, and Viet Nam, Malaysia and Myanmar for selected RREs are a few examples.

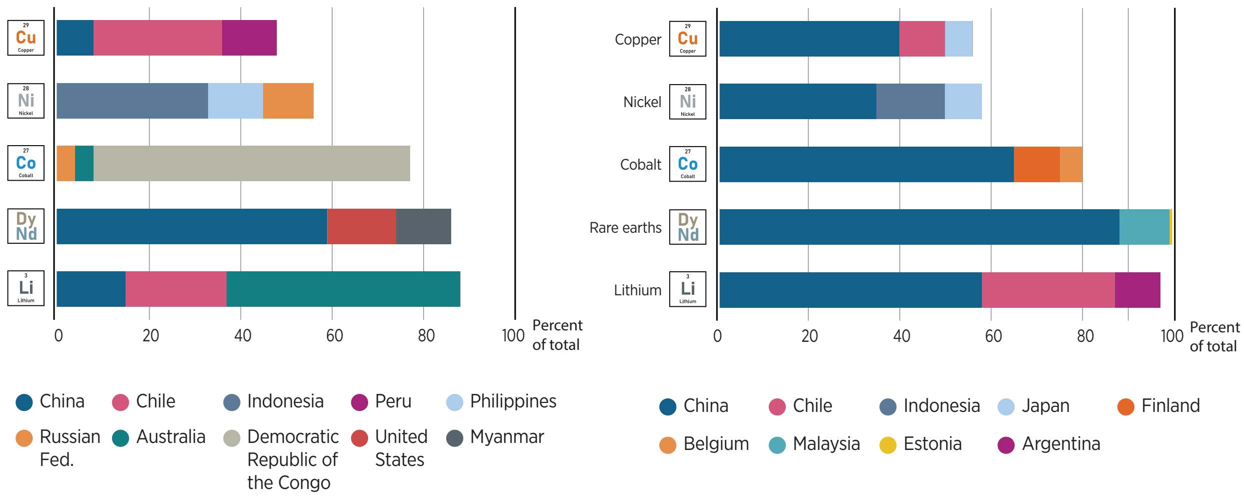
For instance, globally, the top three countries producing copper are Indonesia (33%), the Philippines (12%) and Russian Federation (11%). The top three countries processing nickel are China (35%), Indonesia (15%) and Japan (8%). When it comes to neodymium, the most important RRE in volume terms, most production is centred in China, accounting for 59% of global production, followed by the United States (14.5%) and Myanmar (11.5%). China dominates in processing neodymium, accounting for 88% of the market, followed by Malaysia at 11% and Estonia at 1%. Global reserves of neodymium, a critical REE used in EVs and wind energy technologies, are estimated at 8 Mt. The resource is found in adequate amounts, but short- and medium-term growth in supply may pose a challenge. Most production and processing of neodymium comes from China.

Considering the relevance of the ASEAN region in the global market of critical materials, it seems relevant to highlight some consideration for the case of nickel and RREs.

Figure 56 summarises the top producing and processing countries for select critical materials needed for the energy transition. Many countries in ASEAN are key players, including Indonesia, Malaysia, the Philippines and Myanmar.

Indonesia, Myanmar and the Philippines account for about 45% of global nickel production.

Figure 56 Top countries processing (left) and producing (right) copper, nickel, cobalt, rare earth elements and lithium



Source: (IRENA, 2022b).

Nickel

Global nickel consumption amounted to about 2.4 Mt in 2019. The leading consumers were China and Indonesia. Nickel demand is projected to grow substantially in the next few decades because of its widespread use in battery cathodes. For instance, lithium-ion batteries are typically composed of between 30-80% nickel. Alternatives to nickel, including lithium-iron-phosphate cathodes, could reduce demand for nickel. However, the technical performance of the available alternative battery chemistries is inferior.

There are two main types of nickel deposits: sulphide ore bodies and laterite soils. The importance of hydrometallurgical processing of laterite soils is projected to increase. Nickel reserves are estimated at 89 Mt; resources in classical subsoil ore deposits are estimated at 300 Mt. There is an additional estimated 290 Mt in subsea nickel deposits. Nickel production from underground and open-pit mines was 2.54 Mt in 2019. Nickel demand is projected to exceed supply by 2025. Several factors will affect the supply and demand balance. They include the extent and pace at which EVs are adopted, the battery technology that becomes dominant in the industry, and the way suppliers respond to these changes.

Approximately one-third of global nickel supply is derived from recycled materials (Nickel Institute, 2022). More than 2 000 nickel production projects are currently being developed. In 2019, production took place in 27 countries across all continents. The largest nickel-producing countries are in Southeast Asia and Oceania, which together accounted for 62% of production in 2019. Indonesia has the world's largest share of nickel production, and China does most of the world's nickel processing (DERA, 2022). Indonesia is making large investments in nickel-processing facilities, however, which will shift some processing away from China. These investments stem from Indonesia's recent policy mandating the domestic processing of nickel before export. Nickel will be essential for EVs in the coming years.

Most of the global nickel supply will be sourced from Indonesia, where nickel mining and refining have worse effects on the environment than they do in other countries, mainly because electricity is sourced from coal-powered plants. Decarbonising the electricity supply is challenging, because resources are located in remote areas (Huber, 2021).

REEs

REE deposits are widely distributed. It is economically viable to expand mining in many places, but processing capacity is less readily expandable. Increased mining needs to be also combined with circular economy concepts such as recycling and reuse, as well as innovations to mitigate demand growth.

As mentioned before, some countries in the ASEAN region are already producing or processing neodymium. However, there are also comparatively high concentrations of dysprosium, which occur in ionic clay deposits in South China and Myanmar. Other countries in the region such as Viet Nam hold similar types of resources that are yet to be exploited.

Ion absorption clays in South China and Myanmar accounted for 17% of the world's production in 2020 (around 35 kt). These clays are important because they are enriched with heavy REEs including dysprosium. In Myanmar, production is concentrated in the Kachin and Shan states, and production reports are unreliable. Ion absorption clays are processed through leaching with ammonium sulphate.

INDONESIA'S NICKEL PRODUCTION AND AMBITIONS TO BE SOUTHEAST ASIA'S EV BATTERY HUB

Indonesia is set to produce over 1.2 Mt of nickel pig iron (NPI) this year, and by 2025 Indonesia will be producing well over 1.5 Mt/year. The world will not run out of nickel anytime soon, as identified land-based resources with 0.5% nickel or greater contain at least 300 Mt of nickel, with about 60% in laterites and 40% in sulphide deposits.

To extract nickel, laterite ores require extensive and complex treatment, which has been historically more expensive than sulphide ores. So far markets for NPI and battery grade nickel have functioned independently with battery grade nickel being much more expensive. Tsingshan has developed a revolutionary new technology to process laterite nickel with a substantial reduction of processing cost and pioneered the production of NPI from nickel laterite ores (Metal.digital, 2021).

The world's largest nickel producer is Indonesia, and it has production based one the laterite resource type. The laterite resource vastly exceeds the sulphide resource, a reason why Indonesia is currently expanding its production significantly, with USD 42 billion of planned investments by Fortescue and Tsingshan. Other parties are also investing in the Indonesia nickel mining and processing sector.

Indonesia wants to develop an integrated EV supply chain and become an EV battery producer and exporter. Lithium-ion batteries typically comprise between 30-80% nickel. Southeast Asia's largest economy has the ambitious goal to make batteries with a capacity of 140 GWh in 2030, which is nearly as much as global EV battery production in 2020 (CSIS, 2022)

The country's ambitions are motivated from upstream and downstream the supply chain: the world's biggest nickel producer wants to capitalise on its mineral resources but also aims to reduce emissions by creating a domestic EV market.

Not all nickel mined is used for EV batteries or traded on the London Metal Exchange (LME). Mined nickel can be split into two broad categories: low and high-grade primary nickel. High-grade nickel (Class I) accounts for 55% of all nickel mined, while low-grade primary nickel (Class II) accounts for the remaining 45%. Class I nickel contains at least 99.8% nickel. Class II nickel, such as NPI or iron-nickel, actually contains a relatively small amount of nickel – from 8-16% and 15-55%, respectively (Metal.digital, 2021).

Battery technology exclusively uses Class I nickel for cathode production. Only Class I nickel is traded on the LME due to the high purity standard of the mined metal. Such LME exchange-traded Class I nickel satisfies specific delivery standards (this accounts for less than 25% of total finished nickel supply). Hydrometallurgical processes use Class I nickel sulphides to produce battery grade sulphate NiSO4 (Metal.digital, 2021).

Tsingshan takes NPI and processes it further to high-matte nickel products that contain 75% nickel. Saprolite ore (from laterite soils) is refined and turned into NPI, which is in turn refined into nickel matte and then further processed to make Class I nickel.

Provided that this new process becomes the norm, growing EV battery demand could mean NPI supply being diverted away from stainless steelmaking. Through the new process the supply bottleneck for nickel sulphate has been broken, and the expectation is that Class I and Class II nickel prices will converge, taking into account that conversion of NPI to nickel sulphate adds around USD 5 500-6 500/tonne of nickel.

This process would increase the carbon footprint substantially, contributing 50-70 tonnes of emissions per tonne of nickel mined needed to convert NPI to matte and then further into NiSO4. An alternative process uses high-pressure acid leach technology to recover nickel and cobalt separately from each other from low-grade nickel-oxide laterite ores. The nickel that is recovered is Class I, battery grade nickel sulphate. The technology has been deployed in New Caledonia. However, high capital expenditure and environmental costs have caused it to lag behind current methods (Metal.digital, 2021).

In addition, 39% of global nickel reserves are found in locations that are exposed to high or extreme biodiversity risks – and because nickel typically comes in thin ore deposits, these areas are often destroyed. Proactive environmental, social and governance (ESG) efforts are critical for widespread acceptance of the product.

Vale has conditionally approved the long-awaited Bahodopi nickel project in Indonesia. The project is a joint venture with Chinese firms Tisco and Xinhai and will produce 73 000 tonnes of nickel in NPI for the stainless steel market. It will be Indonesia's most expensive plant, with a capital intensity of USD 31 500 per tonne of nickel, which is 320% higher than other plants in Indonesia.

The Bahodopi project will involve a new gas-fired power plant. This will likely make this the most expensive operating cost in Indonesian NPI (on top of it being the highest capital expenditure plant). Other NPI plants use a combination of coal and solar power. The other NPI producers are also now shifting to build their new plants in Kalimantan, where they will be able to access hydropower in the future, providing a huge cost advantage.

In recent years, a combination of rapid technological progress and scaled-up production rates has led to improved performance and – mostly – a fall in production costs for battery-electric vehicles batteries. This is mainly because of rising raw material costs and the recent semiconductor shortage causing prices to temporarily rise again over the last two years (Roland Berger, 2022).

Based on figures from mid-2021, an average NCM811 battery pack (80% nickel cathode) costs around USD 130 per kWh. Battery costs are heavily influenced by the cell technology used, the production location and the price of raw materials. Cell costs comprise approximately 75% of the total cost of the battery pack. Materials, such as cathode and anode active materials (CAM and AAM), account for 70% of the cost of each cell, with raw and refined materials like cobalt- and nickel-sulphates and lithium salts accounting for more than 30% of cell costs.

South Korean investments are currently building Indonesia's first EV battery plant, scheduled to start production in 2024, as well as its first EV plant. Nickel processing for use in batteries started in 2021, with more projects in the pipeline, mainly due to Chinese investments. Furthermore, Reuters has reported that Tesla has signed an estimated USD 5 billion contract for 5 years with an Indonesian nickel processing company for materials used in its batteries (Electrive, 2022).

SOLAR PV INDUSTRIALISATION OPPORTUNITIES

In 2021 around 257 GW of new renewable power generation capacity was added worldwide. More than one-half was solar PV: about 133-140 GW of newly installed systems was commissioned during 2021 alone (AC), with more than 180 GW modules at DC level. IRENA's WETO shows the need to have 10 TW of renewable power in place by 2030 worldwide according to a 1.5-S pathway, compared to 3 TW installed capacity at the end of 2021. To meet that goal, annual capacity additions need to increase to over 800 GW per year, a threefold increase (IRENA, 2022b). Solar PV has a key role to play worldwide, including in ASEAN.

Solar is a lot cheaper than fossil- or nuclear-based power generation. In 2021, the global weighted-average LCOE of utility-scale solar PV fell by 13% to USD 0.046/kWh. The global weighted-average total installed cost of utility-scale solar PV was USD 857/kW in 2021.

Over 843 GW of PV was in operation in AC terms by the end of 2021, and 1 000 GW in DC terms. According to IRENA's 1.5-S pathway, we need around 16 TW of PV by 2050. Some other scenarios suggest that much more PV will be needed in the coming decades. Utility-scale PV dominates, but rooftop PV accounts for around one-third of global installations, with a smaller role for floating and building integrated PV.

The typical cost of a solar PV project can be split into modules and other costs. While a lot of attention is focused on module manufacturing opportunities, other costs do in fact dominate. These include racks, inverters, grid connection and other components, as well as project preparation. These other costs also represent a significant economic opportunity.

China dominates today's global PV production: polysilicon (66%), wafers (>95%), cells (78%) and modules (72%). By the end of 2022, China is expected to have 500 GW of annual module production capacity and 550 GW of wafer production capacity. In contrast, ASEAN shares are still modest. To be competitive, a full supply chain must be developed at scale. Today's operations must sustain an industry in the 10 GW per year scale.

Deploying the latest technology is one way to create an entry. The average efficiency of crystalline modules – the dominant technology in 90% of market – increased from 14.7% in 2010 to 20.9% in 2021. Further efficiency increases are expected with TOPCon (60 GW of production capacity were added this year) and tandem cells production starting in Germany, and Multijunction further down the road. ESG is also on the radar of the PV industry's development. Eco-design is critical, as is reducing critical material use, not only for sustainability but to scale up production with limited resources. Critical materials mining and processing are other areas that create new economic opportunities. The production of modules requires significant amounts of glass and aluminium, in line with plans for Indonesia Green Industry.

Solar is a variable source. Power systems need flexibility to deal with this variability. This requires new technology but also new market designs and regulations, new operational practices and new business models. Innovations across these four pillars need to be combined to create new solutions. A good example is smart charging of EVs.

We need to ensure there is sufficient flexibility in power systems to deal with solar variability. That includes batteries for day/night storage, new solutions for seasonal storage and long-range hydrogen trade. These flexibility measures also constitute an important economic opportunity.

ENERGY SECURITY IN THE ASEAN REGION

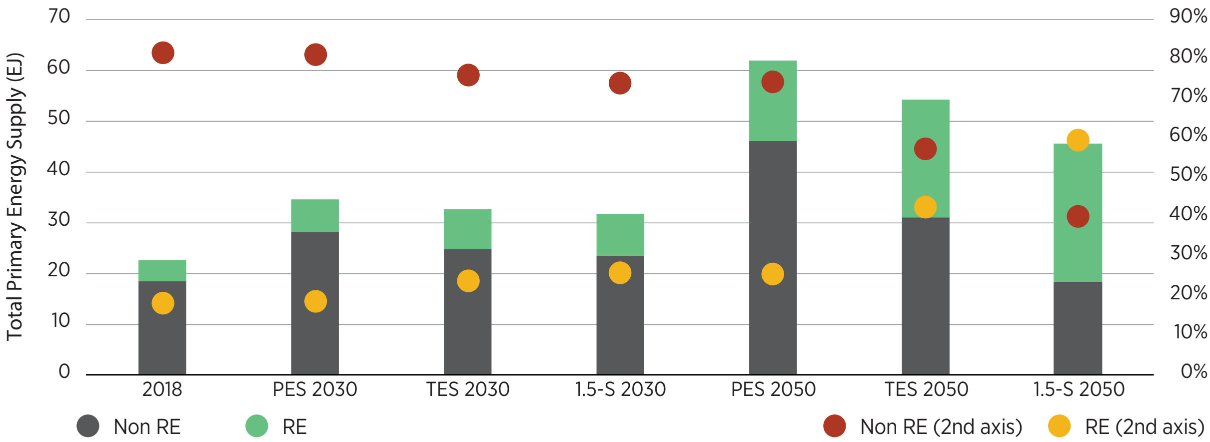
ASEAN countries share the common challenge of energy security, which consists of meeting rising demand for energy in a secure, affordable and sustainable manner. As this outlook shows, overall energy demand will continue to rise, more than doubling over the period to 2050. Therefore, supplying this energy securely is of paramount importance. In this regard, energy security implies greater use of indigenous resources, in particular renewable energy, and a focus on reducing demand growth through energy efficiency.

As outlined in this outlook, the PES case shows growing levels of energy demand and increasing dependence on fossil fuels through higher levels of consumption for these fuels. Economically viable renewable energy potentials are available in the ASEAN region that can significantly lower reliance on fossil fuels. Countries within the region are currently heavily dependent on fossil fuel imports, which can be reduced by building renewable supply while also reaping strategic and economic benefits. This is an ongoing process in the ASEAN region as exemplified by the regional aspirational target of achieving 23% renewable energy in primary energy by 2025, an increase from around 17% today. However, as the PES shows, the region is not on track to meet that aspirational target, and the question remains: how will the region further diversify, and secure, its energy as it moves towards the middle of the century?

In strategic terms, fossil fuel importing countries are vulnerable to risks of supply disruption and price volatility caused by political instability or armed conflicts that may occur in oil and gas-exporting nations. Smaller energy-importing countries may also be subject to pressure or coercion about their energy supply and therefore have less freedom to determine their own strategic priorities and goals (Van de Graaf, *et al.*, 2019).

ASEAN's TPES in 2050 will be dominated by renewables under the 1.5-S.

Figure 57 Renewable energy share in ASEAN TPES



Note: RE = renewable energy.

In contrast, countries that can develop their own renewable sources of energy are better placed to achieve energy security. Renewables enable countries to strengthen their energy security and achieve greater energy independence by harnessing the vast indigenous renewable energy sources that can be found across their territories (Van de Graaf, *et al.*, 2019). The needed shift is evident when comparing the shares of renewable energy in primary energy between today at 18% to 26% in the PES, and the 1.5-S, which increases that share to 60%. In absolute terms, demand from fossil fuels declines from 13 EJ today to 12 EJ in the 1.5-S, compared to an increase to 30 EJ in the PES in 2050.

Adding to this context, energy security is also a key denominator for sustainable economic growth. This outlook highlights the vital need to prepare proactively for the energy transition by encouraging energy efficiency, renewable energy technologies and green solutions by fostering innovation, aligning socio-economic structures with green jobs, and investment with international co-operation, all by implementing long-term energy planning towards energy systems that are flexible, sustainable, just and inclusive.

Forward-looking choices that leaders in government and industry make today in the ASEAN region will create a more prosperous future that can promote regional sustainable economic growth, improve livelihoods, and foster social cohesion and stability. This can only be achieved by promoting the tenets of energy security aligned with renewables, energy efficiency and fostering greater regional economic integration, including the sustained growth of secure and resilient green energy markets.

INVESTMENTS, COSTS AND BENEFITS

5

5. INVESTMENTS, COSTS AND BENEFITS

INVESTMENT NEEDS

A substantial increase in investments is required to accelerate the energy transition in ASEAN. Policy support for energy sectors and co-operation among the ASEAN countries are crucial to enable the reallocation of capital towards sustainable solutions and to ensure active participation from a wide range of investors.

In the shorter term up to 2030, some crucial energy transition technologies will see significant investment. Solar PV is a good example, as it will be key to the region's short-term energy transition. The additional 240 GW of installed capacity will need investment of around USD 150 billion. Investment related to the development of EVs will also play an important role in the overall energy transition effort in the region. Electric chargers are crucial, with the installation of nearly 4 million units necessary by 2030, requiring nearly USD 50 billion. Investments in enabling infrastructure will also be crucial, as planning process and construction take time. Around USD 105 billion needs to be invested in international and domestic transmission, with another USD 69 billion needed in local distribution.

Investment in the power sector and EV infrastructure in this decade is key to the energy transition.

Table 17 ASEAN short-term energy transition investment needs, 1.5-S, 2018-2030

SHORT-TERM INVESTMENT REQUIREMENT 1.5-S (2018-2030)			PARAMETER		TOTAL INVESTMENT (BILLION USD)
POWER		**Solar PV**	Installed capacity (GW)	241	156
POWER		**Other renewable energy** (non-hydro)	Installed capacity (GW)	56	90
POWER		**Hydro**	Installed capacity (GW)	73	56
GRID AND FLEXIBILITY		**Transmission** (international)	km (thousand)	35	13
GRID AND FLEXIBILITY		**Transmission** (national)	km (thousand)	247	92
GRID AND FLEXIBILITY		**Distribution**	km (thousand)	2 739	69
GRID AND FLEXIBILITY		**Storage**	GW	15	8
GRID AND FLEXIBILITY		**Biofuel supply**	million litres	57 475	66
ELECTRIFICATION		**EV chargers**	million units	3.7	47
ELECTRIFICATION		**EV car sales**	million units	13	349

In the long term, an average annual investment of USD 210 billion would be needed up to 2050 in the region to achieve the 1.5-S. This is more than two and a half times the required investment in the PES during the same time horizon. If the region pushes further for 1.5-S RE100, an average investment over the period would need to total USD 230 billion per year.

Many technologies in the 1.5-S have higher upfront investments but are critical mainly to enable the accelerated deployment of key renewable energy technologies in the power sector or to scale up the electrification of transport, buildings and industries as well as green hydrogen projects. The total required investment in the 1.5-S case out to 2050 is sizable, equal to over double the total region's GDP in 2018 and about 60% of 2050 values. However, it is spread out over multiple decades, and on an annual basis it is only around 2-7% of ASEAN's GDP, depending on the year.

On a sector level, investment in the building sector is mostly related to energy efficiency improvement measures. This includes a wide range of renewable and energy efficiency technologies, including light-emitting diode (LED) lamps, more efficient appliances and the development of low energy buildings. The building sector will account for 10% of the region's total energy transition investment until 2050, requiring an annual investment of USD 21 billion.

The transport sector will see higher investment needs, including USD 14 billion annually for EV chargers. The construction of EV charging infrastructure takes up over half of total transport investment. This investment is front-loaded. It needs to grow 60% annually in the short-term heading into the 2030s and then will decline to 8% annually in the latter two decades as we near 2050. Additionally, and initially, there will be an incremental cost of EVs. The energy efficiency investment in the transport sector in ASEAN will require USD 13 billion annually until 2050 under the 1.5-S. Investments in biofuel supply will need to average USD 7-8 billion per year under the 1.5-S up to 2050, which is roughly double what would be invested under the PES.

The industry sector will need to invest over USD 500 billion until 2050 under the 1.5-S, over double the PES level or equal to USD 9 billion in additional annual investment. Industry investment will need to focus on energy efficiency, including best available technologies, practices and processes, as well as circular economy and renewable-based generation technologies.

The power sector will require the largest investment. Investment in generating capacity, grids and storage, and other flexibility measures generally make up around two-thirds of energy system investment in the transition scenarios. In the PES, total investments will reach nearly USD 1 780 billion 2050, with the majority of these investments being in solar PV, coal (including both abated and unabated) and hydro. In the TES, 1.5-S and 1.5-S RE100, however, investment is considerably higher at nearly USD 2 900 billion, USD 4 050 billion and USD 5 120 billion, respectively. Generally, capacity investments make up around two-thirds of power sector investment, with the remaining one-third going into grids, infrastructure, storage and other enabling technologies.

Higher up-front investment is needed in the 1.5-S case.

Table 18 Total ASEAN energy transition requirement by sector and scenario

INVESTMENT REQUIREMENT (BILLION USD)			2018-2030 (USD BILLION) PES	2018-2030 (USD BILLION) TES	2018-2030 (USD BILLION) 1.5-S	2018-2050 (USD BILLION) PES	2018-2050 (USD BILLION) TES	2018-2050 (USD BILLION) 1.5-S RE90	2018-2050 (USD BILLION) 1.5-S RE100
POWER	Renewable energy	Solar PV	71	96	156	555	836	1 104	1 245
POWER	Renewable energy	Wind	56	100	56	56	143	739	1 474
POWER	Renewable energy	Hydro	56	56	56	163	313	367	368
POWER	Renewable energy	Geothermal	15	24	24	32	73	96	99
POWER	Renewable energy	Biomass	10	10	10	18	50	44	67
POWER	Nuclear					90	0	0	0
POWER	CCS	Natural Gas CCS	0	20	22	0	109	104	0
POWER	CCS	Coal CCS				132	307	0	0
POWER	CCS	Biomass CCS				0	0	231	341
POWER	Fossil fuel	Natural Gas	39	39	39	103	39	59	39
POWER	Fossil fuel	Coal	118	90	90	118	90	90	90
GRID AND FLEXIBILITY	Transmission (national)		66	83	92	266	367	461	461
GRID AND FLEXIBILITY	Transmission (intl.)		6	27	29	6	228	246	285
GRID AND FLEXIBILITY	Distribution		50	62	69	200	275	346	346
GRID AND FLEXIBILITY	Storage		3	5	8	43	71	161	306
RENEWABLE END USES	Biofuel supply		38.3	66.3	66.3	112	197	235	235
ENERGY EFFICIENCY	Buildings		58.3	67.7	77.4	343	523	688	688
ENERGY EFFICIENCY	Industry		30.6	46.7	115.7	208	248	509	509
ENERGY EFFICIENCY	Transport		12.9	18.9	31.1	116	298	419	419
ELECTRI-FICATION	EV chargers		6	31	47.2	48	278	419	419
TOTAL INVESTMENT REQUIREMENT (USD BILLION)			**636**	**843**	**989**	**2 609**	**4 445**	**6 318**	**7 391**

Note: Investment totals for 2050 in the TES and 1.5-S RE90 and RE100 for coal and natural gas are already committed in national plans and do not represent additions within those scenarios. These consist of projects that have been built since 2018 or are in the pipeline that occur by 2030 in the PES. The values thus carried over as cumulative investment are from 2018-2050.

COSTS AND SAVINGS

Investment provides a view of the scale of capital that must be mobilised for the various scenarios, but it does not paint a full picture of the total cost of the mix of technologies deployed in a scenario. For this, a calculation of energy system cost is used. This generally includes the investment totals for energy generating technologies, cost of capital for investment, costs for fuel demand, O&M and/or additional costs. Additionally, complementary infrastructure and supply technologies are also assessed, such as for grids and storage, biofuel supply, EV charging, etc. Costs are calculated for each end-use sector and for the power sector.

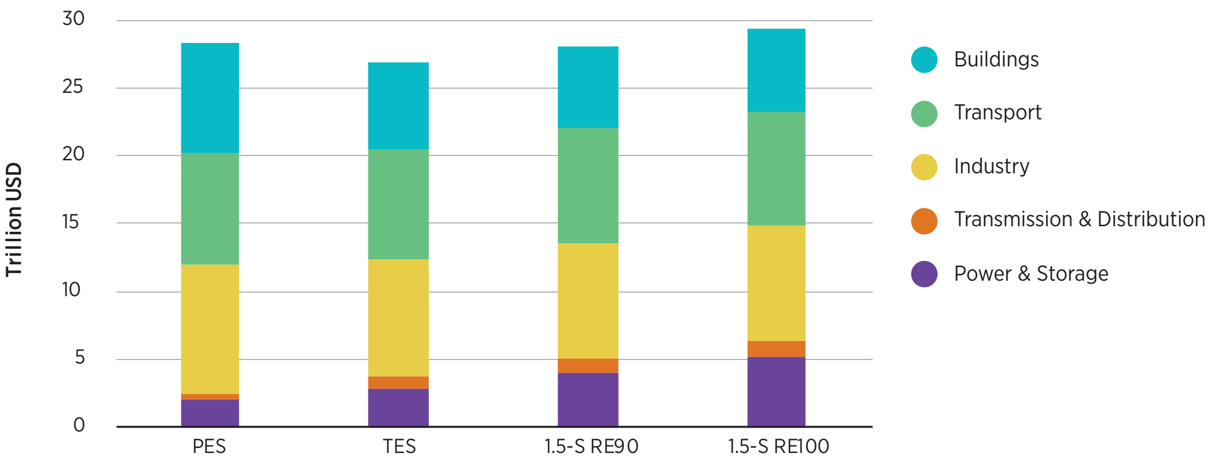
For the end-use sectors cost vary. The overall costs of fuel and electricity used in all end-use sectors reaches more than USD 20 trillion in the 1.5-S for the period to 2050, a number equal to 71% of total energy system cost in the sector. Overall, the energy system costs from the transport sector in the 1.5-S when including fuel, O&M, vehicle disposal and equivalent annual costs account for more than one-quarter of the total energy system costs of the demand sectors, or USD 240 billion every year. However, because of reduced oil demand, the 1.5-S is about USD 9.6 billion cheaper annually than the PES. The total energy system costs for the industry and building sectors are expected to reach USD 270 billion and USD 190 billion per year, respectively, in the 1.5-S. These equals to savings of USD 30 billion and USD 60 billion annually over the PES, also largely due to fuel cost savings and energy efficiency.

The power sector total energy system cost varies, but the total cost of the power system increases compared to the PES because the sector is generating more electricity, and in many cases that electricity is taking the place of the fossil fuels that are no longer used in end-uses. The lowest-cost case for power is the TES, which has the lowest level of generation expansion of the transition scenarios and considers less ambition and lower renewable energy deployment, but at the expense of higher emissions. The TES results in total power system costs about 40% higher than the PES. In the 1.5-S cases, which have higher generation and higher renewables, the cost of RE90 is just less than double that of the PES, and RE100 is 2.6-fold higher. The transition scenarios are more expensive mainly due to more investment being needed up front for generating capacity and investment in complementary infrastructure.

When looking at the total cost for energy provision over the period to 2050, in the PES USD 28.3 trillion will be spent across ASEAN. Of the transition scenarios, the TES has the lowest cost, at USD 27 trillion, but it also has the highest emissions. Of the 1.5-S cases, RE90 is the lowest cost at USD 28.1 trillion, around USD 0.16 trillion lower than the PES. The 1.5-S RE100 has the highest cost, at USD 29.4 trillion, or USD 1.1 trillion higher than the PES.

The total energy system cost for the 1.5-S RE90 is lower than the PES, and the RE100 has slightly higher costs.

Figure 58 ASEAN total energy system cost up to 2050, by scenario



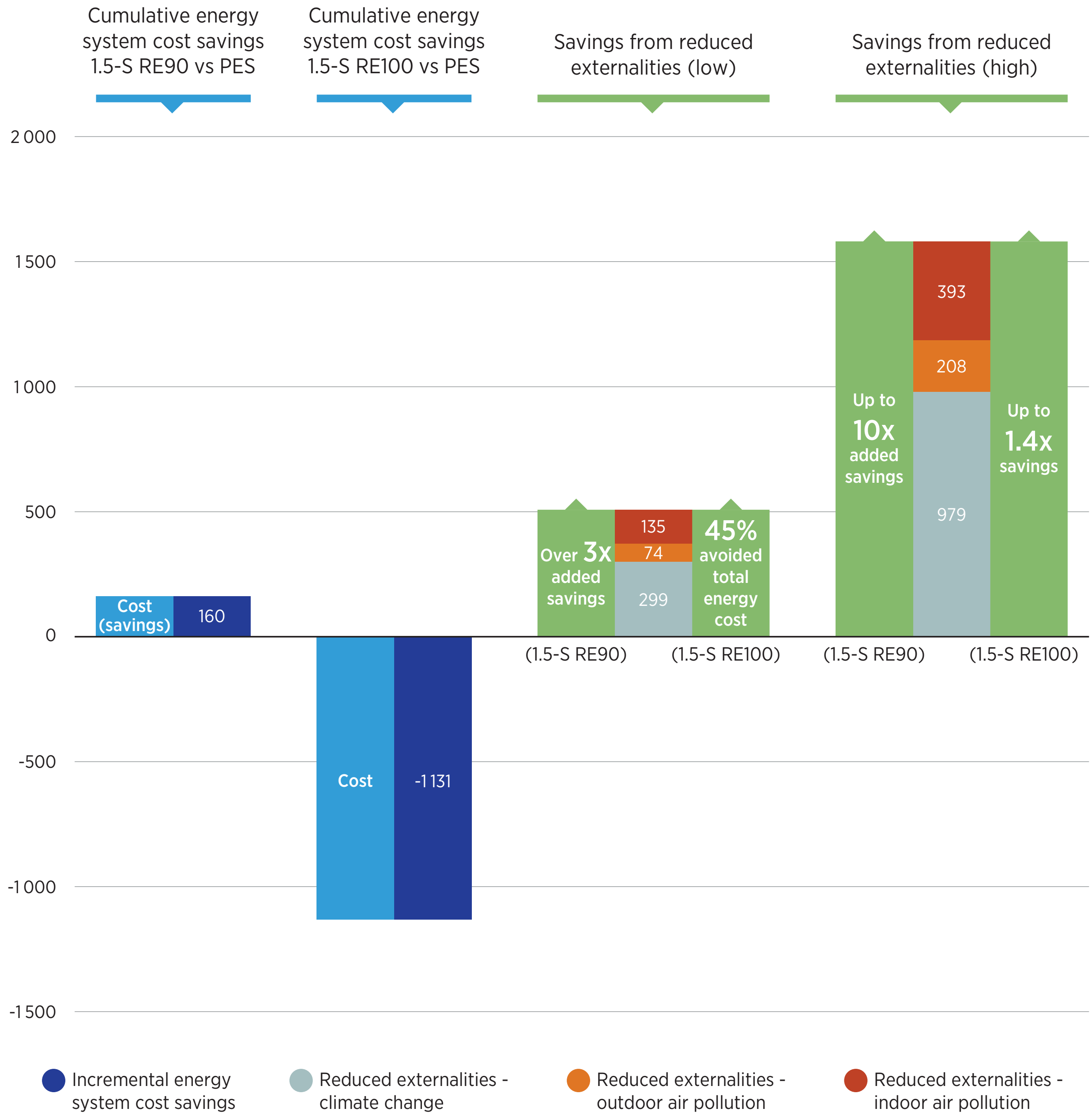
Note: Energy system costs include total investment in infrastructure and energy efficiency, O&M, annuities and fuel costs. The total energy system's cost excludes the purchase of vehicles across all scenarios, including EVs. If included, the 1.5-S would cost an additional USD 9.9 trillion compared to USD 9.1 trillion in the PES.

The carrier transition away from fossil fuel in the demand sectors also helps in reducing the externality cost associated with health, air pollution and climate change. A broad view of the balance between the costs and benefits of the energy transition can be obtained by using estimates of externalities related to pollution and climate change and comparing them with transition costs, including investments, O&M expenditures and subsidies.

The reduced externalities associated with the 1.5-S yield an avoided cost of between USD 16 billion to USD 49 billion annually, or in cumulative terms to 2050 ranging from around USD 508 billion to USD 1 580 billion. The 1.5-S RE90 is less expensive than the PES. The 1.5-S RE100 is slightly more expensive than the PES in energy cost terms (around USD 1 100 billion cumulatively to 2050). However, when considering avoided externalities, such as the high estimate of USD 1 580 billion avoided, the net cost of 1.5-S RE100 could be considered negative and result in wider overall cost savings.

Transitioning towards 1.5-S RE90 is considered the most economical and climate-friendly pathway for the ASEAN region to pursue.

Figure 59 Total energy transition cost savings and reduced externalities, 1.5-S vs PES, cumulative to 2050



ACTIONS NEEDED NOW: END-USE SECTOR FOCUS

6

6. ACTIONS NEEDED NOW: END-USE SECTOR FOCUS

In this section, key transition metrics for the main energy transition scenario, the 1.5-S, are presented for the three end-use sectors of buildings, transport and industry. This is accompanied by a set of proposed measures that could be considered to help achieve the transition outlined in the 1.5-S. These measures serve as an overview of the different actions that need to be taken as soon as possible to foster the decarbonisation of the energy sector and enable the sustainable energy transition.

Table 19 Buildings: Indicators of progress – status in 2018 and view to 2030 and 2050

BUILDING SECTOR	2018	2030		2050		KEY ACTIONS TO ACHIEVE THE 1.5-S
		PES	1.5-S	PES	1.5-S	
Final energy consumption (PJ)	4 093	5 080	4 256	9 983	7 318	• Develop and revise energy efficiency requirements for air conditioners and refrigerators. • Mandate the use of the most efficient appliances in the commercial sector. • Mandate the substitution of LED light bulbs for incandescent, halogen and fluorescent bulbs. • Increase efficiency standards in building codes for new construction and retrofitting. • Implement building certifications (*e.g.* Leadership in Energy and Environmental Design [LEED]). • Deploy district cooling systems that run renewable energy.
Electricity shares in buildings (%)	46%	62%	67%	78%	85%	• Introduce electric stoves as substitutes for traditional fuelwood or LPG cooking stoves. • Introduce electric water heaters as substitutes for LPG or fuelwood boilers for water heating.
Clean cooking (%)	64%	77%	89%	84%	92%	• Develop incentives for the promotion of clean cooking technologies. • Revise current subsidies to fossil fuels for cooking energy carriers.
Solar water heaters (units)	42 500	314 555	1 066 541	2 419 226	8 663 335	• Develop incentive programmes and building standards to promote low-carbon solar water heating technologies to supply heated water in the residential and commercial sectors.

Table 20 Transport: Indicators of progress – status in 2018 and view to 2030 and 2050

		2018	2030		2050		KEY ACTIONS TO ACHIEVE THE 1.5-S
			PES	1.5-S	PES	1.5-S	
TRANSPORT SECTOR	**Total energy consumption** (PJ)	6 444	8 933	8 362	15 583	11 353	• Improve the efficiency of internal combustion vehicles, *e.g.* through fuel efficiency standards. • Reduce transport volume and congestion by modal shift through integrated transport planning.
TRANSPORT SECTOR	**Share of electricity consumption** (%)	-	2%	7%	5%	30%	• Introduce EVs to the fleet, particularly: motorcycles, cars, sport utility vehicles (SUVs), minibuses, buses, and light- and heavy-duty trucks. • Increase efforts to finance investment in electromobility (*e.g.* current initiatives by banks and governments providing clients with special bank loans conditions for EV acquisition). • Deploy smart charging solutions and design tariff framework with local and regional functionalities. • Enable business models and accommodating regulation for EV charging. • Accelerate the shift to electromobility by giving EVs priority in city access and various incentives
TRANSPORT SECTOR	**Biofuel share in transport fuels** (%)	4.8%	10.9%	15.2%	10.4%	24.7%	• Mandate higher levels of biofuel blending, particularly bioethanol, biodiesel and biojet in gasoline, diesel and jet fuel, respectively. • Require increases in biofuel to be sustainability sourced and link sustainability criteria to mandates.

Table 21 Industry: Indicators of progress – status in 2018 and view to 2030 and 2050

	2018	2030 PES	2030 1.5-S	2050 PES	2050 1.5-S	KEY ACTIONS TO ACHIEVE THE 1.5-S
INDUSTRY SECTOR – **Total energy consumption** (PJ)	6 420	11 237	10 464	19 864	16 972	• Reduce energy intensity through improvement of infrastructure design and materials for energy recovery, better practices in O&M, improvement of production processes, etc. • Increase efficiency by adopting industry best practices and implementing measurable, reportable, verifiable (MRV) systems to track the performance of energy efficiency measures.
Electricity share (%)	29%	27%	37%	26%	52%	• Electrify industrial process heating applications.
Renewable energy direct use (PJ) (biomass + solar thermal)	1 011	2 031	1 999	4 046	2 978	• Maximise the recovery and use of biogas and residues. • Use biomass for high-temperature thermal processes (*i.e.* cement production). • Accelerate low-carbon technology deployment for industrial process heating, particularly of solar water heating and geothermal solutions. • Provide financial help to finance the upfront costs of these technologies.
Hydrogen (PJ)	-		68	32	393	• Mandate that hydrogen production come from low- and zero-carbon sources. • Support pilot-scale and, later, commercialisation-scale green hydrogen production and related derivatives.
Hydrogen in non-energy use (PJ)			97	4	703	

REFERENCES

REPORT REFERENCES

ACE (2020a), *The 6th ASEAN Energy Outlook*, ASEAN Centre of Energy, https://aseanenergy.org/the-6th-asean-energy-outlook/

ACE (2020b), "(2021-2025) ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025 Phase II", Asean Centre for Energy.

ACE (2022a), *ASEAN Energy in 2022: Outlook Report*, ASEAN Centre for Energy.

ACE (2022b), *Challenges and Implications of Coal Phase-down to the ASEAN Energy Landscape*, ASEAN Centre for Energy.

ADB (2015), "West Kalimantan Power Grid Strengthening Project: Guidelines for the Economic Analysis of Projects", Asian Development Bank.

AGEP (2021), "Country profiles 2021", *ASEAN-German Energy Programme*, https://agep.aseanenergy.org/country-profiles-2021/

Amante, C., and Eakins, B. W. (2009), "ETOPO1 arc-minute global relief model: procedures, data sources and analysis".

Amatulli, G., *et al.* (2018), "A suite of global, cross-scale topographic variables for environmental and biodiversity modeling", *Scientific data*, vol. 5/1, pp. 1–15., Nature Publishing Group.

ASEAN & UNCTAD (2021), *ASEAN Investment Report 2020-2021*, ASEAN Secretariat, United Nations Conference on Trade and Development.

BloombergNEF (2022), *Energy Transition Investment Trends 2022*, Bloomberg New Energy Finance.

Climate action tracker (2021), Net zero targets: Indonesia.

CSIS (2022), *Indonesia's Battery Industrial Strategy*, Centre for Strategies & International Studies, https://www.csis.org/analysis/indonesias-battery-industrial-strategy

DERA (2022), *Securing raw material supply: Benchmarking of measures of foreign manufacturing companies and recommendations for action*, German Mineral Resources Agency (DERA).

DGE *et al.* (2021), "Technology Data for the Indonesian Power Sector", Directorate General Electricity, Danish Energy Agency, Embassy of Denmark in Jakarta, Ea Energy Analyses.

Diewvilai, R., Audomvongseree, K. (2022). "Possible Pathways toward Carbon Neutrality in Thailand's Electricity Sector by 2050 through the introduction of H2 blanding in natural gas and solar PVwith BESS". *Energies*, Vol. 15, no. 3979.

EC JRC (2017), Cost development of low carbon energy technologies, Joint Research Centre (JRC), European Commission, pp. 77.

Electrive (2022), "Tesla to buy billions worth of nickel in Indonesia", https://www.electrive.com/2022/08/10/tesla-to-buy-billions-worth-of-nickel-in-indonesia/

Friedl, M. A., *et al.* (2010), "MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets", *Remote sensing of Environment*, vol. 114/1, pp. 168–82, Elsevier.

Fritsche, U., *et al.* (2020), *Future transitions for the bioeconomy towards sustainable development and a climate-neutral economy - Knowledge synthesis: Final report*, Publications Office of the EU.

Gao, J. (2017), "Downscaling global spatial population projections from 1/8-degree to 1-km grid cells", *National Center for Atmospheric Research, Boulder, CO, USA*, vol. 1105.

GBEP (2020), *Global bioenergy partnership sustainability indicators for bioenergy: Implementation guide*, Global Bioenergy Partnership.

GCEEP (2020), *Electricity Access 2020 Report*, The Global Commission to End Energy Poverty.

GMS (2022), "Greater Mekong Subregion Program: Energy", https://greatermekong.org/energy

Handayani, K., *et al.* (2022), "Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050", *Applied Energy*, vol. 311, pp. 118580, https://doi.org/10.1016/j.apenergy.2022.118580

Huber, I. (2021), "Indonesia's Nickel Industrial Strategy", Center for Strategic & International Studies, https://www.csis.org/analysis/indonesias-nickel-industrial-strategy

ICAO (2021), *World Air Transport Statistics 2020*, International Civil Aviation Organisation.

IEA (2019), *Establishing multilateral power trade in ASEAN*, Paris: IEA, https://www.iea.org/reports/establishing-multilateral-power-trade-in-asean

IEA (2021), *IEA World Energy Balances 2021*, International Energy Agency.

IEA, IRENA, UNSD, World Bank, WHO (2022), *Tracking SDG 7: The Energy Progress Report*, Washington DC: World Bank

IESR (2019). Levelized cost of electricity in Indonesia. Institute for Essential Services Reform and Agora Energywende.

IRENA (2017), *Geothermal Power: Technology Brief*, Abu Dhabi, UAE, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Aug/IRENA_Geothermal_Power_2017.pdf

IRENA (2018), *Policies and regulations for renewable energy mini-grids*, Abu Dhabi: International Renewable Energy Agency, https://www.irena.org/publications/2018/Oct/Policies-and-regulations-for-renewable-energy-mini-grids

IRENA (2020), *Green hydrogen: A guide to policy making*, Abu Dhabi: International Renewable Energy Agency, www.irena.org/publications/2020/Nov/Green-hydrogen

IRENA (2021a), *Renewable Energy Capacity Statistics 2021*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf (accessed 14 December 2021).

IRENA (2021b), *Green hydrogen supply: A guide to policy making*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022a), *Renewable Energy Statistics 2022*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022b), *World Energy Transition Outlook 2022*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022c), *Bioenergy for the energy transition: Ensuring sustainability and overcoming barriers*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022d), *Geopolitics of the Energy Transformation : The Hydrogen Factor*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022e), *Scaling up biomass for the energy transition: Untapped opportunities in Southeast Asia*, International Renewable Energy Agency.

IRENA (2022f), *Renewable Power Generation Costs in 2021*, Abu Dhabi: International Renewable Energy Agency, https://irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

IRENA (2022g), *Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022h), *Green hydrogen for industry: A guide to policy making*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022i), *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part II - Technology Review of Hydrogen Carriers*, Abu Dhabi: International Renewable Energy Agency.

IRENA (2022j), *Global hydrogen trade to meet the 1.5°C climate goal: Part III - green hydrogen cost and potential*, Abu Dhabi: International Renewable Energy Agency.

IRENA & ACE (2016), *Renewable Energy Outlook for ASEAN: A REmap Analysis*, International Renewable Energy Agency (IRENA); ASEAN Centre for Energy, http://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_ASEAN_2016_report.pdf

IRENA & WEF (2021), *Enabling Measures for Green Hydrogen Roadmap*, International Renewable Energy Agency.

IUCN, *et al.* (2022), "World Database on Protected Areas (WDPA)".

Maclaurin, G., *et al.* (2019), *The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling*, No. NREL/TP-6A20-73067, 1563140, MainId:13369. (p. NREL/TP-6A20-73067, 1563140, MainId:13369), https://doi.org/10.2172/1563140

Meeus, L. (2020), "The Evolution of Electricity Markets in Europe", Edward Elgar Publishing, https://doi.org/10.4337/9781789905472

Metal.digital (2021), “Tsingshan's Nickel Plan – Is Tsingshan's solution for the nickel supply pinch worth the environmental implications”. Metal.Digital: 17/05//2021.

Nalley, S., and LaRose, A. (2022), "Annual Energy Outlook 2022 (AEO2022)".

NEA (2022), *Stimulation of Sustainable Energy Production and Climate Transition : SDE++ 2022 Brochure*, Netherlands Enterprise Agency, https://english.rvo.nl/sites/default/files/2022/07/20220712-English-brochure-opening-round-2022_1.pdf

Nickel Institute (2022), "Is there enough nickel? Reserves, resources and recycling", https://nickelinstitute.org/blog/2020/january/reserves-resources-and-recycling-is-there-enough-nickel/

Ritchie, H., and Roser, M. (2022), "Global CO_2 emissions from fossil fuels", https://ourworldindata.org/co2-emissions (accessed 5 September 2022).

Roland Berger (2022), *Digging deeper: how to manage supply chain risk for lithium-ion batteries*, Wolfgang Bernhart.

SEAISI (2020), *The ASEAN Steel Industry in 2019 and Overcapacity Issues*, Global Forum Stakeholder Event., South East Asia Iron and Steel Institute, https://www.steelforum.org/stakeholders/gfsec-july-2020-seaisi.pdf

SEAISI (2021), *ASEAN Steel Industry: Steel Market Developments*, Presentation on 19th March 2021., South East Asia Iron and Steel Institute, https://www.oecd.org/industry/ind/Item_5_SEAISI.pdf

Service (C3S), C. C. C. (2017), "ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate", *Copernicus Climate Change Service Climate Data Store (CDS)*, vol. 15/2, pp. 2020.

UNFCCC (2021), "Market mechanisms and non-market approaches (Article 6)", https://unfccc.int/process-and-meetings/the-paris-agreement/the-glasgow-climate-pact/cop26-outcomes-market-mechanisms-and-non-market-approaches-article-6#eq-1 (accessed 6 September 2022).

University College Cork (2019), "PLEXOS World", https://energyexemplar.com/plexos-world/

UNSTAT (2020), *2019 Energy Statistics Yearbook*, United Nations Statistics Division.

Van de Graaf, et. al, (2019), A New World: The Geopolitics of the Energy Transformation.

Vimmerstedt, L., *et al.* (2021), *Annual technology baseline: The 2021 electricity update*, National Renewable Energy Lab.(NREL), Golden, CO (United States).

MAJOR REFERENCES FOR COUNTRY ANALYSIS

Regional datasets

(S&P, 2021) S&P Global Platt's World Electric Power Plants Database, S&P Global Market Intelligence.
(Global Data, 2021), Global Data Power Plant Database, Global Data.
(IEA, 2021) IEA World Energy Balances, International Energy Agency.

Brunei Darussalam

ERIA (2019), "Energy Outlook and Savings Potential in East Asia", Economic Research Institute for ASEAN and East Asia, https://www.eria.org/publications/energy-outlook-and-energy-saving-potential-in-east-asia-2019/

GoB (2014), "Energy White Paper", Energy and Industry Department, Prime Minister's Office.
GoB (2017), "Brunei Darussalam's Second National Communication", Energy and Industry Department, Prime Minister's Office, Brunei.
GoB (2020), "Brunei National Climate Change Policy", Government of Brunei.
GoB (2020), "National Determined Contribution Submission, Brunei Darussalam", Government of Brunei.
MOFE (2020), "Key Statistics Indicators Reports, and other statistics", Department of Statistics, Department of Economic Planning and Statistics, Ministry of Finance and Economy.

Cambodia

ADB (2019), "Cambodia Transport Sector Assessment, Strategy and Roadmap", Asian Development Bank.
EAC (2019), "Salient Features of Power Development in Kingdom of Cambodia", Electricity Authority of Cambodia.
ERIA (2019), "Cambodia Basic Energy Plan", Economic Research Institute for ASEAN and East Asia.
GoC (2020), "National Determined Contribution Submission, Kingdom of Cambodia", Government of Kingdom of Cambodia.
MME (2020), "Climate Change Action Plan for Energy Sector 2021 – 2023", Ministry of Mines and Energy.
MOE (2016), "A Design of Low-carbon Development Plan Toward 2050 in Cambodia", Ministry of Environment, Cambodia, https://ncsd.moe.gov.kh/resources/document/design-low-carbon-development-plan-towards-2050
NIS (2019), "General Population Census of the Kingdom of Cambodia 2019", National Institute of Statistics, Ministry of Planning.

Indonesia

DEN (2019), Indonesia Energy Outlook 2019, National Energy Council of Indonesia.
DGE et al. (2021), "Technology Data for the Indonesian Power Sector".
ESDM (2020), "Handbook of Energy and Economic Statistics 2020", Ministry of Energy and Mineral Resources.
ESDM (2021), Statisktik Ketenagalistrikan Tahun 2020", Ministry of Energy and Mineral Resources.
GoI (2017), "Rencana Umum Energy Nasional (RUEN)", Government of Indonesia.
GoI (2021), Nationally Determined Contributions, Government of Indonesia.
IESR (2021), Indonesia Energy Transition Outlook 2021, Institute for Essential Services Reform.
PLN (2021), Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2021-2030, PT PLN (Persero).

Lao PDR

ERIA (2020), Lao PDR Energy Outlook 2020, Economic Research Institute for ASEAN and East Asia.
LSB (2017), Lao Social Indicator Survey II 2017, Survey Findings Report, Vientiane: Lao Statistics Bureau and UNICEF.
LSB (2021), "Lao Statistics Information Services", Lao Statistics Bureau, https://laosis.lsb.gov.la
MEM (2020), Lao PDR's Power Development Plans 2020-2030, Ministry of Energy and Mines.

Malaysia

DOSM (2019), Household Income and Basic Amenities Survey Report 2019, Department of Statistics Malaysia.
GoM (2020), National Determined Contribution Submission, Malaysia, Government of Malaysia.
SEDA (2021), Malaysia Renewable Energy Roadmap (MyRER), Sustainable Energy Development Authority.
ST (2021), Malaysia Energy Statistics Handbook 2020, Energy Commission.

Myanmar

CSO (2021), Myanmar Key Statistics, Central Statistical Organization, www.csostat.gov.mm/
ERIA (2019), Myanmar Energy Statistics 2019, Economic Research Institute for ASEAN and East Asia.
ERIA (2020), Myanmar Energy Outlook 2020, Economic Research Institute for ASEAN and East Asia.
GoM (2014), Myanmar National Energy Policy, Government of Myanmar.
GoM (2020), "National Determined Contribution Submission, Myanmar", Government of Myanmar.

Philippines

ADB (2017), Pathways to Low-Carbon Development for the Philippines, Asian Development Bank
DOE (2018), Philippine Energy Plan 2018-2040, Department of Energy, Republic of Philippines
DOE (2019), Philippine Energy Situationer & Key Energy Statistics 2019, Department of Energy, Republic of Philippines
DOE (2020), Key Energy Statistics 2020, Department of Energy, Republic of Philippines
GoP (2021), Nationally Determined Contribution Submission, Government of Republic of Philippines
Handayani, K., et al. (2022), "Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050", Applied Energy, vol. 311, pp. 118580, https://doi.org/10.1016/j.apenergy.2022.118580
NREB (2020), National Renewable Energy Program 2021-2040, National Renewable Energy Board

Singapore

EMA (2022), Charting the Energy Transition to 2050, Energy Market Authority
GoS (2021), Nationally Determined Contribution Submission, Government of Republic of Singapore
NCCS (2016), Singapore's Climate Action Plan: Take Action Today, For a Carbon-Efficient Singapore, National Climate Change Secretariat, Prime Minister's Office, Singapore
SingStat (2021), Key Statistics, Singapore Department of Statistics, https://www.singstat.gov.sg/

Thailand

DEDE (2019), Energy Balance of Thailand 2019, Department of Alternative Energy Development and Efficiency
EPPO (2021), Energy Statistics, Energy Policy and Planning office (EPPO), Ministry of Energy Thailand
GoT (2020), Nationally Determined Contribution Submission, Government of Kingdom of Thailand
IRENA (2017), Renewable Energy Outlook: Thailand, International Renewable Energy Agency
MoE (2018), Power Development Plan (PDP) 2018-2037, Ministry of Energy and Water Resources
NSO (2021), National Statistics, National Statistics Office, http://www.nso.go.th/

Viet Nam

DEA (2019), Vietnam Energy Outlook 2019, Danish Energy Agency
GoV (2020), "National Determined Contribution Submission, Vietnam", Government of Vietnam.
GSO (2018), Vietnam Household Living Standard Survey 2018, General Statistics Office
GSO (2021), Vietnam Key Statistics, General Statistics Office, https://www.gso.gov.vn/en/statistical-data/
MoIT (2022), Vietnam Power Development Plan (PDP), Ministry of Industry and Trade

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