

Article

A Review of the Status of Fossil and Renewable Energies in Southeast Asia and Its Implications on the Decarbonization of ASEAN

Hon Chung Lau ^{1,2,*} , Kai Zhang ³, Harsha Kumar Bokka ⁴ and Seeram Ramakrishna ⁵ ¹ Low Carbon Energies, Houston, TX 77401, USA² Department of Chemical and Biomolecular Engineering, Rice University, Houston, TX 77005, USA³ Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, AB T2N 1N4, Canada; kai.zhang@ucalgary.ca⁴ Department of Civil and Environmental Engineering, University of Singapore, Singapore 117576, Singapore; hkbokka@u.nus.edu⁵ Department of Mechanical Engineering, University of Singapore, Singapore 117575, Singapore; seeram@nus.edu.sg

* Correspondence: hclau@lowcarbonenergies.com



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Abstract: The ten nations of Southeast Asia, collectively known as ASEAN, emitted 1.65 Gtpa CO₂ in 2020, and are among the most vulnerable nations to climate change, which is partially caused by anthropogenic CO₂ emission. This paper analyzes the history of ASEAN energy consumption and CO₂ emission from both fossil and renewable energies in the last two decades. The results show that ASEAN's renewable energies resources range from low to moderate, are unevenly distributed geographically, and contributed to only 20% of total primary energy consumption (TPEC) in 2015. The dominant forms of renewable energies are hydropower, solar photovoltaic, and bioenergy. However, both hydropower and bioenergy have substantial sustainability issues. Fossil energies depend heavily on coal and oil and contribute to 80% of TPEC. More importantly, renewable energies' contribution to TPEC has been decreasing in the last two decades, despite the increasing installation capacity. This suggests that the current rate of the addition of renewable energy capacity is inadequate to allow ASEAN to reach net-zero by 2050. Therefore, fossil energies will continue to be an important part of ASEAN's energy mix. More tools, such as carbon capture and storage (CCS) and hydrogen, will be needed for decarbonization. CCS will be needed to decarbonize ASEAN's fossil power and industrial plants, while blue hydrogen will be needed to decarbonize hard-to-decarbonize industrial plants. Based on recent research into regional CO₂ source-sink mapping, this paper proposes six large-scale CCS projects in four countries, which can mitigate up to 300 Mtpa CO₂. Furthermore, this paper identifies common pathways for ASEAN decarbonization and their policy implications.

Keywords: ASEAN; Southeast Asia; decarbonization; net-zero; carbon capture and storage; blue hydrogen

1. Introduction

ASEAN is an association of ten Southeast Asian countries (Indonesia, Malaysia, Thailand, Philippines, Vietnam, Singapore, Laos, Cambodia and Brunei) that were formed to accelerate economic growth, social progress and cultural development, and to promote regional peace and stability (Figure 1). With a population of 661 million, ASEAN's GDP, 3.08 trillion USD in 2020, was bigger than that of India (2.66 trillion USD) [1]. Since the 1990s, ASEAN's CO₂ emission has been rapidly increasing due to increased population, urbanization, and economic prosperity. In 2020, ASEAN emitted 1.65 Gt CO₂ from the burning of fossil fuels and cement production [2]. All ASEAN countries are signatories to the Paris Agreement and have pledged to reduce their CO₂ emission to limit the rise in the earth's atmospheric temperature to less than 2 °C above pre-industrial times.

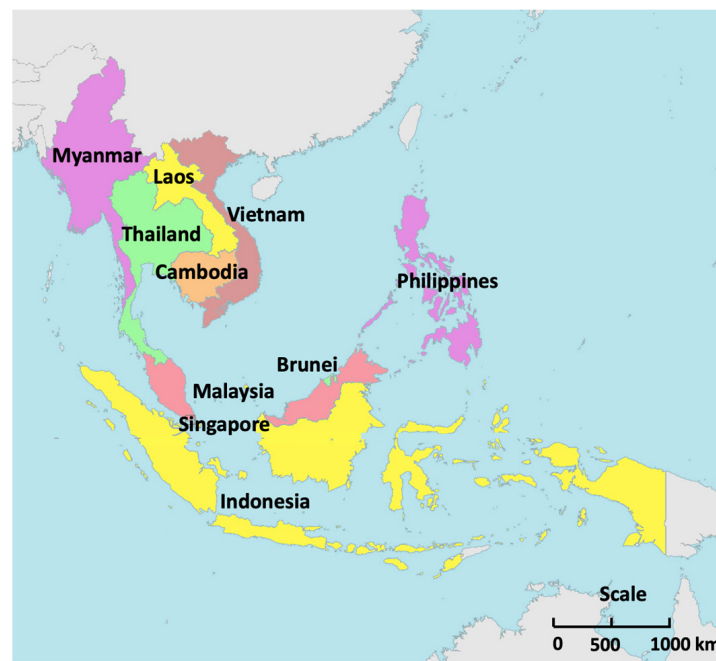


Figure 1. Map of ASEAN countries.

Despite ASEAN's size, population, and economic importance, there have been relatively few studies on the region's decarbonization until recently. Table 1 summarizes the results and research gaps in the relevant studies. Hitherto, most studies are country-specific [3–10] and lack a quantitative assessment of CO₂ storage potential. Recently, Lau et al. (2021) published a roadmap for the decarbonization of Singapore and discussed its implications for ASEAN [7–9]. They propose a cross-border carbon capture and storage (CCS) project to store the CO₂ captured from Singapore and a neighboring country [9]. This was the first time that a cross-border CCS project was proposed in ASEAN.

Although country-specific studies are important in their own right, decarbonization in ASEAN is best tackled on a regional level, as the emitted CO₂ can migrate across national borders. The novelty of this study is its provision of a regional view of energy consumption, CO₂ emission and opportunities for CCS for the ten nations of ASEAN. We believe that a regional view will enable us to determine common pathways for the decarbonization of ASEAN as a region, whereby cooperation between ASEAN countries can accelerate the pace of regional decarbonization.

The goal of this study is to determine decarbonization pathways that are applicable to multiple countries in ASEAN, since they share common characteristics. For example, most countries are densely populated, located near the equator, and have developing economies, which rely heavily on coal for power generation. Some have long coastlines with a large coastal population. The identification of common decarbonization pathways will enable cooperation between ASEAN countries to obtain the technologies, human resources and international financing needed to implement them. For example, ASEAN, as a regional organization, can cooperate with technology providers in the West to transfer technology to the region. In addition, our study can provide insights into regional financial institutes such as the Asian Development Bank to finance the research and development of decarbonization technologies for the region.

All ASEAN countries are signatories of the Paris Agreement. Table 2 lists the national determined ASEAN contributions. Practically, all ASEAN countries have committed to a drastic reduction in CO₂ emissions by 2030. Our study will be relevant for policy-makers in ASEAN governments when setting their national energy policies.

Table 1. Previous studies on CCS in Southeast Asia.

Previous Study	Country	Major Results	Research Gap
Zhang et al. 2022 [3]	Thailand	Major CO ₂ source and sinks in Thailand are identified. Six CCS clusters are proposed.	Study only covers in-country CCS.
Oh (2012) [4]	Malaysia	CCS is needed to decarbonize coal-fired power plants. Challenges include low public awareness, lack of regulatory oversight, high cost and lack of assessment of CO ₂ storage capacity	No quantitative assessment of CO ₂ emission and storage potential.
Lai et al. (2011) [5]	Malaysia	Power sector will benefit from CCS. However, lack of assessment of CO ₂ storage capacity in the subsurface is a key factor.	No quantitative assessment of CO ₂ storage capacity.
Ibrahim et al. (2015) [10]	Malaysia	CCUS is a must-have technology for decarbonization. However, lack of funds is a key factor. Government should raise public awareness and introduce carbon tax, and carbon trading.	No quantitative assessment of CO ₂ storage capacity.
Sukor et al. (2020) [11]	Malaysia	Techno-economic analysis of using CCS to reduce CO ₂ concentration in the produced gas from 37 to 8 mole% in the offshore Tangga Barat project shows positive net present value	No quantitative assessment of CO ₂ storage capacity.
Adisaputro and Saputra (2017) [6]	Indonesia	Both CCU and CCS are needed to reduce CO ₂ emission. In CCU, CO ₂ is used to produce urea and other chemicals.	CO ₂ source-sink mapping not conducted. No breakdown of CO ₂ abatement between CCS and CCU.
Lau and Ramakrishna (2021) [7]	Singapore	CO ₂ sources from Singapore are identified. Centralized post-combustion carbon capture and a regional CCS corridor are proposed.	CO ₂ source-sink mapping is not conducted.
Lau et al. (2021) [8]	Singapore	A roadmap for decarbonization is proposed consisting of post-combustion carbon capture, hydrogen production, biorefining, and use of electric cars and hydrogen fuel cell vehicles.	CO ₂ source-sink mapping is not conducted.
Zhang and Lau (2022) [9]	Singapore, Indonesia, Malaysia	Within 1000 km from Singapore, CO ₂ storage potential is 386 Gt. A CCS corridor is proposed.	Study covers part of Indonesia and Malaysia.
ADB (2013) [12]	Vietnam, Thailand, Philippines, South Sumatra	There is 57 Gt CO ₂ storage potential in these countries.	Study covers only part of Indonesia. Detailed CO ₂ source-sink mapping is not provided.

Table 2. National determined contribution to Paris Agreement by ASEAN countries [13].

Country	Greenhouse Gas Emission Reduction from Business-as-Usual Case by 2030
Indonesia	29% unconditional, 41% conditional on international assistance
Malaysia	45% unconditional reduction in emission intensity compared by 2030 compared to 2005 levels.
Thailand	20% unconditional; 25% conditional
Vietnam	8% unconditional; 25% conditional
Philippines	2.71% unconditional; 72% conditional
Singapore	36% unconditional reduction in emission intensity by 2030 based on 2005 levels. Peak CO ₂ emission at 65 Mtpa or less by 2030. Achieve net-zero by 2050.
Myanmar	50% conditional
Laos	60% unconditional
Cambodia	42% unconditional
Brunei	20% unconditional

2. Objective and Methodology

The objective of this study is to determine the common pathways for ASEAN countries to decarbonize their economies to meet the goal of achieving net-zero CO₂ emissions by the second half of the century.

The methodology of this study is illustrated in Figure 2. First, we determine the status of renewable and fossil energies in ASEAN by analyzing their resource distribution, intensity and the history of installed capacity. Second, we assess the likelihood of replacing fossil energies by renewable energies within the 2030–2050 timeframe. Third, for those energy consumption sectors that will continue to use fossil fuels, we determine the common decarbonization pathways that are applicable to multiple ASEAN countries.

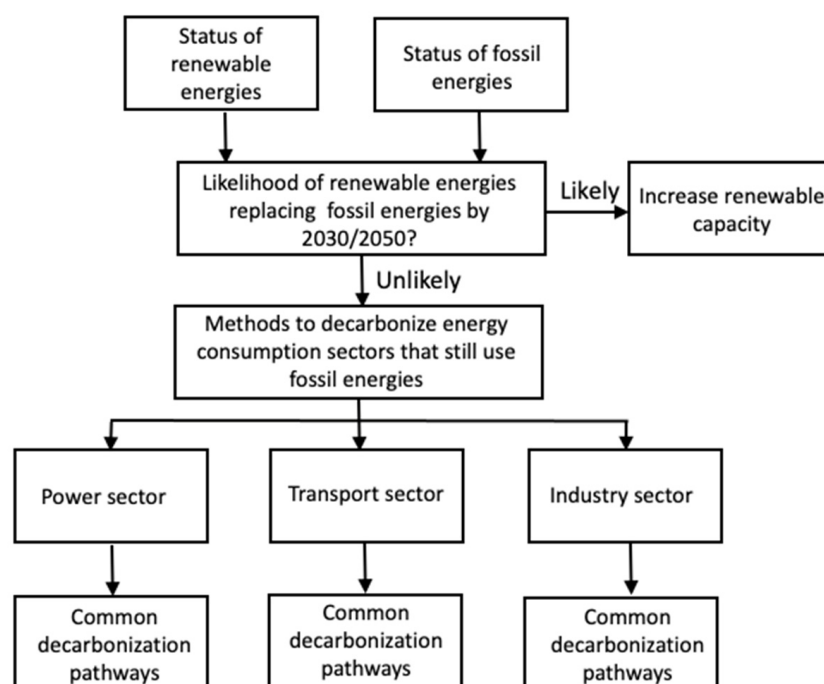


Figure 2. Methodology of study.

One limitation of this methodology is that the assessment of the likelihood of renewable energies replacing fossil energy in the 2030–2050 timeframe is qualitative rather than quantitative. However, it is not without its merits. Although it is based on an extrapolation of historical trends over the last two decades into the next 1–3 decades, it is also grounded in the recognition of substantial sustainability issues with renewable energies, which have yet to be resolved in ASEAN countries. We have also abstained from using scenario studies which are not based on actual governmental commitments to future renewable and fossil fuel plant additions.

3. Energy Resources in ASEAN

ASEAN countries possess both renewable and fossil energy resources. However, their geographical distribution, intensity, and contribution to the national energy mix are different for each country. We will provide their status in this section.

3.1. Status of Renewable Energies in ASEAN

In this section, we will analyze the resource distribution, intensity and history of installed capacity of renewable energies in ASEAN. Five types of renewable energy, namely, hydropower, solar photovoltaic (PV), wind, geothermal and bioenergy, will be discussed.

3.1.1. Hydropower Resources

Figure 3 shows a map of annual precipitation in the Southeast Asia [14]. It can be seen that, within ASEAN, Myanmar, Laos, Vietnam, Malaysia, Thailand, Indonesia and the Philippines, annual rainfall exceeds 200 cm (79 in)/year. The abundance of rainfall, together with plentiful rivers, contribute to the rich hydropower resources in Southeast Asia. It is no wonder that hydropower ranks top in renewable energy in Vietnam, Malaysia, Indonesia, Myanmar, Cambodia, Laos and the Philippines, contributing to 51%, 72%, 59%, 96%, 84%, 99%, and 44%, respectively, of the total renewable energy of these countries. In Thailand, hydropower ranks second in renewable capacity, contributing to 26% of renewable capacity. Only Brunei and Singapore have no hydropower resources due to the lack of land mass.

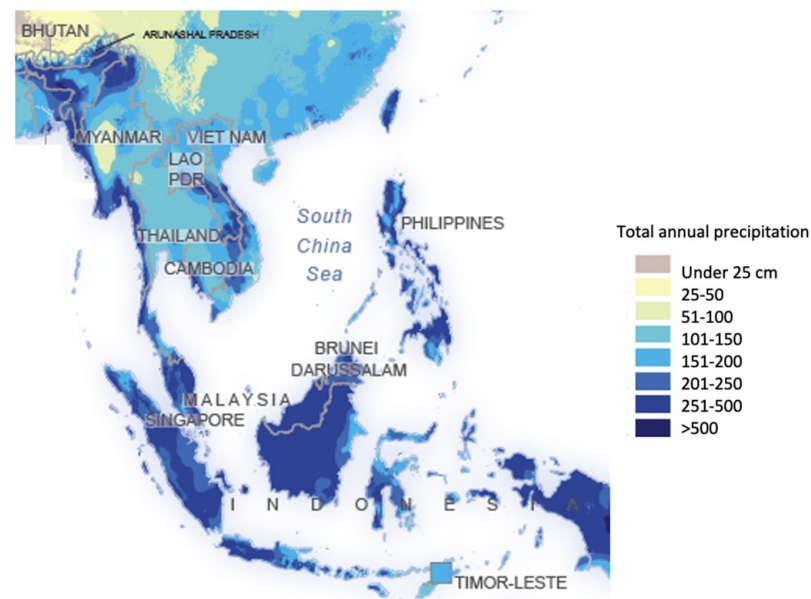


Figure 3. Map of annual precipitation in Southeast Asia [14].

Figure 4 shows the history of installed hydropower capacity in ASEAN. ASEAN's growth in hydropower capacity has risen in the last two decades, and especially in the last decade. Vietnam, Malaysia, Indonesia and Laos are the four countries with the highest hydropower capacity growth rate. As of 2020, ASEAN countries have a total hydropower capacity of 48.8 GW, with 37% residing in Vietnam, 15% in Laos, 13% in Indonesia, and 13% in Malaysia.

3.1.2. Sustainability Issues with Hydropower

Unfortunately, the excessive damming of rivers, especially the Mekong, has had adverse impacts on climate, ecology, agriculture, fishery, and riparian communities. There are already 100 dams completed on the Mekong tributaries, and two on the mainstream in Laos (Xyaburi Dam and Don Sahon Dam) [15]. Another 100 dams are under construction or planned in the lower Mekong basins of Laos, Cambodia, Thailand and Vietnam. Laos and Vietnam have announced plans to add a hydropower capacity of 5 GW and 4 GW, respectively, between 2021 and 2030 [16]. On the other hand, Cambodia has announced the halting of all construction of dams along the Mekong River until 2030, due to ecological concerns [17]. In fact, sustainability issues have been raised in all six countries situated along the Mekong River: China, Myanmar, Thailand, Laos, Cambodia and Vietnam. Evidence shows that dams affect fish migration, river hydrology, and sediment transfers, and negatively impact riparian communities up to 1000 km away [18]. A 2010 environmental impact assessment report commissioned by the Mekong River Commission recommended a 10-year deferment on mainstream dams on the Mekong to determine alternative plans [19].

It is uncertain how many of the planned hydropower stations along the Mekong will come to fruition due to sustainability concerns and uncertain international financing [20].

On the other hand, smaller-scale, run-of-the-river hydropower stations [21], which divert part of a river for electricity generation, are more environmentally friendly and can be used in remote areas. Further use of this technology in ASEAN can be beneficial in rural and mountainous areas outside the reach of national grids.

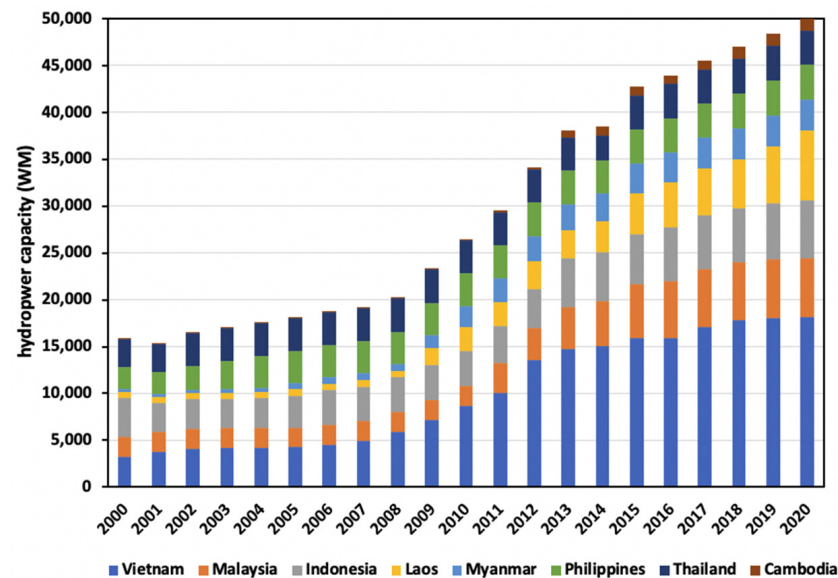


Figure 4. History of hydropower capacity in ASEAN [22].

3.1.3. Solar PV

Figure 5 is a map of solar resources in Asia [23]. It can be seen that southeast Asia has a moderate degree of solar potential but lags behind that in other parts of Asia, such as western China. Additionally, solar PV requires a large land mass, which is a scarce resource in densely populated ASEAN. More importantly, solar PV suffers from a low capacity factor of 10–20%, as sunlight is unavailable at night [22]. Therefore, for the same unit of electricity generation, more installed solar PV capacity is needed compared to other energies. Figure 6 shows the history of installed solar PV in ASEAN [22]. Within ASEAN, Thailand and Vietnam have the most installed solar PV capacity. For Vietnam, solar PV was first installed in 2019. As of 2020, total installed solar PV capacity in ASEAN was 22.8 GW (Figure 6), which is only 47% that of hydropower (Figure 4). It has the second largest installation capacity of all renewable energies in ASEAN.

3.1.4. Wind

Figure 7 is a map of average wind speed at 10 m above sea level for Southeast Asia [24]. Usually, a minimum wind speed of 4 m/s is needed for efficient use of a wind turbine. For most of Southeast Asia, the average wind speed falls below this threshold value. The only exception is the coastal region of Vietnam and the Philippines. As a result, wind is the least-used renewable energy in ASEAN and is used only in the Philippines, Vietnam, Indonesia and Thailand. Wind energy also suffers from a low to moderate capacity factor of 15–40% [22]. As of 2020, the total installed capacity of wind energy in ASEAN was only 2.7 GW, with the majority being onshore wind. Most of the wind capacity growth in the last decade took place in Thailand (Figure 8). Wind energy has the lowest installation capacity among renewable energies in ASEAN.

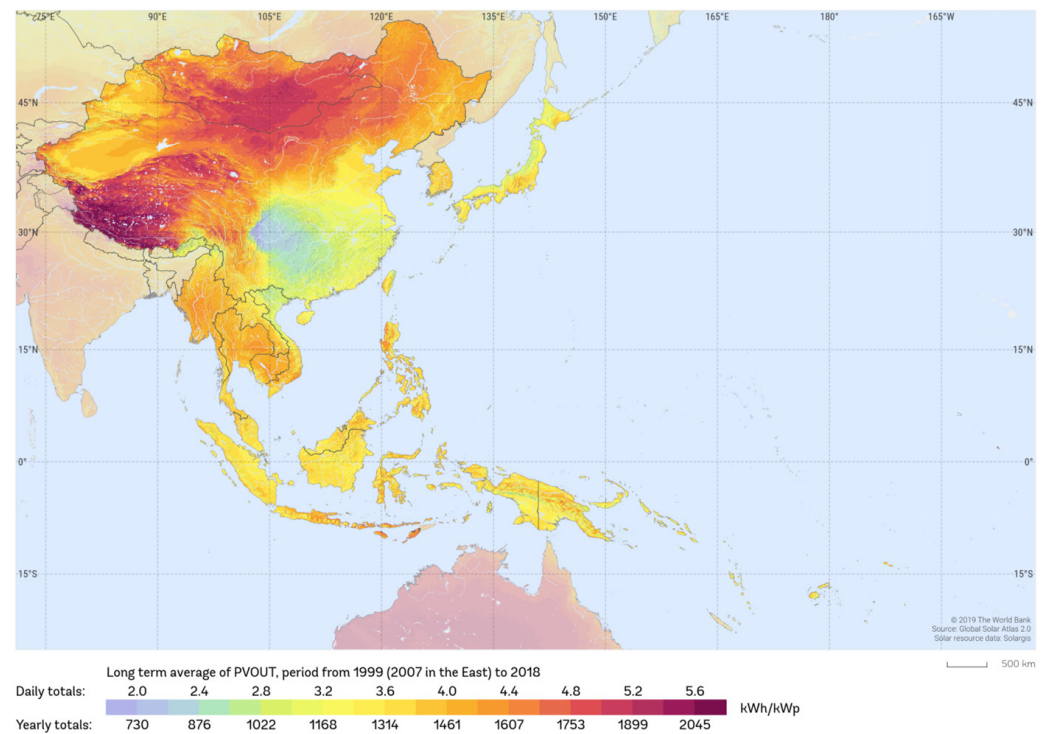


Figure 5. Solar resource map of Asia [23].

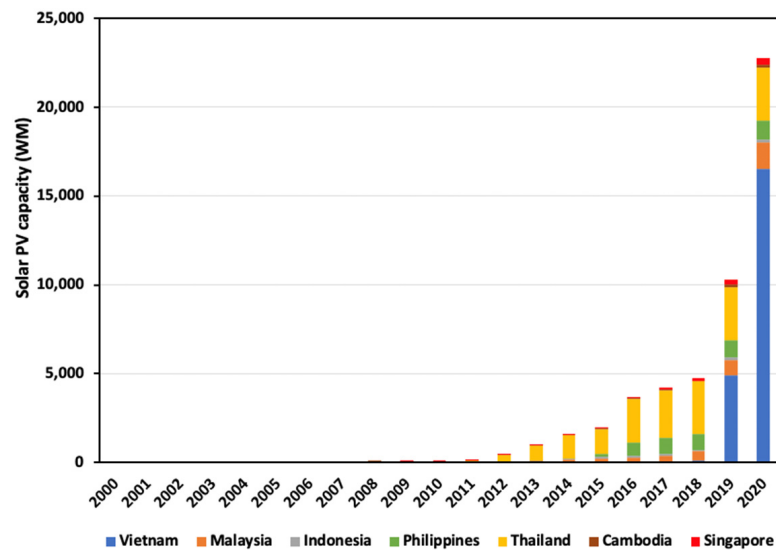


Figure 6. History of installed solar PV capacity in ASEAN [22].

3.1.5. Geothermal

Figure 9 shows a map of the earth's geothermal gradient in aquifers [25], which is a measure of geothermal energy potential. Within ASEAN, Indonesia and the Philippines are the two countries with the most substantial geothermal potential because they are situated within the Ring of Fire [26], where active tectonic movements cause hot magma to rise close to the earth's surface. Figure 10 provides a history of installed geothermal capacity in ASEAN [22]. As of 2020, the total installed geothermal capacity was 4.06 GW, residing roughly equally in the Philippines and Indonesia. However, the addition of new geothermal capacity in these two countries has been limited in recent years. Among renewable energies, geothermal ranks fourth in installation capacity among ASEAN countries.

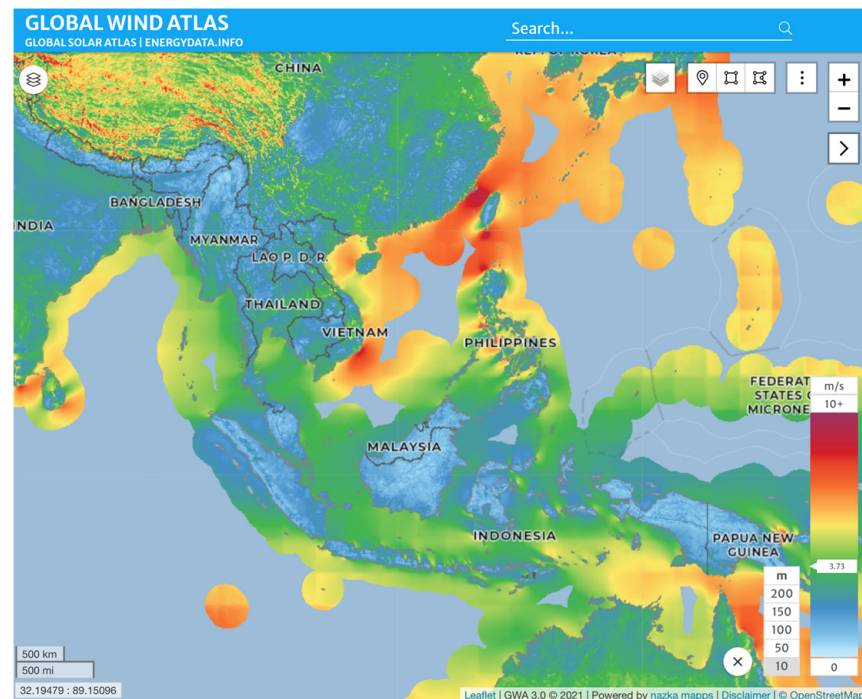


Figure 7. Wind speed map at 10 m above sea level in Southeast Asia [24].

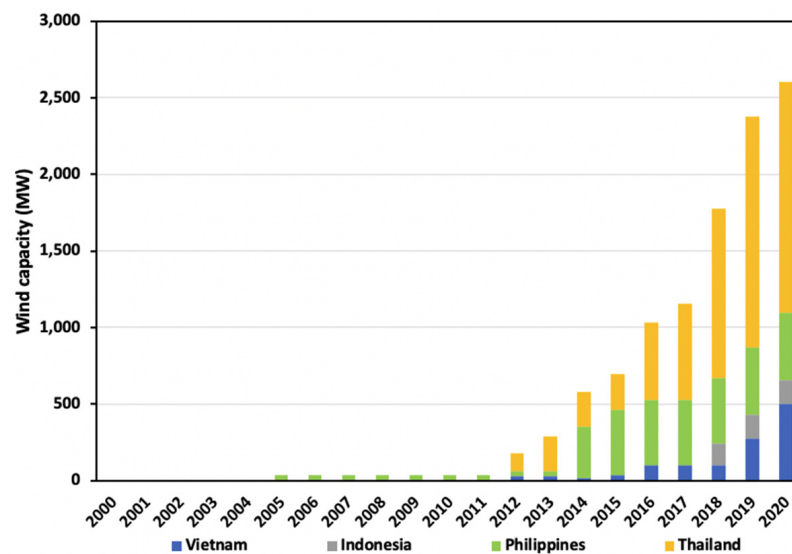


Figure 8. History of installed wind capacity in ASEAN [22].

3.1.6. Bioenergy

Figure 11 shows a map of bioenergy potential in the world, as measured by endocarp yield [27]. Endocarp is a high-lignin feedstock, which is a waste stream from food crops. It is nonedible, not used for livestock feed, and not reintegrated into soil in agriculture. It has an optimal energy-to-weight yield and can be used in small-scale gasification to produce bioenergy. Therefore, it is a measure of potential for a second-generation biocrop [21]. Within ASEAN, Thailand, Indonesia, Malaysia and the Philippines have the highest bioenergy potential. Figure 12 shows the history of bioenergy capacity in ASEAN. As of 2020, the total installed bioenergy capacity in ASEAN was 8.35 GW, with Thailand, Indonesia, and Malaysia contributing to 53%, 23%, and 11%, respectively. Within ASEAN, bioenergy has the third-largest installation capacity among renewable energies.

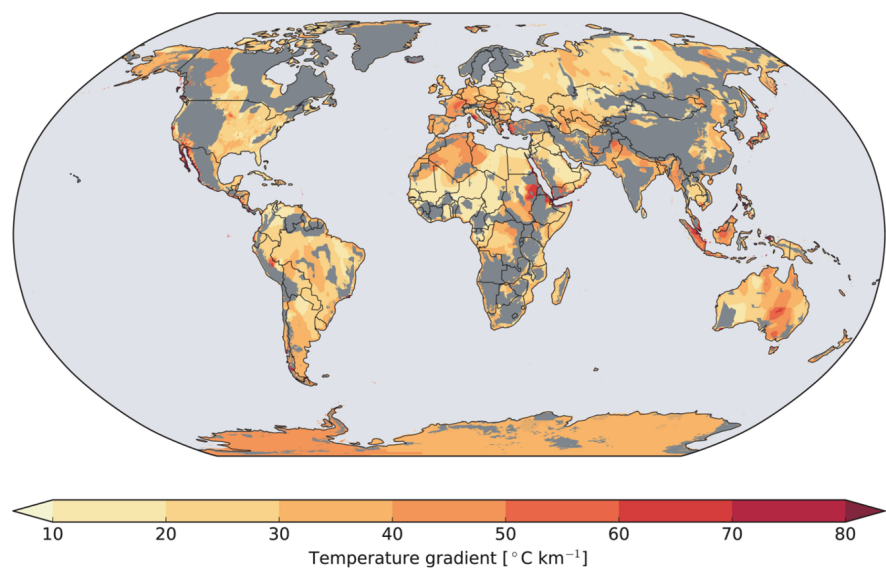


Figure 9. Computed geothermal gradients in aquifers [25].

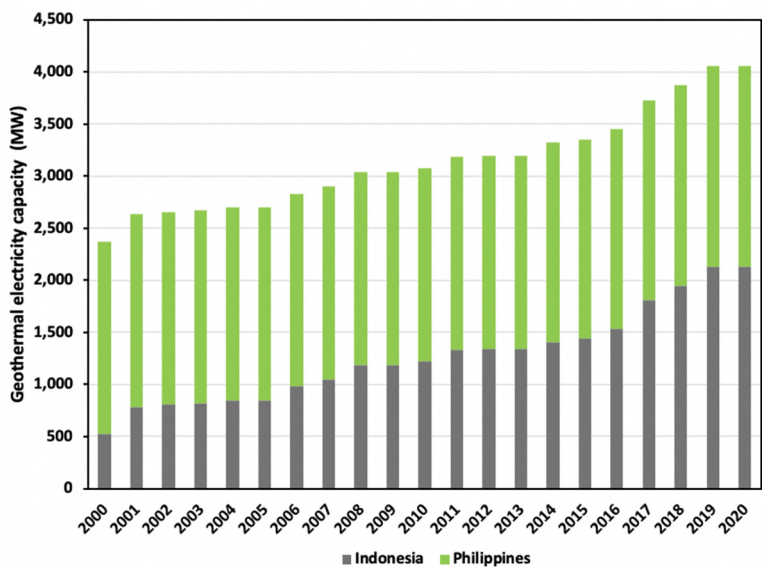


Figure 10. History of installed geothermal capacity in ASEAN [22].

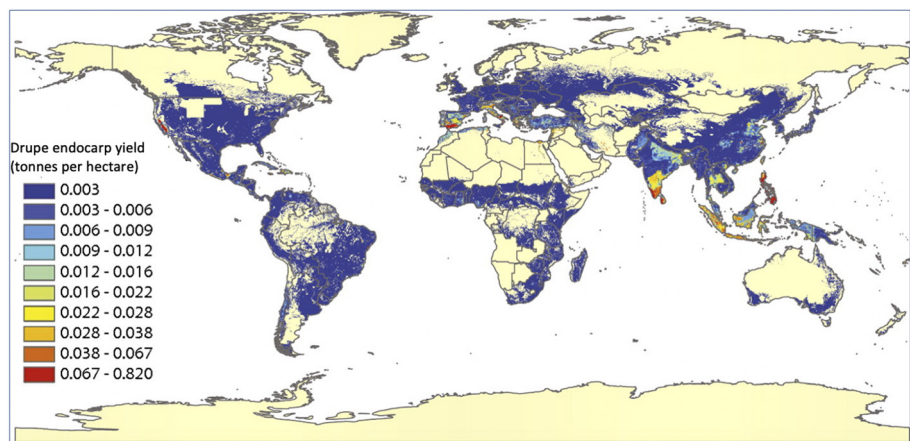


Figure 11. Bioenergy potential in the world [27].

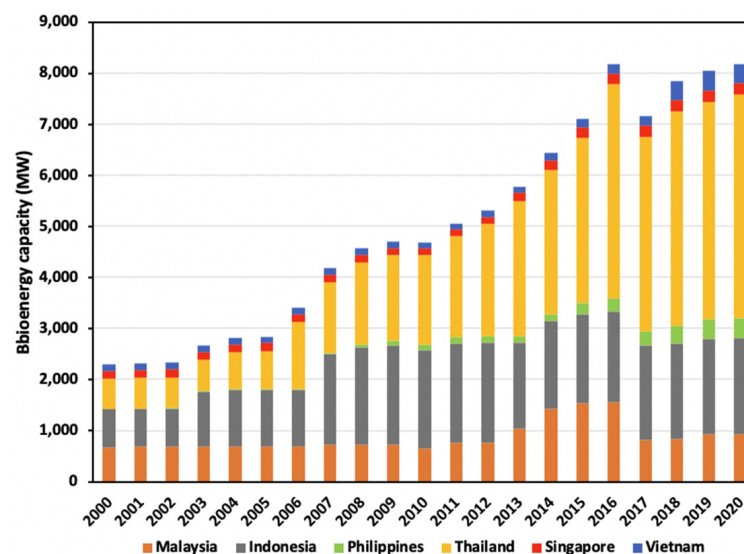


Figure 12. History of installed bioenergy capacity in ASEAN [22].

3.1.7. Sustainability Issues with Bioenergy

Most of ASEAN's bioenergy comes from first-generation biocrops such as palm oil, sugarcane, coconut, and cassava. This creates substantial sustainability issues such as competition for land and water resources, food scarcity, loss of biodiversity, deforestation, destruction of peatland, greenhouse gas emission, soil erosion, rural development, social conflicts, and public health, among others [28]. Unless these issues are managed and minimized, the future of bioenergy in ASEAN is called into question.

The two major biofuels produced in ASEAN are biodiesel and bioethanol. Indonesia's biofuel industry mostly produces biodiesel made from palm oil. It is the world's largest palm oil producer and its second largest exporter [29]. Similarly, Malaysia's major biofuel product is biodiesel made from palm oil. Thailand produces both biodiesel from palm oil and bioethanol from sugarcane and cassava. Philippines produces biodiesel from coconut oil and bioethanol from sugarcane.

The three bioenergy powerhouses of ASEAN, namely, Thailand, Malaysia, and Indonesia, produce 59% (44.5 Mt), 25% (18.7 Mt), and 4% (3.1 Mt), respectively, of the world's palm oil in 2021 [30]. Indonesia, Malaysia and Thailand export 66% (29.5 Mt), 87% (16.2 Mt), and 18% (0.55 Mt), respectively, of their palm oil, mostly to India, China, and the EU. Palm oil is a first-generation biocrop because it is a food crop [21]. It can be converted to biodiesel by transesterification. The use of palm oil as a biofuel has driven up the cost of palm oil for food. Furthermore, the practice of clearing tropical rainforest in Southeast Asia for palm oil plantation has caused the EU to introduce regulations to ban the importation of palm oil for biofuel production [31]. Germany has announced that it will end use of palm oil as a biofuel, beginning in 2023 [32]. At present, palm oil production for biofuel is a controversial topic due to sustainability issues [33–37].

In Indonesia and Malaysia, the key sustainability issues include deforestation, degradation of peatland, increased emission of greenhouse gas, reduction in biodiversity and the rights of local communities [38]. In Thailand, biocrop production has an adverse impact on food security, farming practice, land use and the marginalization of small farmers [39]. In the Philippines, biocrops include rice, corn, coconut, sugarcane, and palm oil [40]. Key sustainability issues include loss of soil fertility when biomass is removed from the soil, competition for water resources, soil erosion, loss of biodiversity, and food scarcity. To alleviate these problems, the government of Philippines is interested in promoting third-generation biocrops such as algae and seaweeds. However, they are still in the early stage of research and development.

3.2. Status of Fossil and Nuclear Energies in ASEAN

In this section, we will analyze the role of coal, oil, natural gas, and nuclear energy in the energy landscape of ASEAN.

3.2.1. Coal

Table 3 provides the coal consumption and production data for ASEAN countries in 2019 [41]. Within ASEAN, Indonesia is the biggest consumer and exporter of coal. All other countries, except Laos and Brunei, have to import coal.

Table 3. Coal data for ASEAN countries in 2019 [41].

Country	Export (10 ³ Short Ton)	Import (10 ³ Short Ton)	Production (10 ³ Short Ton)	Consumption (10 ³ Short Ton)	Net Import (10 ³ Short Ton)
Indonesia	506,111	7462	679,199	152,580	−498,649
Vietnam	1260	45,718	50,361	74,810	44,458
Malaysia	101	37,959	3812	42,860	37,858
Philippines	12,164	29,306	12,356	35,772	17,142
Thailand	71	23,881	15,518	34,047	23,810
Laos	634	17	22,527	20,578	−517
Myanmar	2	322	1572	1893	320
Cambodia	0	5612	0	1864	5612
Singapore	0	811	0	811	811
Brunei	0	0	0	0	0

Figure 13 shows the history of installed coal power capacity in ASEAN [22]. There has been a sharp increase in coal-fired power plants in ASEAN in the last decade, with Indonesia and Vietnam having the largest additions. Both countries are self-sufficient in coal.

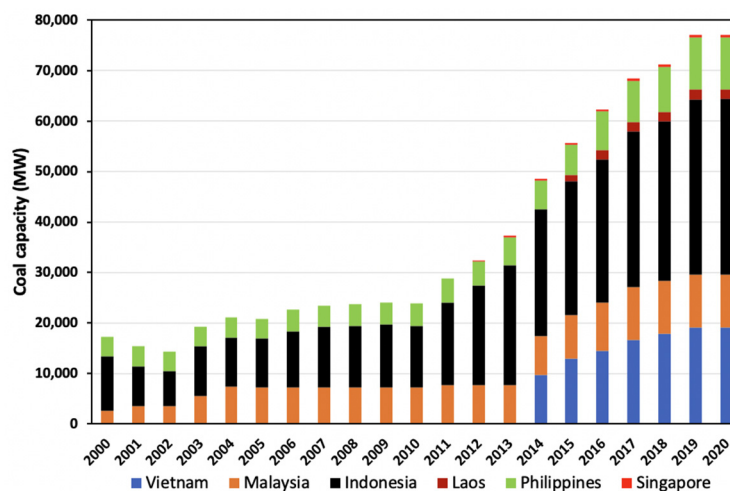


Figure 13. History of installed coal-power capacity in ASEAN [22].

3.2.2. Sustainability Issues with Coal

Among fossil fuels, coal emits the most CO₂ when combusted. The amount of CO₂ produced depends on the coal rank. On average, complete combustion of one short ton (2000 lbs) of bituminous coal containing 66% carbon will generate 2.42 short tons of CO₂. Per million Btu of energy produced, bituminous coal produces 206 lb of CO₂, whereas diesel and natural gas generate 161 lb and 117 lb of CO₂, respectively [42]. Anthracite coal with 92–98% carbon content emits 229 lb of CO₂ per million BTU. Therefore, replacing coal with natural gas as a fuel for power generation or heating will reduce CO₂ emission by from 40 to 50%. Indonesia, Malaysia, Malaysia and the Philippines are heavily dependent on coal for power generation. Switching from coal to natural gas for power generation will

be a low-hanging fruit for these countries if a long-term natural gas contract can be secured at an affordable cost.

3.2.3. Natural Gas

Figure 14 shows the history of installed gas capacity in ASEAN [22]. Brunei, Singapore, and Malaysia have the most installed gas capacity. However, the total gas capacity in ASEAN has grown only slightly in the last five years, and at a much slower rate than that of coal (Figure 13).

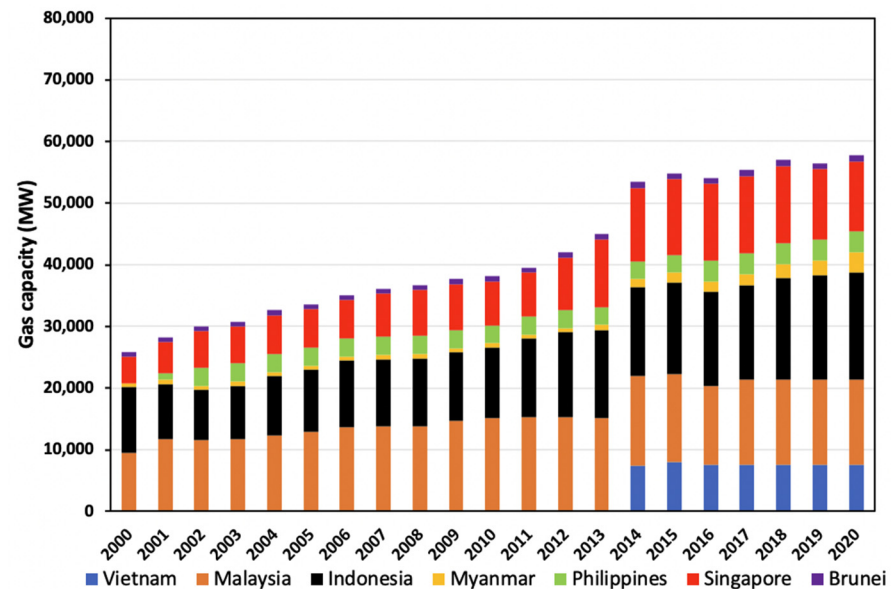


Figure 14. History of installed gas power capacity in ASEAN [22].

3.2.4. Oil

Figure 15 shows the history of electricity capacity for oil in ASEAN. In general, power generation by oil is much lower than that generated by coal or gas in ASEAN (Figures 13 and 14), and overall oil capacity has been relatively constant in recent years.

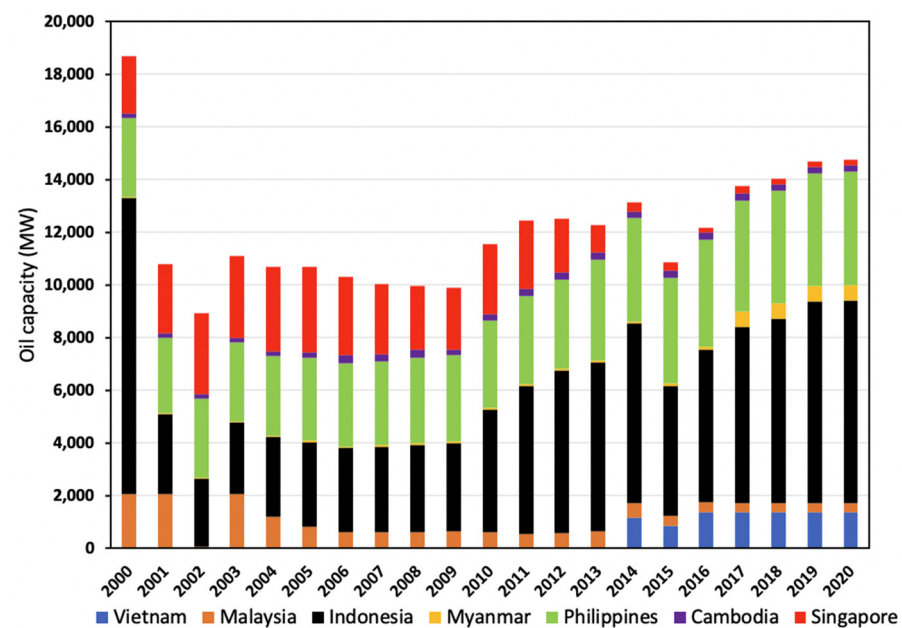


Figure 15. History of installed oil-power capacity in ASEAN [22].

3.2.5. Nuclear Energy

At present, there are no nuclear power plants in ASEAN. However, in recent decades, ASEAN governments have expressed interest in harnessing nuclear power, although their efforts have been sporadic and not underpinned by action plans. Among them, Indonesia, Malaysia, Vietnam, and the Philippines are the more likely to install nuclear power plants by 2030–2035, given their overall readiness [43]. However, public acceptance of nuclear power in ASEAN is low, except in Indonesia. ASEAN countries are densely populated, and it is difficult to construct a nuclear power plant that is far from a population center. This will magnify the health, safety and environmental impact should an accident occur. Unless public acceptance of nuclear power improves, the future of nuclear energy in ASEAN is likely to be limited.

4. Can Renewable Energies Replace Fossil Energies in ASEAN?

In ASEAN, renewable energies are mostly used for power generation. Consequently, we analyze how successful they have been in the last two decades in replacing fossil energies in power generation. This analysis will determine how likely they are to fully or partially replace fossil energy in power generation from 2030 to 2050.

4.1. Status of Electricity Capacity and Generation in ASEAN

Figures 16 and 17 show the history of installed electricity capacity and electricity generation in ASEAN, respectively [22]. In Laos and Cambodia, hydropower dominates all other forms of electricity capacity (Figure 16). For the rest of ASEAN, fossil power dominates all other forms of electricity capacity. In Vietnam, electricity generation by solar PV is relatively small, despite its significant capacity, due to its low utilization factor. Figure 18 shows the history of electricity generation by renewables versus fossil. Both fossil and renewable energies have grown since 2000. However, as of 2019, renewable electricity generation contributed to only 25% of total electricity generation in ASEAN. Over the last two decades, renewables' contribution to power generation has grown from 20% to 25%, with most of the increase occurring after 2015.

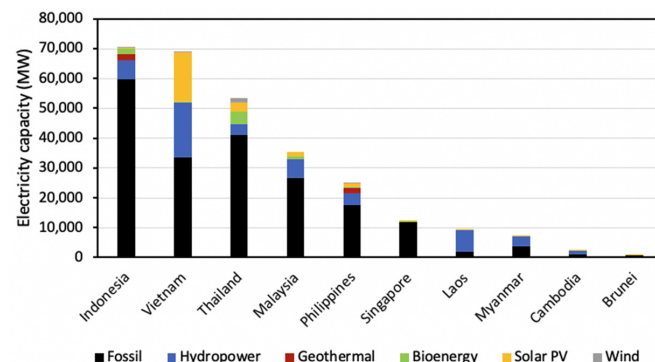


Figure 16. ASEAN electricity capacity by type in 2019 [22].

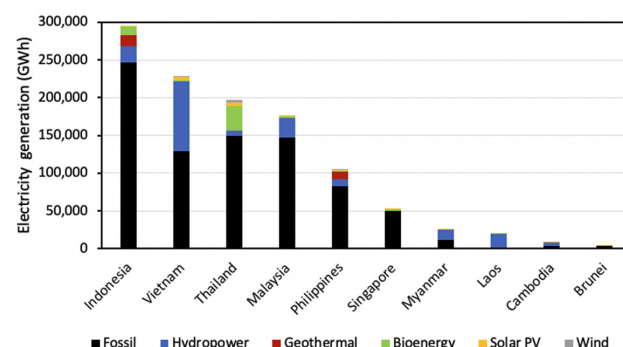


Figure 17. ASEAN electricity generation by type in 2019 [22].

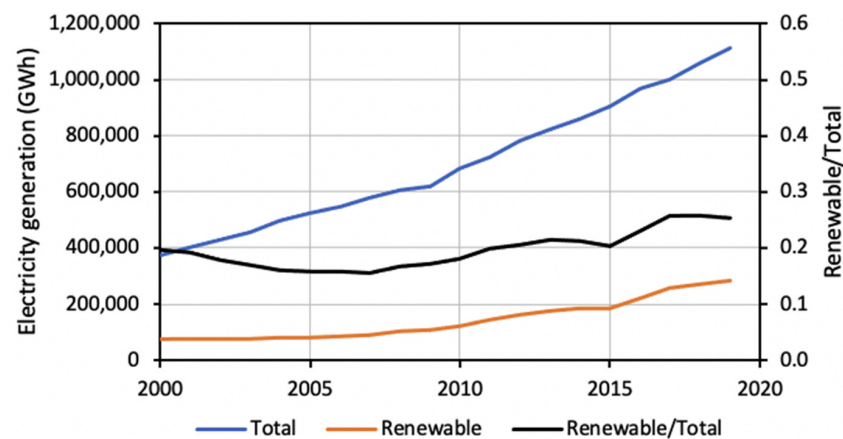


Figure 18. History of fossil and renewability electricity generation in ASEAN [22].

4.2. Status of Energy Consumption in ASEAN

Figure 19 shows the history of renewable energy consumption as a percent of total final energy consumption (TFEC) [44]. TFEC includes contributions from all energy-consumption sectors. All ASEAN countries, except Thailand and Malaysia, show a decreasing trend. For ASEAN overall, the ratio of renewable to total energy consumed dropped from 38.5% in 2000 to 30.3% in 2015. This decreasing trend is concerning, as it reveals that renewable energy has not gained ground over fossil energy in the last two decades. If this decreasing trend continues, ASEAN countries will not be able to achieve net-zero CO₂ emission by 2050 or soon afterwards. It also reveals that the historical rate of the addition of renewable energies is not fast enough to allow ASEAN to reach peak CO₂ emissions by 2030 and begin reducing afterwards.

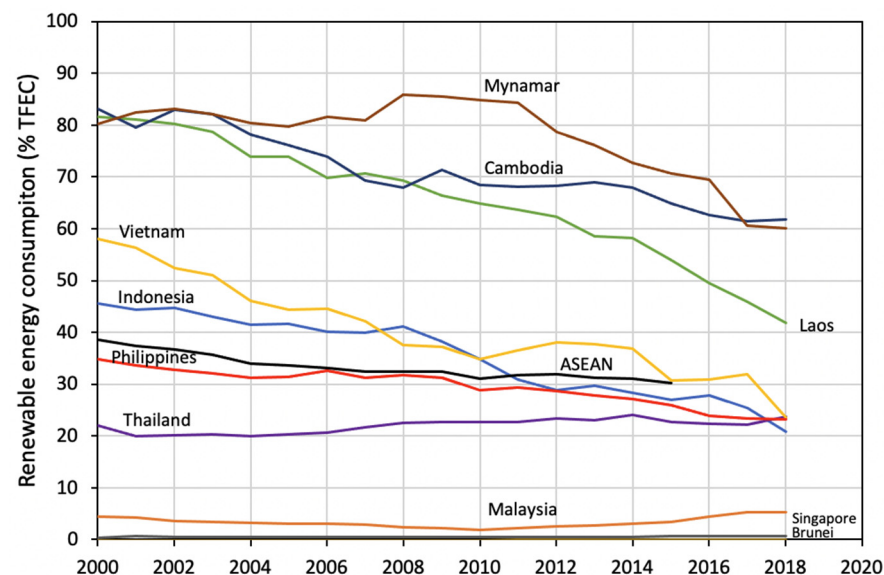


Figure 19. History of renewable energy consumption as percent of TFEC in ASEAN [44].

Figure 20 shows the total primary energy supply (TPES) in ASEAN in 2018 [22]. In 2018, renewable energies, coal, oil, and gas contributed to 20%, 25%, 35% and 20% of TPES, respectively. Oil was the dominant form of energy in TPES, followed by coal. Figure 21 shows energy-related CO₂ emissions in ASEAN in 2019 [22]. In 2019, ASEAN emitted 1.759 Gt of energy-related CO₂, of which 38% came from the power sector, 24% from the transport sector and 23% from the industry sector. The building sector contributed to only 5% of CO₂ emissions. Consequently, decarbonizing the power, transport and industry sectors should be the top priority of ASEAN's energy transition.

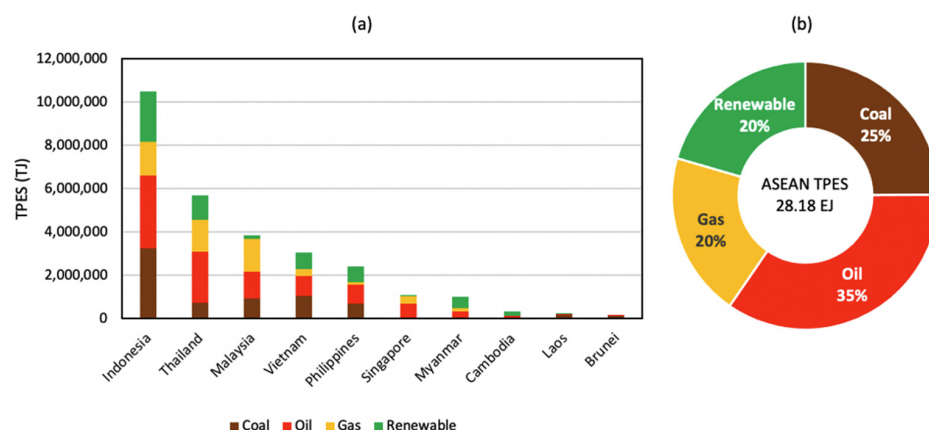


Figure 20. ASEAN TPES in 2018 by (a) country, and (b) energy type [22].

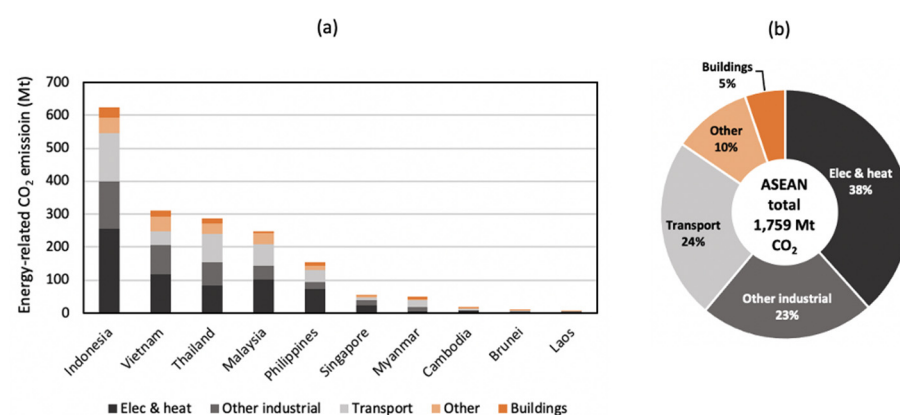


Figure 21. ASEAN energy-related CO₂ emission in 2019 by (a) country, and (b) sector [22].

Three observations from our analyses are revealing. First, the contribution of renewable energies to total power generation in ASEAN was stagnant between 2000 and 2015, and has only increased since then (Figure 18). In the last two decades, it has only grown from 20% in 2000 to 25% in 2019. Second, and more importantly, the contribution of renewable energies to TFEC has decreased in the last two decades (Figure 19), dropping from 38.5% in 2000 to 30.3% in 2015. The second observation reveals that, overall, renewable energies have been losing ground to fossil energies, despite two decades of capacity additions. Third, there are substantial sustainability issues with both hydropower and bioenergy in ASEAN, such as over-damming of the Mekong River and the clearing of rainforest in Borneo. These issues need to be dealt with before the capacity of hydropower and bioenergy can be significantly increased. These observations lead us to the assessment that it is unlikely that renewable energies will replace fossil energies within the 2030–2050 timeframe. The likely scenario is that fossil energies will remain an important part of the energy mix in the period leading up to 2050. Therefore, in addition to increasing renewable power capacity, ASEAN countries need to invest in technologies to reduce CO₂ emission from the three energy-consumption sectors that will continue to consume fossil fuels between now and 2050. This will be discussed in the next section.

5. Decarbonization of Major Energy-Consumption Sectors

The aforementioned discussion has shown that, as of 2018–2019, renewable electricity generation was only 25% of total electricity generation (Figure 19) and renewable energy contributed only to 20% of TPES (Figure 20). Furthermore, renewable energies' contribution to TFEC has lost ground to fossil energy in the last two decades. These trends reveal that, although renewable electricity generation has gained ground over fossil electricity generation over the last two decades (Figure 18), renewable energies usage in all sectors has

actually lost ground to fossil energies (Figure 19). This observation is significant. It reveals that the addition of renewable electricity capacity in the power sector was inadequate to compensate for the increased use of fossil energies in the transport and industry sectors. As energy consumption in all three sectors grew in the last two decades due to increased economic activities, the growth of fossil energy usage in the transport and industry sectors has more than offset the increased contribution of renewable energies in the power sector. Consequently, the decarbonization of ASEAN must address the decarbonization of the transport and industry sectors. Just increasing renewable electricity capacity in the power sector is inadequate to decarbonize ASEAN. ASEAN nations must start to address the decarbonization of the transport and industry sectors now if they are to achieve net-zero by the middle of the century or soon afterwards.

5.1. Decarbonizing the Power Sector

Our analysis has shown that decarbonization of the power sector requires more than the addition of renewable capacity for at least two reasons. First, both hydropower and bioenergy have substantial sustainability issues. It is doubtful that the planned new additions will materialize. Second, even with new additions of renewable capacity, fossil electricity will likely be the dominant form of electricity until 2050, and possibly beyond. Consequently, ASEAN countries need to consider decarbonizing fossil power generation by CCS technologies. There are at least two ways to do this. First, one can use CCS to capture, transport and store the CO₂ that is emitted from existing fossil power plants. Post-combustion carbon capture can be retrofitted into existing fossil power plants or incorporated into new-built fossil power plants. Second is the replacement of coal by natural gas for power generation. The repurposing of existing coal-fired power plants to natural gas-fired power plants should be considered. According to the U.S. Energy Information Administration (EIA), more than 100 coal-fired power plants in US have been replaced or converted to natural gas-fired power plants since 2011 [45]. Two different methods can be used to switch coal-fired power plants to natural gas-fired power plants. The first method is to retire the coal-fired plant and replace it with a new natural gas-fired combined cycle (NGCC) plant. The second method is to convert the boiler of a coal-fired power plant to burn natural gas. The best overall strategy is to repurpose existing coal-fired power plants into natural gas-fired power plants, stopping the building of new coal-fired power plant, and incorporating CCS into existing, repurposed and new gas-fired power plants. CCS, therefore, is the key technology to decarbonize current and new-built fossil power plants. At present, it is the only technology capable of removing CO₂ from a plant on the scale of a million tonnes per year [46].

5.2. Decarbonizing the Transport Sector

The transport sector was responsible for 24% of energy-related CO₂ emissions in ASEAN in 2019 (Figure 21b). It consists of road, rail, ship and aviation transport. In ASEAN, rail transport is only a minor form of transport. Road transport emits more CO₂ than other forms of transport. At present, the chief means of decarbonizing road transport is to replace internal combustion engine (ICE) vehicles with electric vehicles (EVs). Within ASEAN, Thailand plans to sell only EVs, beginning in 2035 [47], with Singapore beginning in 2040 [48], and Indonesia in 2050 [49]. However, replacing ICE vehicles with EVs only replaces mobile CO₂ emissions with stationary CO₂ emissions at the power plants, which has to be mitigated by either using renewable electricity or CCS for fossil fuel plants. Another way to decarbonize the transport sector is to replace ICE vehicles with hydrogen fuel cell vehicles (HFCV). HFCVs are more efficient than EVs for long-distance transport and for carrying goods [50]. However, in ASEAN, the infrastructure for HFCV is even less available than that for EVs. Therefore, the use of HFCVs will likely take place in the distant future.

For marine transport, a high-readiness technology is the use of hydrogen for fuel. Prototypes of hydrogen-power ships have been built in Japan, USA and Norway. An

alternative is to power ships with ammonia, which is a more easily transported hydrogen carrier than hydrogen. At present, there is not a large enough supply of industrial hydrogen in ASEAN for use in transport sector.

For aviation, a high-readiness technology is the use of biofuels for fuel. In the US, United Airlines flew its first 100% biofuel-powered passenger flight in December 2021 [51]. Boeing has already announced it will produce 100% biofuel planes by 2030 [52]. Within ASEAN, Singapore has the biggest biorefinery, producing 1.3 Mtpa aviation biofuels [53]. Thailand, Indonesia and Malaysia are major producers of bioenergy, while Singapore is a major center for biorefining. As Southeast Asia is well-connected to the rest of the world by aviation, using biofuels for aviation is a suitable way to decarbonize the aviation industry. However, an increase in biorefinery capacity will be needed.

5.3. Decarbonizing the Industry Sector

Among the various energy-consumption sectors, the industry sector is the most difficult to decarbonize. This sector consists of heavy industries, such as chemical and petrochemical, iron and steel, cement and fertilizer production. In these industrial plants, fossil fuels are used for high-temperature (exceeding 1000 °C) heating and sometimes as feedstock.

There are several ways to decarbonize this sector. The first is to electrify high-temperature heating. However, this is impractical because the current cost of electricity is several times that of heating in most countries [54]. The electrification of high-temperature heating may be a long-term solution, but more research and development are needed [55].

The second is to install CCS technology to mitigate the CO₂ that is emitted from industrial plants. This method is technologically feasible. However, it will increase the cost of the products and may decrease its commercial competitiveness.

The third method is to replace fossil fuels with hydrogen for high-temperature heating. In this case, fossil fuel boilers have to be replaced by, or converted to, boilers that consume hydrogen. As an energy carrier, hydrogen does not produce any CO₂ at the point of consumption. If this option is taken, blue hydrogen, produced from coal or natural gas with CCS to mitigate the produced CO₂, will be preferred, as it is about half as costly as the green hydrogen produced by the electrolysis of water with renewable electricity [56].

Replacing fossil fuels with blue hydrogen will probably be the best long-term solution [46]. Within ASEAN, there is currently no production of either blue or green hydrogen. However, a blue hydrogen industry in Indonesia, which has plenty of coal resources, could be attractive if an ASEAN market for hydrogen is established.

5.4. Role of CCS in Decarbonization of ASEAN

Since fossil fuels will continue to be part of the energy mix of ASEAN in the medium future, it is only reasonable to consider technologies that can mitigate CO₂ emissions from the burning of fossil fuels. In fact, it is generally agreed that, without carbon capture, utilization and storage (CCUS) technologies, decarbonization will be more costly and complicated [57]. In a recent report, the International Energy Agency (IEA) concluded that net-zero cannot be achieved without CCUS technologies [58]. Carbon capture technologies generally include pre-combustion, post-combustion, and oxy-fuel combustion [46]. Among these, post-combustion is the most technologically ready. There are many carbon utilization technologies, such as converting CO₂ into chemicals or using it in the production of other products, such as building materials. However, these processes are energy-intensive and often require the use of catalysts. Furthermore, they are not ready for large-scale implementation [59]. At present, carbon capture and storage (CCS) is the only technically ready for the large-scale (million tonnes per year) mitigation of CO₂ [59]. In CCS, the CO₂ captured from plants is compressed and shipped by pipelines or ships to a suitable site for storage in a subsurface reservoir, such as an oil reservoir, gas reservoir, or a saline aquifer [46]. When CO₂ is injected into a partially depleted oil or gas reservoir, it may lead to increased oil or condensate recovery. In the literature, these processes are known as

CO₂-enhanced oil recovery (EOR) or enhanced gas recovery (EGR). Some authors classify CO₂-EOR and CO₂-EGR as carbon utilization, since CO₂ is used to produce incremental oil or gas [59]. In this paper, CO₂-EOR and CO₂-EGR are classified as CCS technologies, as the injected CO₂ can be designed to be stored permanently in the reservoir.

5.4.1. CO₂ Storage Capacity in ASEAN's Sedimentary Basins

All three types of CO₂ storage space (oil reservoir, gas reservoir, saline aquifer) reside within a sedimentary basin. Research has shown that, in general, about 98% of CO₂ storage capacity comes from saline aquifers and only 2% from oil and gas reservoirs [3,46,60].

Figure 22 shows a map of major sedimentary basins in ASEAN. There is no lack of sedimentary basins in which CCS can be applied, especially along the coastal regions of Vietnam, Thailand, Malaysia, Indonesia, and the Philippines. Furthermore, these basins have been extensively explored for oil and gas. Many oil and gas fields have been under production for decades.

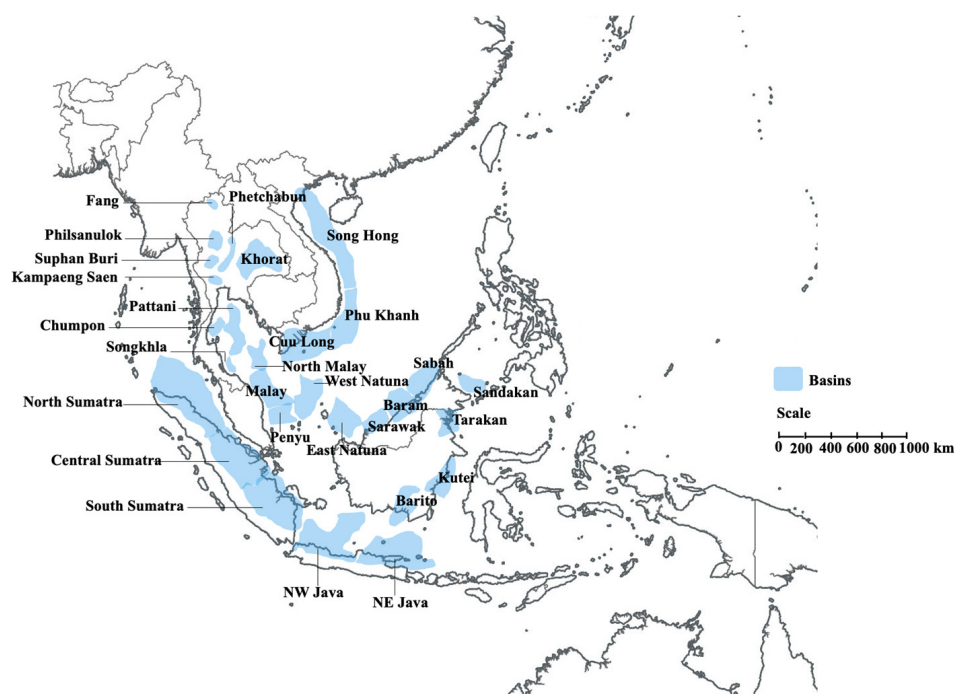


Figure 22. Major sedimentary basins in ASEAN.

Table 4 gives the authors' estimate of the CO₂ storage capacity in selected sedimentary basins in Indonesia, Malaysia, and Thailand, based on published research. In these basins alone, there is a mid-CO₂ storage capacity of 465 Gt. A total of 98% of this capacity resides in saline aquifers, 2% in gas fields, and less than 1% in oil fields. These basins can store 282 years of CO₂ emission from all ASEAN countries (1.65 Gtpa in 2020).

5.4.2. First-Mover CCS Projects across ASEAN

Table 5 shows the six first mover CCS projects proposed by the authors, based on the results of CO₂ source-sink exercises [3,7–9,61]. These projects involve Singapore, Indonesia, Malaysia, and Thailand. Each CO₂ source in each project emits 10 Mtpa or higher. However, not all of this is captured. All in-country CO₂ source-sink distances are 250 km or less, over which CO₂ can be transported by pipelines. The first three projects involve a cross-border shipment of CO₂ from Singapore to Indonesia or Malaysia over a distance between 250 and 890 km, either by pipelines or by ships. The last three projects are in-country projects in Thailand. If all these projects are implemented, they have the potential to capture and store up to 300 Mtpa CO₂ from these four countries.

Table 4. CO₂ storage capacity in selected sedimentary basins in ASEAN.

Country	Basin	Gas Fields (Mt)			Oil Fields (Mt)			Saline Aquifers (Mt)			Reference
		Low	Mid	High	Low	Mid	High	Low	Mid	High	
Indonesia	Central Sumatra	68	73	77	146	156	167	2813	11,032	30,338	[9]
	South Sumatra	599	639	678	44	47	51	6873	26,954	74,123	[9]
	West Sumatra	67	71	76	22	23	24	9755	38,255	105,202	[9]
	North Sumatra	1694	1780	1866	7	7	8	28,557	111,900	307,973	[9,61]
	NW Java	138	147	156	53	58	62	7100	27,842	76,564	[9]
	East Natuna	2171	2316	2461	0	0	0	15,286	59,944	164,846	[9]
	Subtotal	4737	5026	5314	271	291	313	70,384	275,927	759,046	
Malaysia	Malay	1381	1448	1538	158	174	191	19,315	75,746	208,301	[9]
	Pengyu	0	0	0	8	8	9	7058	27,678	76,114	[9]
	Subtotal	1381	1448	1538	165	182	200	26,373	103,424	284,415	
Thailand	Khorat	93	104	115	0	0	0	16,008	62,775	172,631	[3]
	Pattani	784	868	953	23	25	27	1285	5040	13,860	[3]
	Malay	691	743	796	0	0	0	874	3426	9420	[3]
	Fang	0	0	0	2	2	2	69	271	746	[3]
	Kamphaeng Saen	0	0	0	1	1	1	42	164	451	[3]
	Phetchbun	0	0	0	0	0	0	83	324	891	[3]
	Philsanulok	0	0	0	15	16	17	341	1337	3675	[3]
	Suphan Buri	0	0	0	0	0	0	100	393	1080	[3]
	Chumpon	0	0	0	2	2	3	751	2945	8099	[3]
	Songkhla	0	0	0	2	2	3	231	907	2495	[3]
Subtotal		1567	1715	1864	45	49	53	19,784	77,582	213,348	
Total		7685	8189	8716	481	522	565	116,541	456,933	1,256,809	

Table 5. Proposed first-mover CCS projects in ASEAN.

CO ₂ Sink			CO ₂ Source			CO ₂ Transport		Reference	
Country	Field & Basin	CO ₂ Storage Capacity (Mt)	Type of CO ₂ Source	Location	Country	CO ₂ Emission (Mtpa)	CO ₂ Transport		Source-Sink Distance (km)
Indonesia	Arun gas field, North Sumatra (onshore)	1230	Power chemical, refinery	Jurong Island	Singapore	32	Ship	890	[7–9,61]
			Power, cement, refinery	North Sumatra	Indonesia	10	Pipeline	250	[7–9,61]
Indonesia	Minas oil field, Central Sumatra (onshore)	113	Power, chemical, refinery	Jurong Island	Singapore	32	Pipeline	200	[7–9]
			Power, cement, refinery	Central Sumatra	Indonesia	19	Pipeline	250	[7–9]
Malaysia	Dulang, Tapis, Seligi oil fields, Malay Basin (offshore)	106	Power, cement, chemical, refinery	Jurong Island	Singapore	32	Ship or pipeline	440	[9]
			Cement, iron & steel, power, refinery	Peninsular Malaysia	Malaysia	137	Pipeline	250	[9]
Thailand	Saline aquifers in Phitsanulok, Supan Buri, Phetchabun basins (onshore)	2053	Cement in Saraburi, power in Kamphaeng Phet	Saraburi	Thailand	41	Pipeline	20 to 200	[3]
Thailand	Saline aquifers in Khorat Basin (onshore)	62,775	Petrochemical, iron & steel, refinery, power	Bangkok & Rayong	Thailand	77	Pipeline	100 to 200	[3]
Thailand	Saline aquifers in Chumpon Basin (offshore)	2945	Gas processing, cement, power	Nakhon Si, Nakhon Sri Thammart, Surat Thai, Krabi, Phuket	Thailand	10	Pipeline	50 to 200	[3]

Among all the CCS projects shown in Table 5, the Arun gas condensate field is the largest onshore gas field, with an in-place volume of 17 Tcf gas and 840 million bbl of condensate [62]. Minas is the largest oil field in ASEAN, with an OOIP of 9 billion bbl of 36°API light crude [63,64]. They are both in the mature stage and ready for CCS. The Arun gas condensate field and Minas oil field are the most promising candidates to perform a large-scale CCS project in ASEAN. Detailed reservoir simulations and a site-specific economic evaluation are needed for field development planning.

5.5. Sustainability Rating of Decarbonizing Technologies

In this section, a sustainability rating for various decarbonization technologies is proposed. Table 6 rates the various decarbonization technologies with respect to five categories: (1) CO₂ emission, (2) material footprint, (3) impact on people, (4) impact on animals, and (5) impact on environment. This is only a qualitative rating. However, technologies rated as having a high impact on any one of these five attributes are currently not sustainable and would need further mitigation measures before they should be applied at scale. However, no technology is completely without sustainability issues. Before their application to individual ASEAN countries, a technology mapping exercise should be conducted to determine the readiness and impact of each technology [7,8].

Table 6. Sustainability rating for decarbonization technologies.

Sector	Technology	Description	Sustainability Rating				
			CO ₂ Emission	Material Footprint	Impact on People	Impact on Animals	Impact on Environment *
All	Grey H ₂	H ₂ from fossil fuels	High	Moderate	High	High	high
	CCU	Convert CO ₂ to products	Low	Moderate	Low	Low	Low
	Green H ₂	H ₂ from renewable electricity	Low	Moderate	Low	Low	Low
Power & industry	CCS corridor	CCS with economies of scale	Low	Moderate	Low	Low	Low
Power	Nuclear	Nuclear power plant	Low	High	High	High	High
	Hydropower	Hydroelectricity	Low	High	High	High	High
	Bioenergy	Bioenergy power plant	Low	Moderate	High	High	High
	Wind	Wind turbines	Low	Low	Low	Moderate	Low
	Geothermal	Geothermal power plant	Low	Moderate	Low	Low	Low
	Solar	Solar PV, CSP	Low	Moderate	Low	Low	Moderate
	Coal→gas	Replace coal by gas	Moderate	Low	Low	Low	Moderate
	CP-CCS	Coal-fired power plant with CCS	Low	Moderate	Low	Low	Low
	GP-CCS	Gas-fired power plant with CCS	Low	Moderate	Low	Low	Low
	Bio-aviation	Biofuel for aviation	Low	Moderate	High	High	High
Transport	HFCV	Hydrogen fuel cell vehicles	Low	Moderate	Low	Low	Low
	EV	Electric vehicles	Low	Moderate	Low	Low	Low
	H ₂ -marine	H ₂ fuel for ship	Low	Moderate	Low	Low	Low
Industry	Coal→H ₂ -CCS	Blue H ₂ from coal with CCS	Moderate	Moderate	Low	Low	Low
	Gas→H ₂ -CCS	Blue H ₂ from gas with CCS	Moderate	Moderate	Low	Low	Low
	Ind-CCS	Use CCS for industry plants	Low	Moderate	Low	Low	Low

* Impact on environment other than CO₂ emission.

6. Decarbonization Pathways for ASEAN

Based on the aforementioned discussion, common decarbonization pathways for ASEAN countries are given as follows.

6.1. Increasing the Share of Sustainable Renewable Energies in Power Generation

There is a need to increase the share of renewable energies in electricity generation in all ASEAN countries, except Laos, where 97% of electricity comes from hydropower. However, the type of renewable electricity is country-specific.

The dominant form of renewable energy in Laos, Cambodia, Myanmar, and Vietnam is hydropower, which is mainly obtained from damming the Mekong River and its tributaries. Cambodia has already announced that all construction of dams along the Mekong River will be halted due to ecological concerns [65]. The same concerns are also present in Laos, Myanmar and Vietnam. Over-damming of the Mekong River may cause climate change such as floods and drought, loss of river sediment, fish population, agricultural land, and the re-settlement of riparian communities [66]. ASEAN faces a difficult dilemma in renewable energy. If the major planned hydropower projects are slowed down due to environmental concerns, it will be difficult for renewables' share in electricity generation

to substantially increase in the next decade. Solar PV will not be sufficient to fill the gap, mainly due to its low-capacity utilization. Bioenergy also has considerable sustainability issues, of which the chief is the clearing of rainforests, which are important carbon sinks. Geothermal energy is only applicable to the Philippines and Indonesia. Furthermore, there is no planned increase in geothermal power in these two countries. Wind energy is hampered by the lack of adequate wind speed in most ASEAN countries [67]. Indeed, large-scale increases in renewable electricity face substantial headwind in ASEAN.

6.2. Switching from Coal to Gas in Power Generation

Switching from coal to gas for electricity generation is a low-hanging fruit for ASEAN countries, except Singapore, Myanmar and Brunei, where coal plays a minor or no role in electricity generation. This switch will potentially reduce CO₂ emissions by roughly one-half. The levelized cost of electricity (LCOE) of a natural gas combined cycle power plant is similar to or lower than that of a pulverized coal power plant [68]. However, importing natural gas requires the construction of expensive LNG terminals and negotiation of long-term gas contracts. Within ASEAN, LNG terminals only exist in Malaysia, Indonesia, Singapore and Brunei. However, for countries which produce a significant amount of natural gas, such as Indonesia, Malaysia, and the Philippines, this option should be a priority.

6.3. Electricification of Road Transport

Targets to phase out or reduce the use of ICE vehicles have been announced in Indonesia, Thailand and Singapore [69]. Malaysia has plans to increase the number of EV charging stations to 1000 by 2025 [70]. However, ASEAN lags behind other regions of the world, e.g., China, EU and North America, in incentivizing its citizens to adopt EVs. It should be noted, however, that using EVs to replace ICE vehicles only moves CO₂ emission from vehicles to power stations, which also need to be decarbonized, either by using renewable energies or CCS for fossil power plants. However, the large-scale push for EVs is the best chance to decarbonize road transport in ASEAN. The use of biofuels such as biodiesel and bioethanol for road transport should also be encouraged, with due regard to sustainability.

Other ways to decarbonize the transport sector include using hydrogen as fuel for ships and biofuels for aviation. However, these are of secondary priority compared to decarbonizing road transport, which is the major source of CO₂ emissions in the transport sector.

6.4. Hydrogen Fuel for Marine Transport

Replacing petroleum-based marine fuel by low-carbon hydrogen is a technically feasible and will go a long way toward decarbonizing the marine industry. Since green hydrogen will likely not be ready in large quantities for the foreseeable future, use of blue hydrogen for marine fuel will be a practical solution. This pathway, however, requires the building of a blue hydrogen industry within ASEAN.

6.5. Biofuels for Aviation

Replacing petroleum-based aviation fuels with biofuels is also technically feasible, as discussed earlier. This pathway, however, requires using sustainable methods to produce biofuels. Instead of palm oil, second-generation biocrops, which make use of the inedible part of plants, animal fats, food waste, and used cooking oil, will be more sustainable than clearing rainforests for palm oil plantations. This pathway requires an increase in biorefinery capacity in ASEAN.

6.6. Blue Hydrogen for Industry

At present, renewable energies are mostly used for electricity generation and are not available for use in the industry sector for high-temperature heating. Therefore, heavy

industries such as cement factories, iron and steel mills, and chemical plants use either coal or gas for high-temperature heating, resulting in substantial CO₂ emissions. To decarbonize these hard-to-decarbonize industries, hydrogen can be used to replace coal or gas. When hydrogen is combusted, it produces heat and water; no CO₂ is emitted. In addition, hydrogen may be used as raw material for these industries, thus reducing the need for petroleum.

Industrially, hydrogen can be produced from the electrolysis of water using renewable electricity. This is commonly called green hydrogen. However, this is the most expensive form of hydrogen, and it is not available in ASEAN as there is not enough renewable energy for electricity generation, let alone green hydrogen production. On the other hand, hydrogen can also be produced from fossil fuels, using either coal gasification or steam methane reforming (SMR). In either process, CO₂ is emitted. If this CO₂ is vented into the atmosphere, the resultant hydrogen is called brown or grey hydrogen. If the emitted CO₂ is captured and stored in the subsurface, it is called blue hydrogen [71].

From a decarbonization perspective, blue hydrogen is a good candidate to decarbonize the industry sector, as green hydrogen is currently unavailable or too expensive [56,71]. Both coal gasification and SMR are mature technologies and can be used at scale for blue hydrogen production in ASEAN.

For Indonesia, which exports a large amount of coal, converting coal to blue hydrogen and exporting the surplus after domestic consumption to Japan, Korea or other ASEAN countries can increase revenue. It should be noted, however, that CCS is an enabling technology for blue hydrogen production.

6.7. CCS Corridors

With the inadequacy of renewable energies to replace fossil fuels for electricity generation in ASEAN for the foreseeable future, fossil fuels power plants will continue to play a major role in electricity generation. Consequently, there is a need to decarbonize them using CCS. Post-combustion carbon capture is a relatively mature technology and can be implemented at scale in fossil fuel power plants [46]. In addition, post-combustion CCS can also be used in industry plants to decarbonize the industry sector.

In general, anthropogenic CO₂ can be stored in three types of subsurface reservoir: an oil reservoir, gas reservoir, or saline aquifers [46]. Generally speaking, about 98% of the subsurface storage capacity is found in saline aquifers, and 2% in oil and gas reservoirs. Our own research has shown that there is enough subsurface storage capacity in ASEAN to store more than two centuries of anthropogenic CO₂ emissions [46]. However, there is no commercial CCS project operating in ASEAN, although a couple of CO₂-EOR pilots are being planned in partially depleted oil fields [72–74].

Recently, we have proposed the use of large-scale CCS projects to decarbonize Singapore, Indonesia, Malaysia and Thailand [3,7,8,75]. To accelerate the implementation of CCS, we also propose establishing one or more CCS corridors in ASEAN, where CO₂ from more than one country can be shipped to a common sink for permanent storage. By making use of economies of scale, the cost of CO₂ capture, transportation and injection can be significantly reduced. These first-of-their-kind, cross-border CCS projects will mitigate CO₂ in the order of tens of million tons per year, which will be on par with the largest CCS projects being planned in Europe [75].

7. Policy Implications

It is the government's job to promulgate long-term energy policies that promote a low-carbon economy. Achieving net-zero is one the biggest engineering tasks faced by humanity. It will not come cheaply or without help from governments. It will involve the partnership of both the private and public sectors. In addition, ASEAN can achieve net-zero faster if there is intergovernmental cooperation. Some of the policy implications of this study are as follows.

7.1. Dealing with Sustainability Issues with Hydropower and Bioenergy

At present, there are substantial sustainability issues with both hydropower and bioenergy in ASEAN. The adverse ecological, environmental, and social impacts of over damming of the Mekong River need to be addressed through intergovernmental coordination among China, Myanmar, Laos, Thailand, Cambodia and Vietnam. In addition, the governments of Thailand, Indonesia and Malaysia need to address deforestation and related issues connected to palm oil plantations.

7.2. Establishing a Roadmap for Electric Vehicles

Replacing ICE vehicles by EVs is a key part of decarbonizing the transport sector. More ASEAN countries need to establish targets and incentives to phase out ICE vehicles. Concomitantly, an infrastructure for charging stations needs to be built.

7.3. Introducing a Credible Carbon Tax

Introducing a credible carbon tax is key to national and regional decarbonization. At present, Singapore is the only ASEAN country with a carbon tax. Indonesia will impose one on coal-fired power plants by April 2022 [76]. Malaysia plans to introduce a carbon tax between 2021 and 2025, but has yet to announce concrete plans [77]. A carbon tax is needed to incentivize companies to decarbonize their operations. Other incentives include a carbon credit and setting up a carbon-trading system within ASEAN.

7.4. Holding Public Engagement on CCS

As discussed, CCS is a must-have tool for decarbonization. However, more public engagements are needed to increase public awareness and acceptance of this technology. These engagements should be attended by trusted experts such as government officials, technology providers, and representatives of higher-learning institutes. In these engagements, the benefits and risks of CCS should be discussed. In addition, the potential economic benefits of new CCS industries and their employment opportunities should be presented.

7.5. Establishing Cross-Border CCS Corridors

Establishing cross-border CCS corridors within ASEAN can go a long way toward accelerating the implementation of large-scale CCS projects. However, intergovernmental coordination needs to be held to promote the passing of laws governing the cross-border movement of CO₂ and transfer of long-term liability of CCS from the operator to the state.

7.6. Setting a National Hydrogen Strategy

Hydrogen is an important part of the energy transition. The sooner a government sets its hydrogen strategy, the better it will be in the planning of long-term energy policies. To date, about thirty countries have hydrogen-specific strategies [78]. No ASEAN country has announced one to date. Within Asia, Japan [79], South Korea [80], India [81], Australia [82], and New Zealand [83] have announced their hydrogen strategies or visions. China is formulating one [84]. ASEAN countries need to make up their minds on hydrogen sooner than later.

7.7. Public-Private Partnerships to Promote Energy Transition

Decarbonizing involves complicated logistics and the transfer of technologies between companies, industries and countries. The implementation of large-scale energy transition projects, such as CCS, is best carried out by public-private partnerships (PPP). PPPs can be useful in project management, international financing, and technology transfer between local and foreign partners. A good example is the Longship CCS project of Norway, which is a joint partnership between the Norwegian government and several companies [85].

8. Discussions

Several findings from this study are new and differ from those of previous studies [3–12]. Previous studies were country-specific studies and did not provide a regional view of energy usage. This study, for the first time, analyzes the energy mix of all ten ASEAN countries, revealing that, in the last two decades, renewable energies have been losing ground to fossil energies in their contribution to the total final energy consumption. This trend is alarming and, unless it is reversed, net-zero in ASEAN cannot be achieved by 2050. Second, most previous studies [4–6,12] did not discuss the sustainability issues with renewable energies in ASEAN. This study has revealed key sustainable issues with hydropower and bioenergy, which are two key renewable energies in ASEAN. This study suggests that future research should address the over-damming of the Mekong and other major rivers for hydropower and the clearing of rainforests for first-generation biocrop plantation. Third, whereas previous studies investigated the importance of CCS in the power industry [4,5,10], this study has shown that CCS underpins the decarbonization of not only the power sector, but also the transport and industry sectors of ASEAN. The electrification of road transport will transfer mobile CO₂ emission to power plants, which will also need CCS for decarbonization if they burn fossil fuels. CCS will also need to produce blue hydrogen to decarbonize hard-to-decarbonize industries. Fourth, most previous studies lack a quantitative evaluation of CO₂ storage capacity in ASEAN [4–6,10,11]. This study has summarized the recent research on quantitative CO₂ source-sinking mapping, revealing that there is enough CO₂ storage potential in ASEAN's oil and gas fields, and saline aquifers to store over two centuries of CO₂ emission. Consequently, future effort should focus on the large-scale implementation of CCS projects through the use of CCS corridors.

9. Conclusions

The following conclusions can be drawn from this study:

1. As of 2018, ASEAN's TPES consisted of 20% renewables, 25% coal, 35% oil and 20% gas.
2. As of 2019, renewable electricity contributed to only 20% of total electricity generation, while fossil electricity contributed to 80%.
3. In the power sector, hydropower, solar PV and bioenergy are the three dominant forms of renewable energy in ASEAN. However, both hydropower and bioenergy suffer from substantial sustainability issues, such as over-damming of the Mekong River for hydropower, and deforestation caused by palm oil plantations for bioenergy.
4. Despite the increase in renewable electricity capacity in ASEAN in the last two decades, the ratio of renewable energy consumption as a percent of TFEC has dropped from 39% in 2000 to 30% in 2015, with a continuing trend. This reveals that, in the last two decades, the addition of renewable electricity in the power sector was more than offset by the increased use of fossil energies in the other sectors. As fossil energies will remain an important part of the energy mix in the period leading to 2050, it is crucial that ASEAN countries consider the use of CCS to decarbonize all fossil-fuel-consuming sectors.
5. Research has shown that there is enough CO₂ storage space in ASEAN's sedimentary basins to store more than two centuries of anthropogenic CO₂ emissions, with the majority residing in saline aquifers, and the remaining in oil and gas reservoirs.
6. This and other recent studies propose six first-mover CCS projects, which could mitigate up to 300 Mtpa CO₂ from Thailand, Indonesia, Malaysia, and Singapore.
7. Decarbonization pathways for ASEAN countries follow the following common themes: (1) increasing share of sustainable renewable energies in power generation, (2) switching from coal to gas in power generation, (3) electrification of road transport, (4) hydrogen for marine transport, (5) biofuels for aviation, (6) blue hydrogen for industry, and (7) CCS corridors.
8. A number of energy policy implications follow from this study. They include: (1) dealing with sustainability issues with hydropower and bioenergy, (2) establishing a roadmap for EVs, (3) introducing a credible carbon tax, (4) holding public engagements on CCS,

- (5) establishing cross-border CCS corridors, (6) setting a national hydrogen strategy, and (7) using public–private partnerships to promote energy transition.
9. Future research should focus on three areas. The first is how ASEAN countries can increase hydropower without over-damming major rivers such as the Mekong. The second is how to increase bioenergy without further clearing ASEAN’s remaining rain-forests for first-generation biocrop plantations. The third is a detailed characterization of ASEAN’s saline aquifers to identify the best ones for CO₂ storage.
 10. ASEAN governments can work together to implement the seven common pathways for decarbonization, for example, by partially funding CCS projects, establishing CCS corridors, introducing a carbon-trading system, and funding research on sustainable hydropower and bioenergy.

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Nomenclature

ASEAN	Association of Southeast Asian Nations
bbl	Barrel
Bio-aviation	Use biofuels for aviation
Blue H ₂	Hydrogen produced from fossil fuels with CCS
BTU	British thermal unit
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization, and storage
Coal→gas-power	Replace coal by gas for power generation
Coal→H ₂ -CCS	Hydrogen production by coal gasification with CCS
CO ₂	Carbon dioxide
CO ₂ -EGR	Carbon dioxide enhanced gas recovery
CO ₂ -EOR	Carbon dioxide enhanced oil recovery
CP-CCS	Coal-fired power plant with carbon capture and storage
CSP	Concentrated solar power
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
EJ	10 ¹⁸ Joule
EV	Electric vehicle
Gas→H ₂ -CCS	Hydrogen production by methane steam reforming with CCS
GP-CCS	Gas-fired power plant with carbon capture and storage
GDP	Gross domestic product
GW	10 ⁹ W
GWh	10 ⁹ Wh
Green H ₂	Hydrogen produced by electrolysis with renewable electricity
Grey H ₂	Hydrogen produced from fossil fuels without CCS
ICE	Internal combustion engine
Ind-CCS	Use CCS in industrial plants
H ₂	Hydrogen
H ₂ -marine	Hydrogen fuel for ships
HFCV	Hydrogen fuel cell vehicle
Solar PV	Solar photovoltaic
Gt	10 ⁹ tonnes
Gtpa	10 ⁹ tonnes per annum
Mt	10 ⁶ tonnes
Mtpa	10 ⁶ tonnes per annum
OOIP	Original oil-in-place, bbl

Tcf	10 ¹² cubic ft
TFEC	Total final energy consumption
TPES	Total primary energy supply

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