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Research paper

# Decarbonization of ASEAN's power sector: A holistic approach

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ABSTRACT

Coal and natural gas have dominated ASEAN's power sector in the past and contributed to 77% of power generation in 2019. To achieve net-zero by 2050, ASEAN countries need to decarbonize their power sector in the next three decades. This paper performs a technology screening exercise for ten decarbonization technologies for the power sector based on a holistic approach of sustainability, security, affordability, reliability, technology readiness and technology impact. This exercise has resulted in country-specific ranking of technologies which can inform policymakers of ASEAN countries. Overall speaking, simultaneous utilization of both fossil and non-fossil technologies is needed rather than waiting for certain technologies to mature. On the fossil side, switching from coal to gas for power generation and implementing carbon capture and storage (CCS) in coal- and gas-fired power plants have the highest decarbonization potential. Therefore, eleven first-mover CCS projects are proposed with the potential to mitigate up to 22% of energy-related $CO_2$ emission in ASEAN in 2019. On the renewable side, hydropower has the highest potential but sustainability issues due to overdamming of the Mekong River needs to be addressed. Further addition of capacity will likely come from run-of-the-river hydropower plants. Within ASEAN, there is medium to high potential for further usage of agricultural resides as biomass for power generation, especially in Indonesia, Thailand, Malaysia and the Philippines. Solar photovoltaic (PV) has medium potential in ASEAN countries with high land mass but more research and development (R&D) is needed in grid improvement and energy storage technologies. Within ASEAN, wind energy suffers from a low average wind speed but there are exceptions. More R&D is needed in the deign of low wind speed wind turbines. Geothermal resources are found only in Indonesia and the Philippines and are under-utilized. Further implementation will require favorable government polices to incentivize private investment and streamlining permitting, among others. Energy policies that promote rapid decarbonization of ASEAN's power sector based on our findings are also discussed.



## 1. Introduction

All ten nations which constitute the Association of Southeast Asian Nations (ASEAN) (ASEAN Secretariat News, 2022) are signatories to the Paris Agreement and have pledged to reduce their greenhouse gas emission to limit the rise in atmospheric temperature to less than 2 °C from pre-industrial times (United Nations, 2022). Although ASEAN countries have an aspiration to achieve net-zero $CO_2$ emission around 2050 or soon afterwards, detailed plans to achieve this have yet to be announced. Fig. 1 gives the per capita GDP of ASEAN countries which varies over a wide range (World Bank, 2022). According to the World Bank's classification, Singapore and Brunei are high-income countries; Malaysia and Thailand are upper middle income countries; Indonesia, Philippines, Vietnam, Laos and Cambodia are lower middle income countries; and Myanmar is a low-income country.

In 2020, ASEAN countries emitted 1.65 Gt $CO_2$ from the burning of fossil fuels (Our World in Data, 2022). The power and heating sector contributed to 38% of this and was the largest $CO_2$ emitter sector (International Renewal Energy Agency (IRENA), 2022). Consequently, decarbonizing the power sector is the first and probably most important step in overall decarbonization (Lau et al., 2022b).

Table 1 summarizes the results of recent studies on the decarbonization of ASEAN and the research gap. Hitherto, most research centers on using renewable energies such as solar PV, wind, and modern biomass (Boyle, 2012) or converting $CO_2$ into useful products (Bui et al., 2018). Although R&D in these topics is important, country-specific research is needed to guide national governments in setting their decarbonization policies (Oh, 2010; Lai et al., 2011; Ibrahim et al., 2015; Sukor et al., 2020; Adisaputro and Saputra, 2017; Zhang et al., 2022; Lau and Ramakrishna,

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**Table 1**
Summary of recent studies on the decarbonization of Southeast Asia.

| Previous study | Country studied | Results | Research gap |
|---|---|---|---|
| Asian Development Bank (ADB) (2013) | Vietnam, Thailand, Philippines, S. Sumatra | There is 57 Gt of $CO_2$ storage potential in the study area. | Study covers only part of Indonesia. Detailed $CO_2$ source–sink mapping is not provided. Results are dated & need updating. |
| Oh (2010); Lai et al. (2011); Ibrahim et al. (2015) and Sukor et al. (2020) | Malaysia | Studies discuss the importance of CCS to decarbonize the power sector. | Studies lack quantitative assessment of $CO_2$ storage capacity |
| Adisaputro and Saputra (2017) | Indonesia | Both CCU and CCS are needed to mitigate $CO_2$ emission. | Study lacks quantitative assessment of $CO_2$ abatement by CCU and CCS. |
| Zhang et al. (2022) | Thailand | Study identifies major $CO_2$ sources and sinks and proposed six CCS clusters. | Study is specific to Thailand. |
| Lau and Ramakrishna (2021); | Singapore | Study identifies fourth industrial revolution technologies for decarbonization of Singapore | Study is specific to Singapore. |
| Lau et al. (2021a) | Singapore | Study identifies $CO_2$ sources from Singapore and proposes using centralized post-combustion carbon capture in Jurong Island and a regional CCS corridor. | Study is specific to Singapore, parts of Indonesia and peninsular Malaysia. |
| Zhang and Lau (2022a) | Singapore, Malaysia, Indonesia | There is 386 Gt of $CO_2$ storage capacity in subsurface reservoirs within 1000 km from Singapore | Study covers only covers West Malaysia, Sumatra, NW Java. |
| Lau et al. (2022b) | ASEAN countries | Study reviews the status of fossil & renewable energies in ASEAN and proposes decarbonization pathways. | Study does not provide methodology to screen decarbonization technologies. |
| Lau (2022a) | ASEAN countries | Study proposes country-specific decarbonization pathways through a technology mapping exercise. | Energy trilemma (sustainability, security, affordability) issues are not included in technology mapping exercise. |
| Lau (2022b) | ASEAN countries | Study screens decarbonization technologies via sustainability, affordability, security, readiness and impact. | Technology reliability issues not addressed. |
| Phoumin et al. (2020) | ASEAN countries | Study discusses outlook for power generation, issues facing renewable electricity and the need for high quality energy infrastructure. | Study does not include quantitative assessment of technologies. |

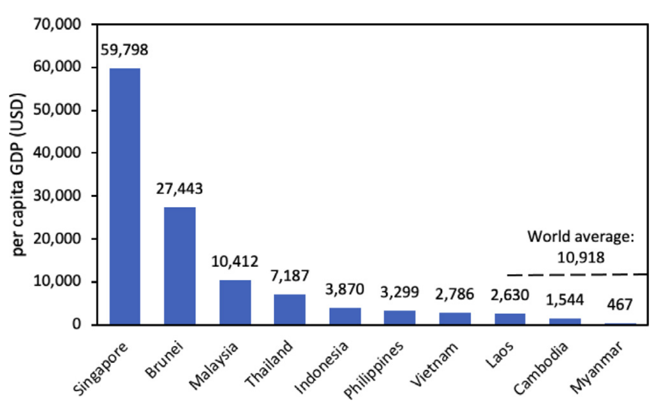


**Fig. 1.** Per capita GPD of ASEAN in 2020 (World Bank, 2022).

2021; Lau et al., 2021a). This is because each country has its own unique circumstances, such as, availability of energy resources, level of economic prosperity, cost of capital, local expertise, and vulnerability to climate change, etc.

Furthermore, research that spans across energy systems is needed to compare the pros and cons of different energies (Lau et al., 2022b). In addition, a regional view of decarbonization is also important as what happens in one country can affect a neighboring country (Zhang and Lau, 2022a; Asian Development Bank (ADB), 2013). This is because when countries work together for decarbonization, they can achieve more by learning from each other's experience and leveraging economies of scale.

In a series of recent articles, the present author has reviewed the status of fossil and renewable energies in Southeast Asia and discussed country-specific, and sector-specific decarbonization pathways (Lau et al., 2022b; Lau, 2022a,b). As a continuation of these studies, this paper seeks to provide country- and region-specific views (Phoumin et al., 2020) on energy systems used in the power sector. This study also compares the efficacy of both fossil and renewable energies in power generation in ASEAN countries.

There is an urgency to decarbonizing ASEAN countries by 2050 or soon afterwards. There are only three decades left to achieve this task. Any delay in taking actions will only make the task more difficult and costly. In practical terms, ASEAN countries do not have the luxury to wait for technologies to mature. Energy policies must be taken to select and speed up the deployment of decarbonization. Decarbonization requires bold actions by policy makers, technology providers, financial investors as well as ordinary citizens.

## 2. Objective and methodology

The objective of this study is to select the technologies that have the highest potential to decarbonize the power sector of the ten countries of ASEAN and then draw policy implications. There are three novel features of this study. First, it includes all ten ASEAN countries which few previous studies did. Second, decarbonization technologies are screened on a country-by-country basis using a holistic criterion which includes sustainability, affordability, security, reliability, readiness and impact. Third, this study also provides a regional view on decarbonization by proposing policy recommendations which are generally applicable to multiple ASEAN countries.

The methodology of this study is given in Fig. 2. First, we consider the status of fossil and renewable energies for

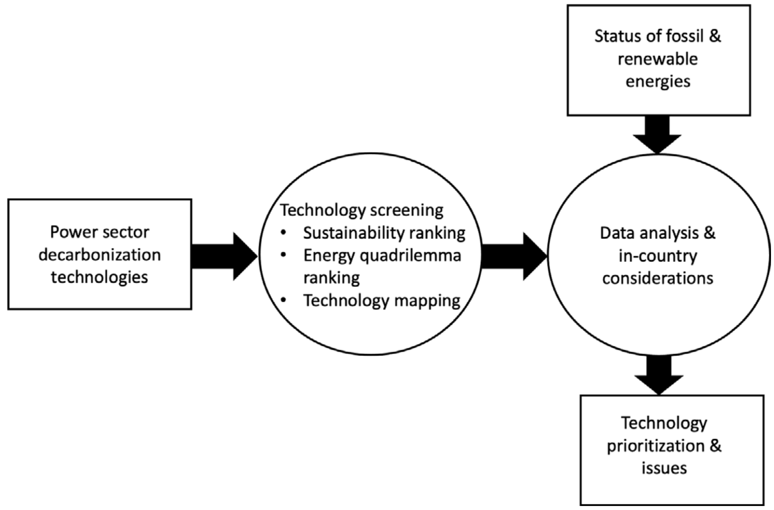


**Fig. 2.** Methodology of study.

electricity generation in each ASEAN country. Next, we assess the ten decarbonization technologies (Table 2) for the power sector in terms of their sustainability ranking, energy quadrilemma ranking and technology mapping (Fig. 2, Table 3).

In this study, a technology's sustainability is ranked according to its $CO_2$ emission, impact on people, animals and environment (Lau et al., 2022b). This goes further than most studies which consider only $CO_2$ emissions as the measure of sustainability. It should be noted that renewable energies such as hydropower, solar PV and wind have sustainability issues regarding impact on people, animals, and environment, despite the fact that they have a low $CO_2$ footprint. The detailed criteria for the ranking exercise is given in Tables A.1 and A.2 in the Appendix.

Energy quadrilemma adds reliability to the energy trilemma of energy sustainability, security, affordability. An energy's sustainability has been discussed in the previous paragraph. A technology's security is ranked according to whether it is domestically available, and the degree of reliance on import. A technology's affordability is ranked according to the levelized cost of electricity (LCOE) which measures the lifelong cost of producing electricity including both capital and operating cost. It is a widely accepted method to compare the cost of different electricity generation technologies. A technology's reliability is ranked according to whether it is available on a continuous basis, i.e. on its utilization capacity factor. A technology's readiness is ranked according to its technology readiness level (TRL), a description of which is given in Table A.4 in the Appendix. A technology's impact is ranked according to its potential penetration of the power sector (Lau, 2022a).

The ten decarbonization technologies (Table 2) are chosen because of their high technology readiness level (TRL) of 7 to 9. In this study we have excluded carbon capture and storage (CCU) and renewable energy storage, e.g. by battery because they have TRL of 6 or lower. Energy efficiency is important for decarbonization but excluded from this study because it deals with the demand side of energy which is outside the scope of this paper.

There are two limitations of this study. First, we have not included all decarbonization technologies. Decarbonization technologies that are excluded can be included later when their TRL increases. Second, we have excluded blue and green hydrogen because, from a $CO_2$ abatement perspective, they are better used in decarbonizing the transport and industry sectors instead of the power sector (Lau, 2021).

**Table 2**
Decarbonization technologies for the power sector.

| Technology | Description |
|---|---|
| Coal → gas | Replacing coal by gas for power generation |
| CP-CCS | Coal-fired power plant equipped with CCS |
| GP-CCS | Gas-fired power plant equipped with CCS |
| Hydro | Hydropower plant |
| Geo | Geothermal power plant |
| Solar PV | Solar photovoltaic power plant |
| Wind | Wind turbine |
| Bio | Modern biomass power plant |
| Nuclear | Nuclear power plant |

## 3. Status of renewable and fossil electricity generation in Southeast Asia

Tables 4 and 5 give the energy mix for electricity generation in ASEAN countries in 2019 by amount and percentage, respectively (International Energy Agency (IEA), 2022b). In 2019, ASEAN produced 1,129 TWh of electricity. Of this, 43% came from coal, 2% from oil, 34% from gas, 14% from hydropower, and only 7% from other renewable energies (Fig. 3a). Together, renewable energies contributed to only 21% of total electricity generation in ASEAN.

Countries with the highest percentage of renewable energies were Laos (63.5%), Cambodia (48.5%), Myanmar (43.5%) and Vietnam (31.3%). These countries, together with Malaysia and Indonesia relied heavily on hydroelectricity (Table 4).

Countries that relied heavily on coal for electricity generation were Indonesia (59.1%), the Philippines (54.6%), Vietnam (49.9%), Malaysia (45.9%), and Cambodia (43.0%) (Table 4).

Countries that relied heavily on gas for electricity generation were Singapore (95.0%) and Brunei (89.2%) (Fig. 4b and Table 4).

Other forms of renewable energies contributed insignificantly to electricity generation. Bioenergy contributed to only 3.3%, geothermal to 2.2%, solar PV to 1.146% and wind only to 0.52%.

Figs. 3b and 4a show that the ASEAN countries that consumed the most electricity in 2019 were Indonesia (26%), Vietnam (21%), Thailand (19%), and Malaysia (16%).

The history of electricity generation of individual ASEAN countries is given in Figs. 5–6. Results are summarized below.

### 3.1. Indonesia

Indonesia relies heavily on coal for power generation (59.1%). Furthermore, it is a net exporter of coal (Table 4, Fig. 5a). Coal,

**Table 3**
Technology screening criteria.

| | Sustainability | Security | Affordability | Reliability | Readiness | Impact |
|---|---|---|---|---|---|---|
| Screening criteria | • $CO_2$ emission<br>• Material footprint<br>• Impact on human, animals, and environment | • In-country availability<br>• Multiple foreign suppliers | LCOE ($/MWh) | Utilization capacity factor (%) | Technology readiness level (TRL) | Potential sector penetration (%) |
| Low (ranking of 1) | • Ranked high impact in any sustainability category | • Unavailable in country<br>• Must be imported | >120 | <20 | 1 to 3 | <5 |
| Medium (ranking of 2) | • Ranked medium impact in any sustainability category<br>• No category ranked high in impact | • Available in small amount in country, or<br>• Some import needed | 80 to 120 | 20 to 40 | 4 to 6 | 5 to 10 |
| High (ranking of 3) | • Ranked low impact in all sustainability categories | • Readily available in country, or<br>• No import needed | <80 | >40 | 7 to 9 | >10 |

**Table 4**
Electricity generation by amount in ASEAN, 2019 (International Energy Agency (IEA), 2022b).

| Electricity (GWh) | Indonesia | Vietnam | Thailand | Malaysia | Philippines | Singapore | Laos | Myanmar | Cambodia | Brunei | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 174 493 | 118 806 | 35 581 | 80 633 | 57 890 | 650 | 11 406 | 2 262 | 3734 | 484 | 485 939 | 43.03 |
| Oil | 9 997 | 2 213 | 236 | 969 | 3 752 | 217 | 0 | 109 | 732 | 47 | 18 272 | 1.62 |
| Gas | 61 332 | 42 507 | 121 117 | 65 156 | 22 354 | 51 760 | 0 | 11 321 | 0 | 4400 | 379 947 | 33.65 |
| Hydro | 21 185 | 66 117 | 6 446 | 26 666 | 8 025 | 0 | 19 738 | 10 518 | 4025 | 0 | 162 720 | 14.41 |
| Geo | 14 100 | 0 | 1 | 0 | 10 691 | 0 | 0 | 0 | 0 | 0 | 24 792 | 2.20 |
| Solar PV | 118 | 4 818 | 5 146 | 943 | 1 246 | 410 | 41 | 45 | 93 | 2 | 12 862 | 1.146 |
| Wind | 484 | 722 | 3 670 | 0 | 1 042 | 0 | 0 | 0 | 0 | 0 | 5 918 | 0.52 |
| Bio | 13 393 | 2 802 | 18 308 | 1 410 | 1 015 | 260 | 47 | 0 | 91 | 0 | 37 366 | 3.31 |
| Waste | 21 | 0 | 176 | 0 | 25 | 1 173 | 0 | 1 | 0 | 0 | 1 396 | 0.12 |
| Total | 295 123 | 238 025 | 190 681 | 175 777 | 106 040 | 54 470 | 31 232 | 24 256 | 8675 | 4933 | 1 129 212 | 100.00 |

**Table 5**
Electricity generation in percentage by fuel type in ASEAN, 2019 (International Energy Agency (IEA), 2022b).

| % | Indonesia | Vietnam | Thailand | Malaysia | Philippines | Singapore | Laos | Myanmar | Cambodia | Brunei |
|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 59.1 | 49.9 | 18.7 | 45.9 | 54.6 | 1.2 | 36.5 | 9.3 | 43.0 | 9.8 |
| Oil | 3.4 | 0.9 | 0.1 | 0.6 | 3.5 | 0.4 | 0.0 | 0.4 | 8.4 | 1.0 |
| Gas | 20.8 | 17.9 | 63.5 | 37.1 | 21.1 | 95.0 | 0.0 | 46.7 | 0.0 | 89.2 |
| Hydro | 7.2 | 27.8 | 3.4 | 15.2 | 7.6 | 0.0 | 63.2 | 46.4 | 46.4 | 0.0 |
| Geo | 4.8 | 0.0 | 0.0 | 0.0 | 10.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Solar PV | 0.0 | 2.0 | 2.7 | 0.5 | 1.2 | 0.8 | 0.1 | 0.2 | 1.1 | 0.0 |
| Wind | 0.2 | 0.3 | 1.9 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Bio | 4.5 | 1.2 | 9.6 | 0.8 | 1.0 | 0.5 | 0.2 | 0.0 | 1.0 | 0.0 |
| Waste | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 2.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Renewable | 16.7 | 31.3 | 17.6 | 16.5 | 20.8 | 1.2 | 63.5 | 43.5 | 48.5 | 0.0 |

gas, and hydropower contributed to 59.1%, 20.8%, and 7.2% of electricity generation in 2019, respectively (Table 5). Indonesia has been increasing its coal power capacity rapidly since 2010. In 2019, renewable energies contributed to 17% of power generation (Table 5).

### 3.2. Malaysia

Malaysia relies heavily on both coal (45.9%) and gas (37.1%) for power generation (Table 4, Fig. 5b). It is a net exporter of gas and a net importer of coal. It has been increasing its hydropower capacity since 2015. Hydropower contributed to 15.2% of power generation in 2019 (Table 4).

### 3.3. The Philippines

The Philippines relies heavily on coal for power generation (54.6%) (Table 4, Fig. 5c). Gas, geothermal and hydropower contributed to 21.1%, 10.1% and 7.6% of power generation in 2019 (Table 4).

### 3.4. Vietnam

Vietnam relies heavily on coal for power generation (49.9%) (Table 4, Fig. 5d). Hydropower and gas contributed to 27.8% and 17.9% of power generation in 2019 (Table 2). The country has been rapidly increasing it hydropower capacity since 2005 (Fig. 4d).

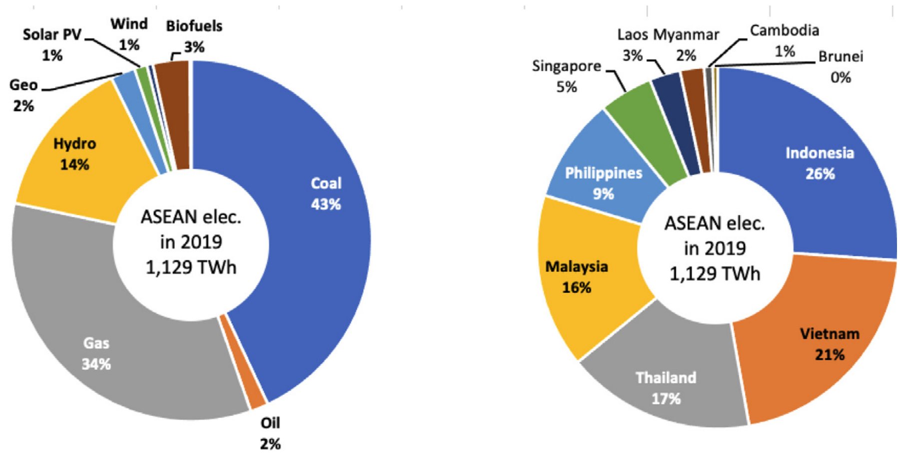


**Fig. 3.** ASEAN electricity generation in 2019 by (a) fuel type, and (b) country (International Energy Agency (IEA), 2022b).

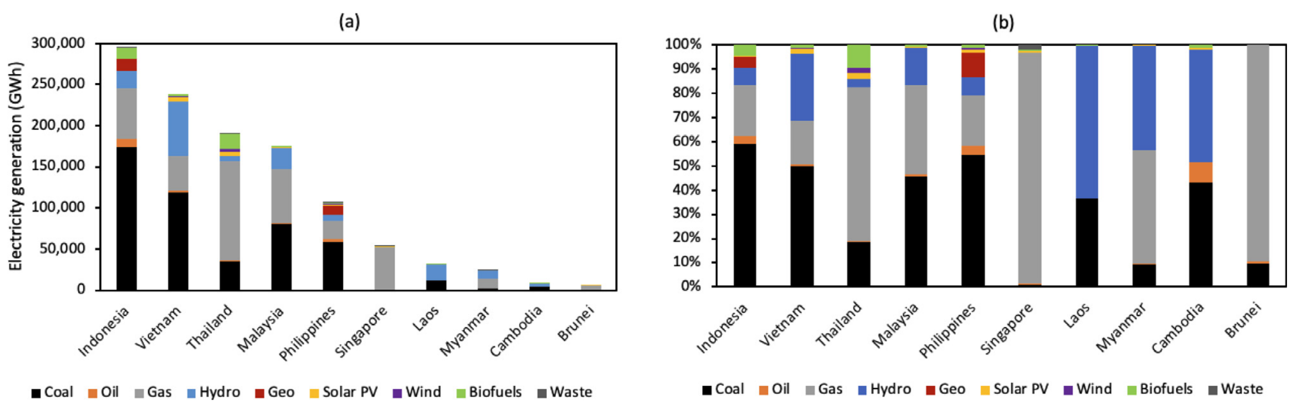


**Fig. 4.** Electricity generation (a) by amount, and (b) by percentage in ASEAN, 2019 (International Energy Agency (IEA), 2022b).

*3.5. Thailand*

Thailand relies heavily on gas for power generation (63.5%) (Table 4, Fig. 6a) as is a net importer of gas. Coal and bioenergy contributed to 18.7% and 9.6% of power generation in 2019 (Table 4).

*3.6. Myanmar*

Myanmar relies heavily on gas (46.7%) and hydropower (46.4%) for power generation (Table 4, Fig. 6b). Coal contributed only to 9.3% of power generation in 2019 (Table 4).

*3.7. Cambodia*

Cambodia relies heavily on hydropower (46.4%) and coal (43.0%) for power generation (Table 4, Fig. 6c). Oil contributed to 8.4% of power generation in 2019 (Table 4).

*3.8. Laos*

Laos relies exclusively only hydropower (63.2%) and coal (36.5%) for power generation (Table 4, Fig. 5d). Other forms of energies contributed to little (Fig. 6d).

*3.9. Singapore*

Singapore relies heavily on gas (95%) for power generation in 2019 (Table 4, Fig. 7a). Gss is imported from other countries. Other forms of energies contribute to little for power generation (Fig. 6a).

*3.10. Brunei*

Brunei relies exclusively on gas (89.2%) for power generation in 2019 (Table 4, Fig. 7b). Coal contributed to 9.8% of power generation in 2019 (Table 4). The country is a net exporter of oil and gas.

## 4. Results of technology screening

For each ASEAN country the ten technologies described in Table 2 are screened according to their sustainability, security, affordability, reliability, readiness and impact.

For sustainability, we screen each technology according to $CO_2$ emission, impact on people, animals and environment. $CO_2$ emission can be determined from existing operations. We use the $CO_2$ emission from US fossil fuel power plants as a benchmark (Table A.1). $CO_2$ emission from US coal, gas and oil power plants are 1.011 kg/kWh, 0.413 kg/kWh and larger than 0.9661 kg/kWh, respectively (United States Energy Information Administration (EIA), 2022). In this study, $CO_2$ emission less than 0.37 kg/kWh is regarded as low. Emission larger than 0.45 kg/kWh is regarded as high, and emission between 0.37 and 0.45 kg/kWh is regarded as medium (Table A.1). In determining the impact on people, animals, and environment, we modify the risk assessment matrix (RAM) commonly used in the oil and gas industry for assessment. This modified RAM includes assessment on the severity of impact and the probability of occurrence (Table A.2). For impact on people, a medium impact means major injury or fatality has occurred in another country that deploys this technology but not the country under consideration. A high impact means a fatality

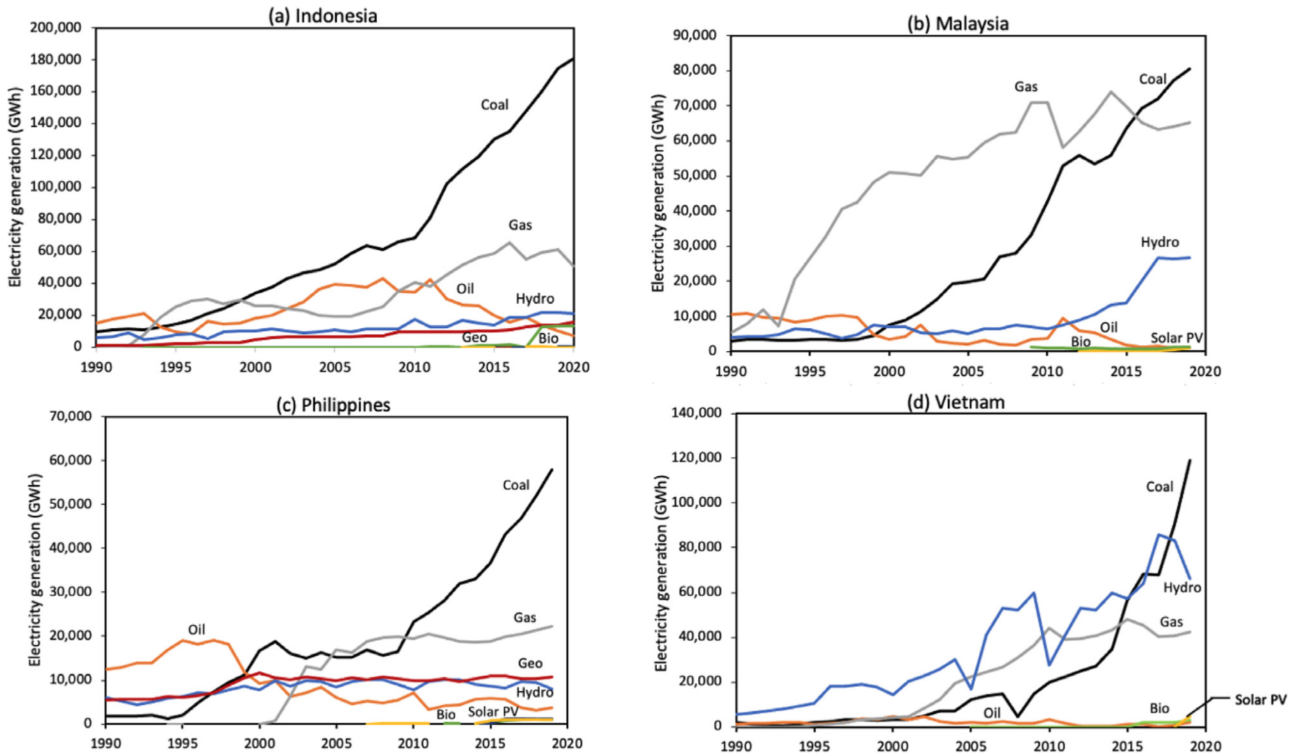


**Fig. 5.** History of electricity generation in (a) Indonesia, (b) Malaysia, (c) Philippines, and (d) Vietnam (International Energy Agency (IEA), 2022b).

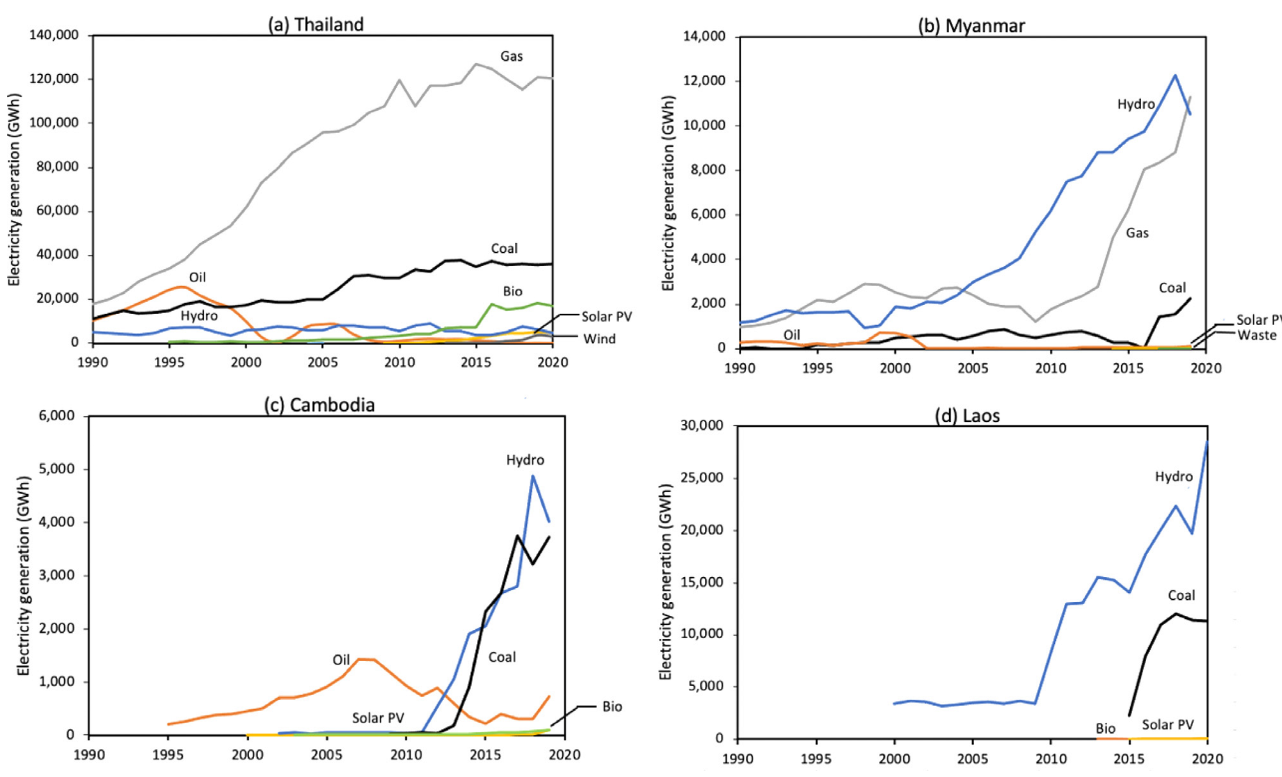


**Fig. 6.** History of electricity generation in (a) Thailand, (b) Myanmar, (c) Cambodia, and (d) Laos (Lau, 2021).

has occurred in the country under consideration. A high impact ranking means this has occurred in the country under consideration. For impact on animals, a medium impact ranking means fatality of an endangered has occurred in other countries, but not in the country under consideration. For impact on environment, a medium ranking means local to massive adverse environment impact has occurred in other countries. A high impact ranking means such occurrence in the country under consideration. The criteria for reliability, affordability, security, readiness and impact are described in the Methodology section of this paper. Results are summarized below.

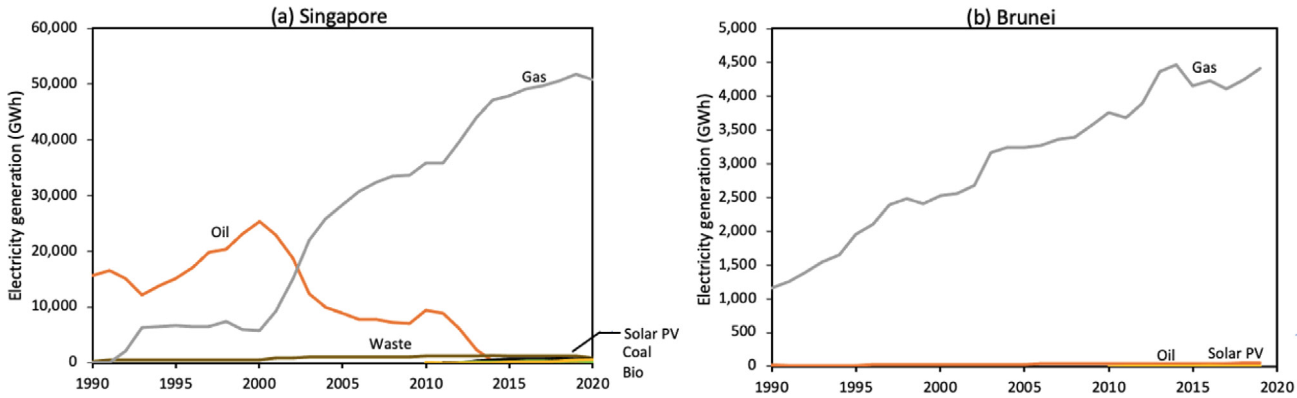


**Fig. 7.** History of electricity generation in (a) Singapore, and (b) Brunei (International Energy Agency (IEA), 2022b).

**Table 6**
Technology screening for Indonesia.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | High | High | High | Low | Med | High | High | High | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity factor (%)[c] | 37 | 75 | 83 | 1 | 12 | 45 | 45 | 45 | 86[d] |
| Readiness | TRL[e] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | 5–10 | 5–10 | <5 | <5 | >10 | >10 | >10 | <5 |
| Overall assessment on potential in country | | Med | Med | Med | Low | Low | High | High | High | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[e]Data source: Ref. Bui et al. (2018).

### 4.1. Indonesia

The following observations can be made from results shown in Table 6 and Fig. 8.

1. Coal → gas and GP-CCS are the fossil technologies with high overall potential. Next is CP-CCS.

2. Hydropower is the renewable technology with high potential. However, further increase in installed capacity may be limited due to sustainability concerns and relatively low capacity factor (37%) compared to other ASEAN countries. Run-of-the river hydropower can be useful.

3. Geothermal and bioenergy have medium potential. Indonesia has plenty of geothermal resources. However, addition of capacity will require favorable energy polices to incentivize private investment.

4. Bioenergy for power generation is relatively expensive and competes with already large-scale palm oil plantation for biodiesel for the transport sector.

5. Solar PV suffers from low reliability because of low capacity utilization of 9% (Table 6) (International Energy Agency (IEA), 2022b).

6. Wind suffers from both low reliability because of low capacity utilization (1%) and low availability because of low wind speed.

7. There is scope for consideration of nuclear energy by import or domestic production if sustainability issues can be managed.

With coal and gas producing 59% and 21%, respectively, of Indonesia's electricity in 2019 (Table 5), the decarbonization technologies with the biggest impact are CP-CCS, GP-CCS and coal → gas. Among renewable energies, hydropower, bioenergy and geo have medium decarbonization potential. For hydropower, the use of run-of-the-river hydropower will likely avoid the sustainability issues related to damming of major rivers. Due to its large land mass and abundance rain and sunshine, Indonesia has rich bioenergy resources for power generation via biomass pellets produced from residues of oil palm, rice, sugarcane, rubberwood and acacia for combined heat and power generation. Geothermal energy requires policies to incentivize private investment. However, energy policies that favor these fossil and renewable decarbonization technologies need to be promulgated by the government.

### 4.2. Malaysia

The following observations can be made from results shown in Table 7 and Fig. 9.

1. GP-CCS , CP-CCS and coal → gas are the fossil technology with high decarbonization potential.

2. Hydropower is the renewable energy with medium potential. However, further addition may be difficult due to sustainability issues. Run-of-the-river hydropower should be considered as it has no such issues.

3. Bioenergy for power generation is expensive and competes with already large palm oil plantations used for the transport sector.

4. Solar PV suffers from reliability issues because of low capacity utilization of 6% (Table 7) (International Energy Agency (IEA), 2022b).

5. Wind suffers from low capacity factor of 27% and low security due to low wind speed.

6. There is no geothermal resources in Malaysia.

7. Nuclear energy deserves consideration if sustainability issues can be managed.

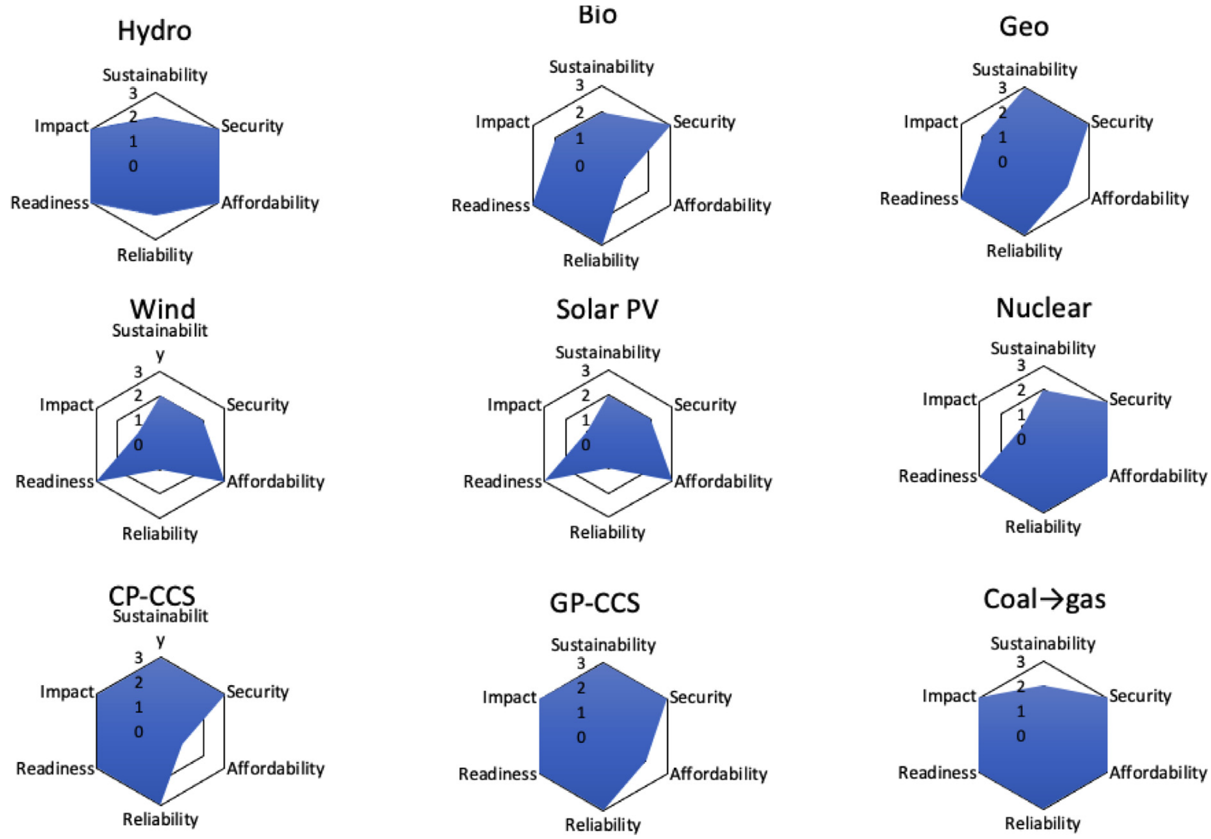


**Fig. 8.** Results of technology screening for Indonesia.

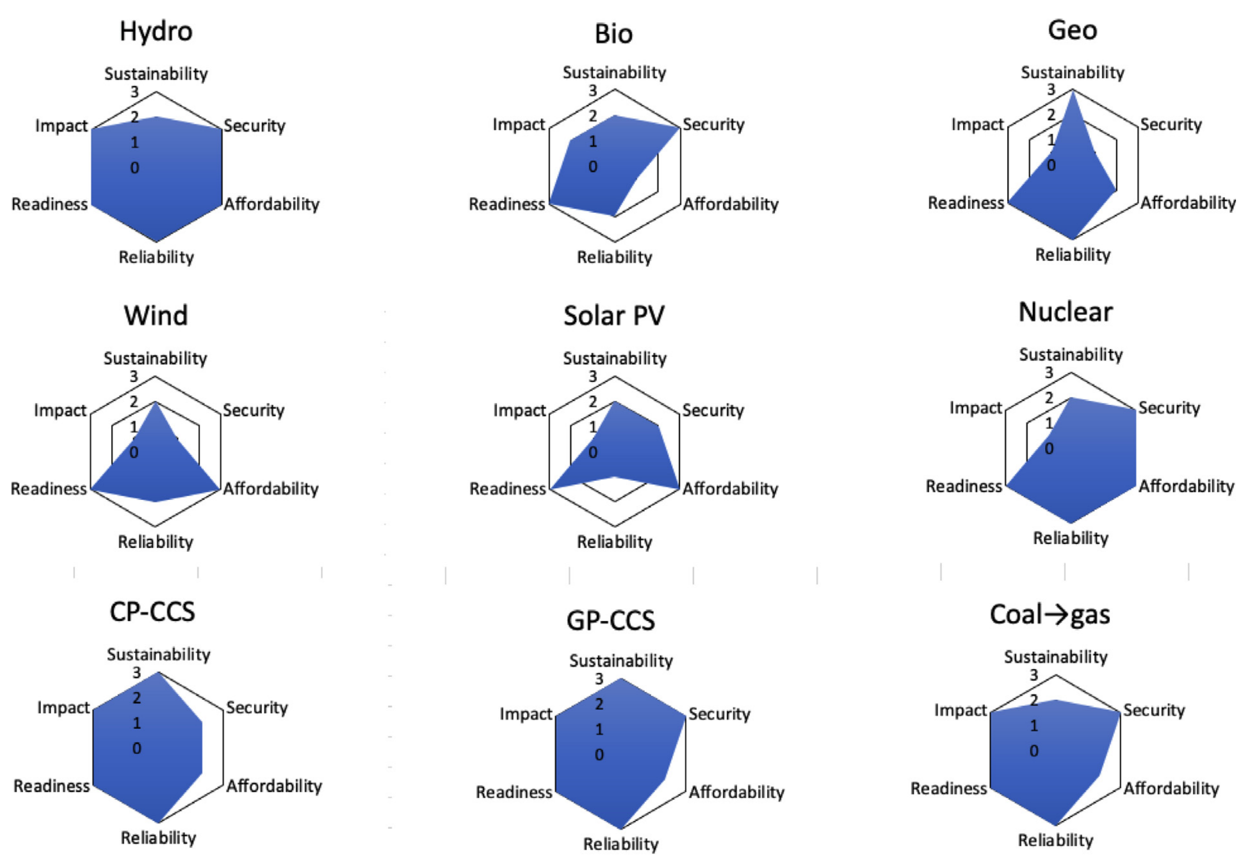


**Fig. 9.** Results of technology screening for Malaysia.

**Table 7**
Technology screening for Malaysia.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | High | High | Low | Low | Med | Med | High | High | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity factor (%)[c] | 47 | 31 | 59[d] | 27[d] | 6 | 61 | 61 | 61 | 86[e] |
| Readiness | TRL[f] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | 5–10 | <5 | <5 | <5 | >10 | >10 | >10 | <5 |
| Overall assessment on potential in country | | High | Med | Low | Low | Low | High | High | High | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Estimated from ASEAN average
[e]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[f]Data source: Ref. Bui et al. (2018).

**Table 8**
Technology screening for the Philippines.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | Med | High | High | Med | Med | Med | High | High | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity[c] factor (%) | 28 | 33 | 63 | 27 | 15 | 53 | 53 | 53 | 86[d] |
| Readiness | TRL[e] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | 5–10 | >10 | <5 | <5 | >10 | >10 | >10 | <5 |
| Overall assessment of potential in country | | Med | Med | High | Low | Low | High | High | High | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[e]Data source: Ref. Bui et al. (2018).

With 46% and 37% of Malaysia's power produced from coal and gas in 2019 (Table 5), the decarbonization technologies that have the biggest impact are coal → gas, GP-CCS and CP-CCS. Among renewable energies, hydropower and bioenergy have high and medium decarbonization potential, respectively. New addition to hydropower will likely come from run-of-the-river hydropower to avoid sustainability issues with large dams. Wood pellets and chips from acacia and rubber plantation may be used for direct combustion for combined power and heat generation. However, energy policies that favor these fossil and renewable decarbonization technologies need to be promulgated by the government.

### 4.3. The Philippines

The following observations can be made from results shown in Table 8 and Fig. 10.

1. Coal → gas and GP-CCS are the fossil technologies with high decarbonization potential.
2. CP-CCS also has high potential. However, it is more costly than GP-CCS.
3. Geothermal is the renewable technology with high potential as the country has abundant geothermal resources.
4. Hydropower has medium potential but further capacity addition is limited due to low capacity factor (28%) and sustainability issues. Run-of-the-river hydropower should be considered.
5. Bioenergy has medium potential, but is expensive and competes with bioenergy for transport.
6. Solar PV suffers from reliability issues because of low capacity utilization of only 15% (Table 8) (International Energy Agency (IEA), 2022b).
7. Wind has low security because of low wind speed (Table 8) (International Energy Agency (IEA), 2022b).
8. Nuclear is worth considering if sustainability issues can be managed.

With 55% and 21% of Philippines' electricity produced from coal and gas, respectively, the decarbonization technologies with the biggest potential are coal → gas, CP-CCS and CP-CCS. Among renewable energies, geothermal energy has the biggest potential, followed by hydropower. Geothermal energy requires high capital investment. Hydropower will likely benefit from run-of-the-river hydropower stations. Favorable government polices in the implementation of these technologies are needed.

### 4.4. Vietnam

The following observations can be made from results shown in Table 9 and Fig. 11.

1. Coal → gas, CP-CCS and GP-CCS are the fossil technologies with high potential.
2. Hydropower has high potential but capacity addition may be limited by sustainability issues. Run-of-the-river hydropower should be considered.
3. Solar PV has high potential but suffers from low reliability because of a low utilization capacity of only 18% (Table 9) (International Energy Agency (IEA), 2022b).

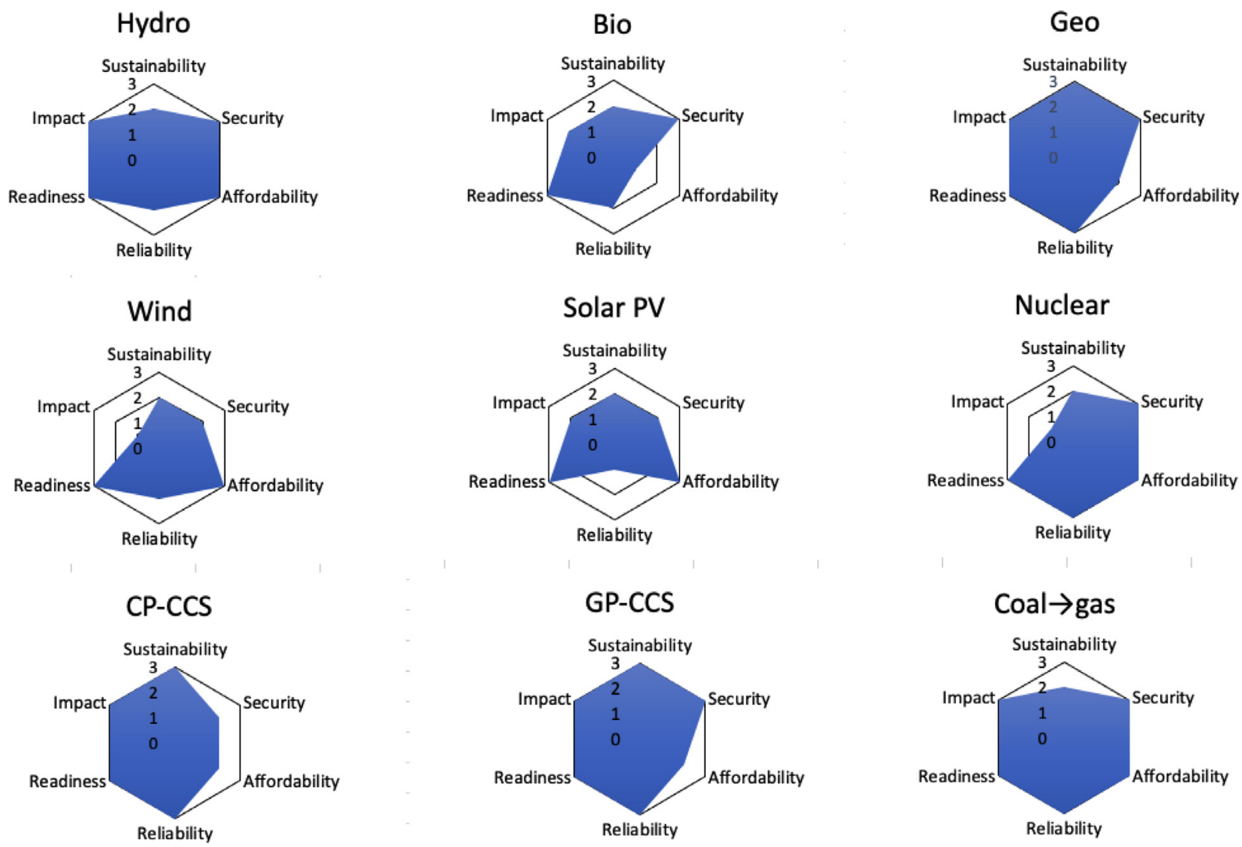


**Fig. 10.** Results of technology screening for the Philippines.

**Table 9**
Technology screening for Vietnam.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | High | Low | Low | Low | Med | Med | High | High | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity[c] factor (%) | 41 | 10 | 59[d] | 46 | 18 | 54 | 54 | 54 | 86[e] |
| Readiness | TRL[f] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | 5–10 | <5 | <5 | >10 | >10 | >10 | >10 | <5 |
| Overall assessment on potential in country | | High | Low | Low | Low | High | High | High | High | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Estimated from ASEAN average.
[e]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[f]Data source: Ref. Bui et al. (2018).

4. Wind and geothermal suffer from low in-country availability because of low wind speed and lack of geothermal resources.
5. Bioenergy for power generation suffers from high cost and low capacity factor of 10% (Table 9) (International Energy Agency (IEA), 2022b)
6. Nuclear energy is worth considering if sustainability issues can be managed.

With 50% and 18% of Vietnam's electricity produced from coal and gas, respectively, in 2019 (Table 5), the decarbonization technologies with the highest potential are coal → gas, CP-CCS and GP-CCS. Among renewables, hydropower has high potential. However, sustainability issues with the damming of the Mekong River needs to be addressed. Solar PV has high potential and can be further expanded.

### 4.5. Thailand

The following observations can be made from results shown in Table 10 and Fig. 12.

1. CP-CCS, GP-CCS and coal → gas are the fossil technologies with high decarbonization potential.
2. Bioenergy is the renewable energy with high potential. However, it is expensive and competes with land space for bioenergy used for the transport sector.
3. Solar PV has medium potential, but suffers from low reliability due to its low capacity factor of 19%.
4. Hydropower suffers from low reliability due to its low capacity factor of 17%.
5. Wind energy suffers from low availability due to low wind speed.

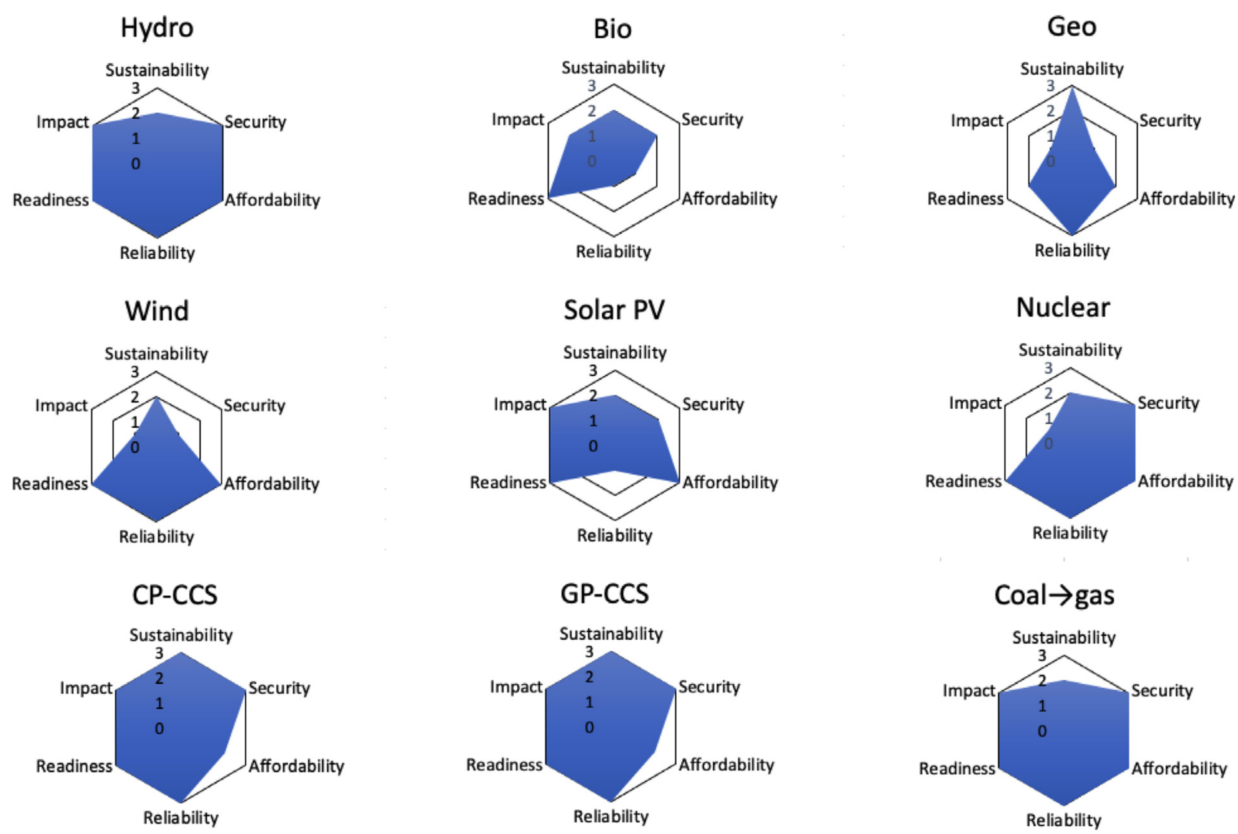


**Fig. 11.** Results of technology screening for Vietnam.

**Table 10**
Technology screening for Thailand.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | Med | High | Low | Med | High | Med | Med | Med | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity[c] factor (%) | 17 | 84 | 42 | 27 | 19 | 43 | 43 | 43 | 86[d] |
| Readiness | TRL[e] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | <5 | >10 | <5 | <5 | 5–10 | >10 | >10 | >10 | <5 |
| Overall assessment on potential in country | | Low | High | Low | Low | Med | High | High | High | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[e]Data source: Ref. Bui et al. (2018).

6. Geothermal resources are lacking in Thailand.
7. Nuclear energy is worth considering if sustainability issues can be managed.

With 64% and 19% of Thailand's electricity produced from gas and coal, respectively, in 2019, the decarbonization technologies with high potential are coal → gas, GP-CCS and CP-CCS. Among renewables, bioenergy has high potential. Agricultural residues e.g. sugarcane bagasse, rice straw and husks, palm kernel shell, empty fruit bunches and oil trunks can be used for direction combustion for combined power and heat generation.

### 4.6. Myanmar

The following observations can be made from results shown in Table 11 and Fig. 13.

1. GP-CCS is the fossil technology with high decarbonization potential.
2. CP-CCS and coal → gas have medium potential.
3. Hydropower is the renewable energy with high potential. However, sustainability issues with damming of the Mekong River needs to be resolved.
4. Other renewable energies have little impact on power generation, due to low in-country availability.
5. Nuclear energy is not recommended due to low level of local expertise.

With 47% of Myanmar's electricity coming from gas in 2019 (Table 5), GP-CCS is the decarbonization technology with high potential. Among renewable hydropower which produced 46% of Myanmar's electricity in 2019 has high decarbonization potential. However, major sustainability issues from the overdamming of the Mekong River needs to be addressed.

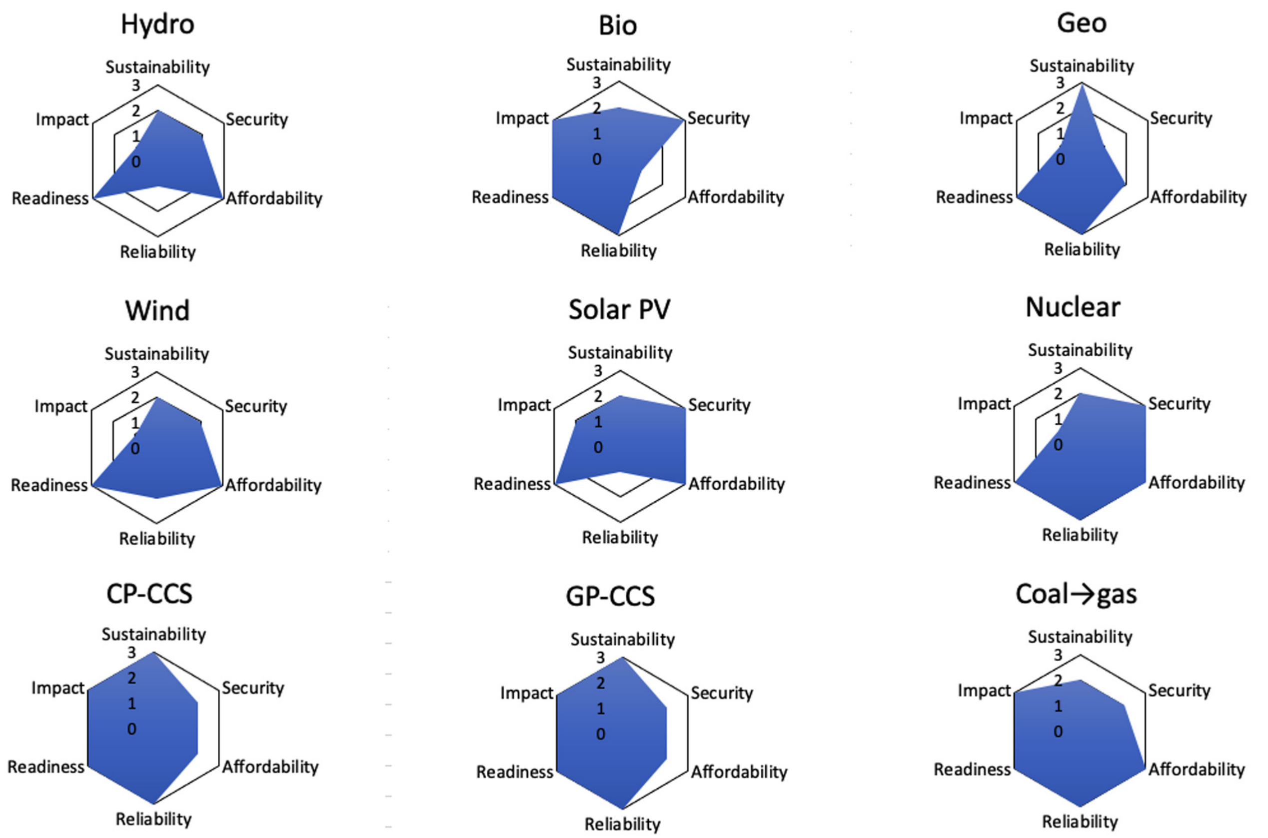


**Fig. 12.** Results of technology screening for Thailand.

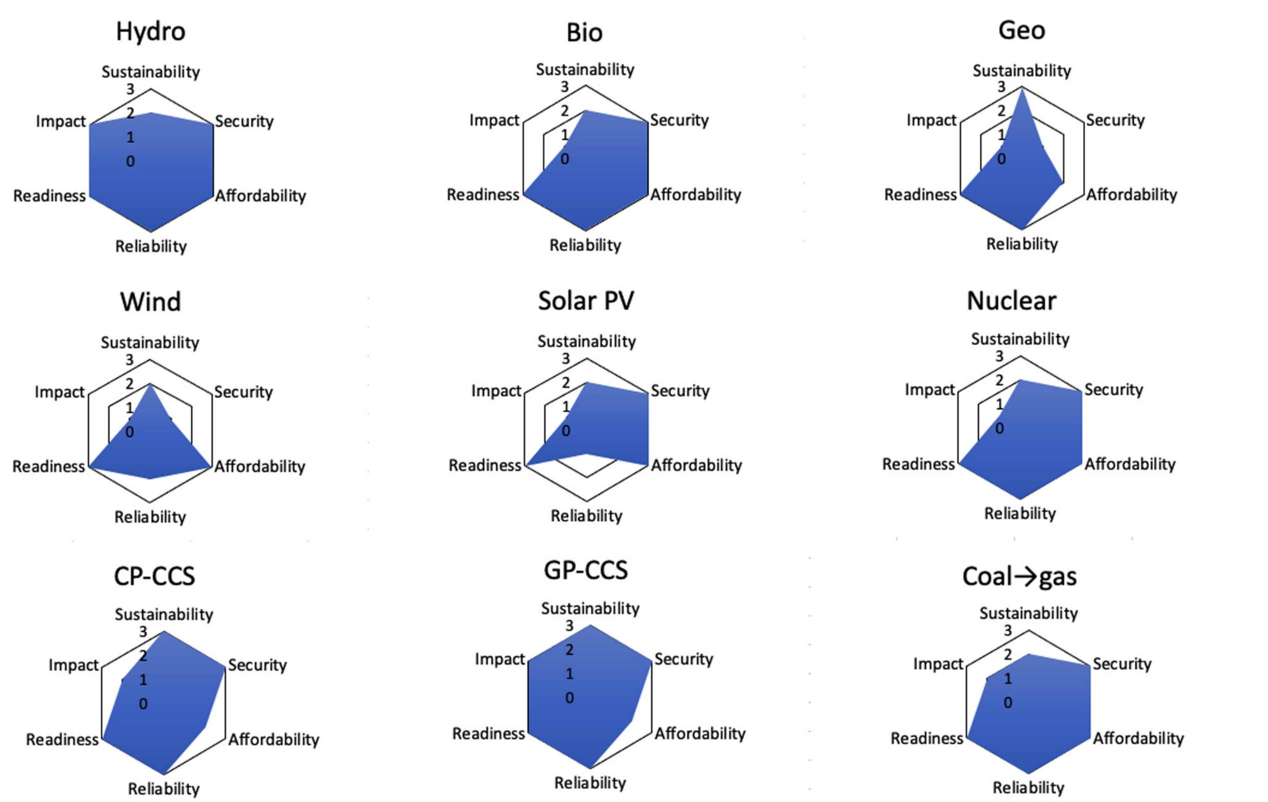


**Fig. 13.** Results of technology screening for Myanmar.

**Table 11**
Technology screening for Myanmar.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | High | High | Low | Low | High | Med | High | High | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity[c] factor (%) | 45 | 51 | 0 | 38 | 9 | 48 | 48 | 48 | 86[d] |
| Readiness | TRL[e] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | <5 | <5 | <5 | <5 | 5–10 | >10 | 5–10 | <5 |
| Overall assessment on potential in country | | High | Low | Low | Low | Low | Med | High | Med | Low |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[e]Data source: Ref. Bui et al. (2018).

**Table 12**
Technology screening for Cambodia.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | High | High | Low | Low | Med | Low | Low | Low | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity[c] factor (%) | 35 | 23 | 59[d] | 14 | 11 | 54 | 54 | 54 | 86[e] |
| Readiness | TRL[f] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | <5 | <5 | <5 | 5–10 | >10 | <5 | <5 | <5 |
| Overall assessment on potential in country | | High | Low | Low | Low | Med | Med | Low | Low | Low |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Estimated from ASEAN average.
[e]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[f]Data source: Ref. Bui et al. (2018).

### 4.7. Cambodia

The following observations can be made from results shown in Table 12 and Fig. 14.

9. CP-CCS is the fossil technology with medium decarbonization potential due to large amount of electricity (43%) generated by coal-fired power plants (Table 5). Coal, however, has to be imported.
10. Hydropower is the renewable energy with high potential. However, sustainability issues need to be managed with damming of the Mekong River.
11. Solar PV has medium potential. However, it suffers from low reliability due to a capacity factor of only 11%.
12. Bioenergy for power generation is expensive and suffers from a low capacity factor compared to other ASEAN countries.
13. Wind energy suffers from low wind speed and a low capacity factor of 14%.
14. There is no geothermal resources in Cambodia.
15. Nuclear energy is not recommended due to low level of in-country expertise.

As 46% of Cambodia's electricity came from hydropower in 2019 (Table 5), this is the renewable energy with high decarbonization potential. However, further expansion of capacity requires addressing sustainability issues with over damming of the Mekong River. Next in decarbonization potential is CP-CCS, if a suitable $CO_2$ storage location can be found.

### 4.8. Laos

The following observations can be made from results shown in Table 13 and Fig. 15.

1. CP-CCS is the fossil technology with high decarbonization potential as large amount of power (36%) is generated by coal-fired power plants (Table 5). Coal is produced domestically.
2. Hydropower is the renewable energy with high decarbonization potential. However, sustainability issues with the damming of the Mekong River need to be resolved.
3. Solar PV suffers from low reliability because its capacity factor is only 14%.
4. Bioenergy, geothermal and wind suffer from low in-country availability.
5. Nuclear energy is not recommended due to lack of local expertise.

With 63% of Lao's electricity produced from hydropower in 2019 (Table 5), hydropower is the highest potential decarbonization technology. However, sustainability issues with overdamming of the Mekong River need to be addressed. Next in decarbonization potential is CP-CCS as 36% of the country's power came from domestically produced coal.

### 4.9. Singapore

The following observations can be made from results shown in Table 14 and Fig. 16.

1. GP-CCS is the fossil technology with high decarbonization potential as most of the power in Singapore is generated by gas-fired power plants. However, due to absence of in-country $CO_2$ storage capacity, $CO_2$ has to be stored in a neighboring country.
2. Solar PV has medium potential, but suffers from low reliability due to a low capacity utilization of 12% (Table 14) (International Energy Agency (IEA), 2022b).

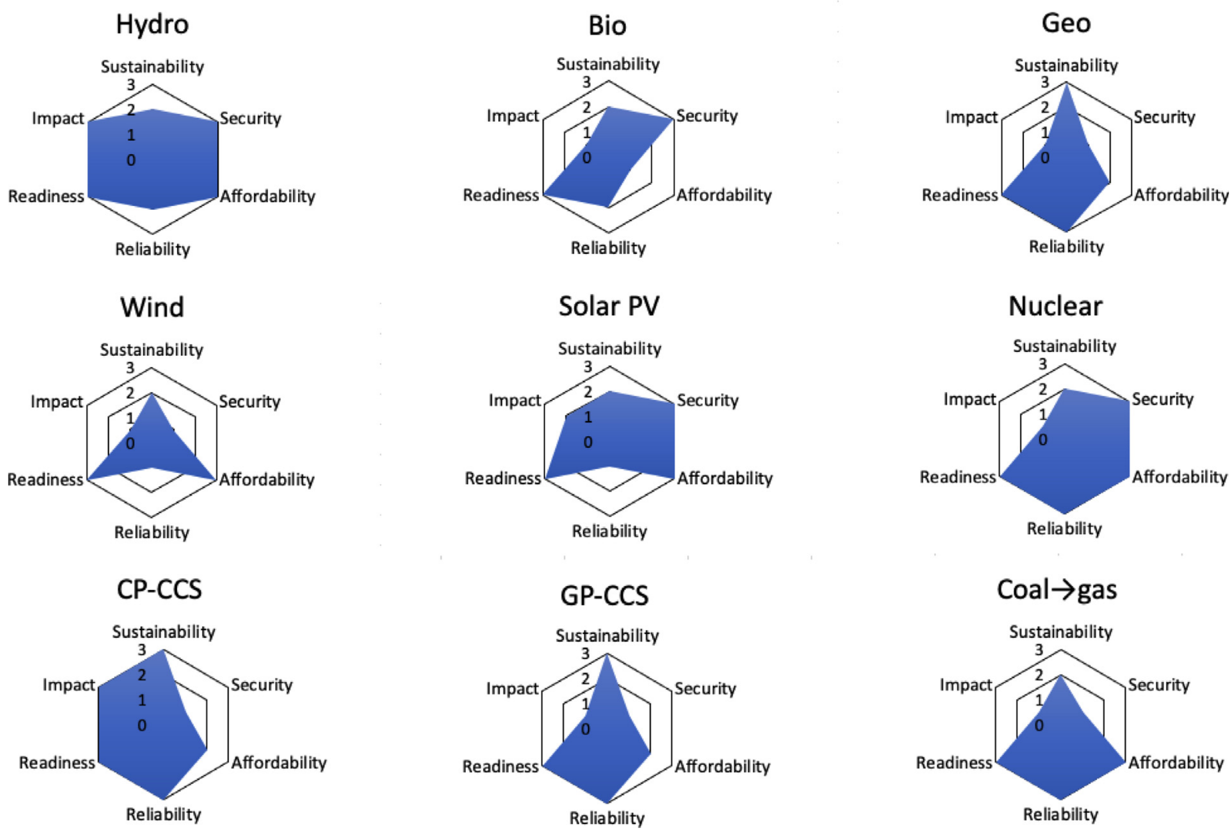


**Fig. 14.** Results of technology screening for Cambodia.

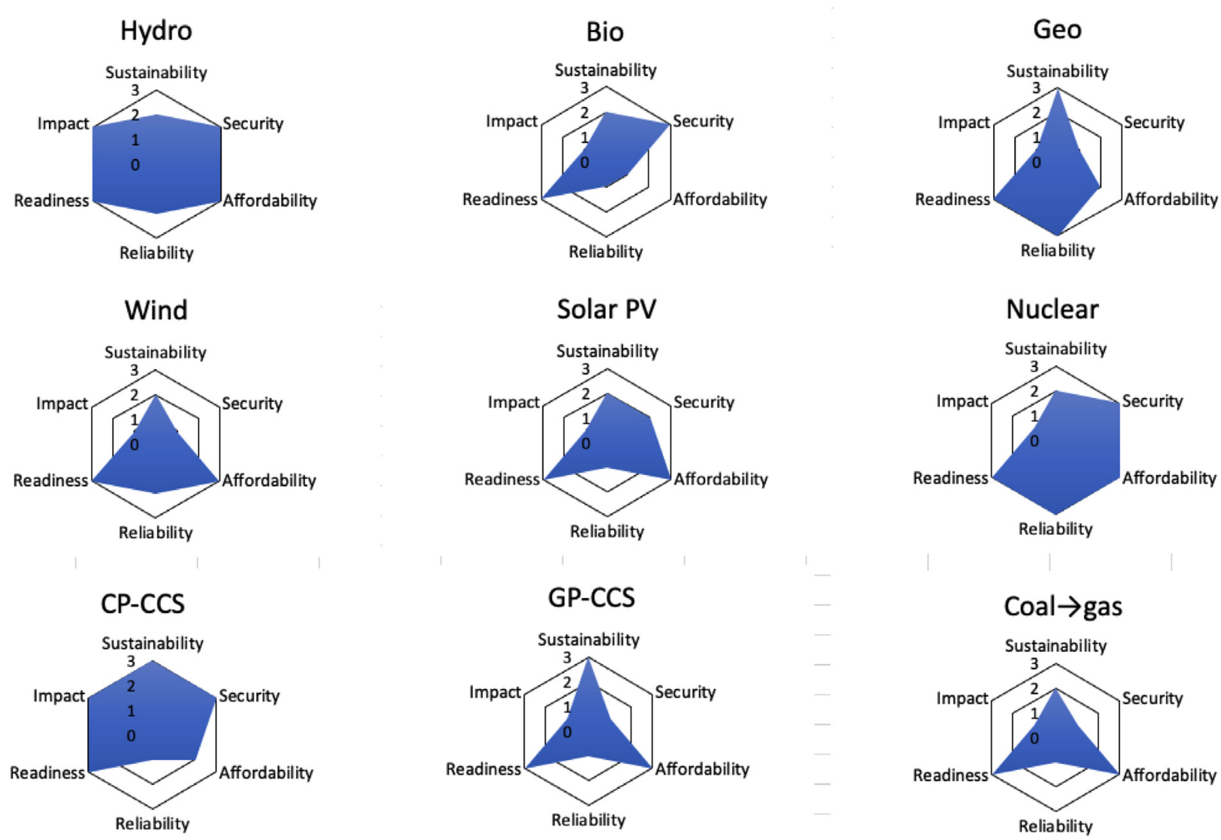


**Fig. 15.** Results of technology screening for Laos.

**Table 13**
Technology screening for Laos.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustain. | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | High | High | Low | Low | Med | High | Low | Low | High[a] |
| Afford. | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliab. | Capacity[c] factor (%) | 35 | 13 | 59[d] | 27[d] | 14 | 4 | 4 | 4 | 86[e] |
| Readiness | TRL[f] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | >10 | <5 | <5 | <5 | <5 | >10 | <5 | <5 | <5 |
| Overall assessment on potential in country | | High | Low | Low | Low | Low | High | Low | Low | Low |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Estimated from ASEAN average.
[e]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[f]Data source: Ref. Bui et al. (2018).

**Table 14**
Technology screening for Singapore.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustain. | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | Low | Med | Low | Low | Low | Low | Low | Low | High[a] |
| Afford. | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliab. | Capacity[c] factor (%) | 39[d] | 100 | 59[d] | 40 | 12 | 48 | 48 | 48 | 86[e] |
| Readiness | TRL[f] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | <5 | <5 | <5 | <5 | 5–10 | <5 | >10 | <5 | <5 |
| Overall assessment on potential in country | | Low | Low | Low | Low | Med | Low | High | Low | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Estimated from ASEAN average.
[e]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[f]Data source: Ref. Bui et al. (2018).

3. Other renewable energies have little impact on decarbonization due to low in-country availability.
4. It is worth considering nuclear energy if sustainability issues can be managed.

With 95% of its Singapore's power produced from gas in 2019 and limited renewable resources, the technology with the highest decarbonization potential is GP-CCS if the $CO_2$ can be stored in a neighboring country. Alternatives include importing hydropower from its neighbor.

### 4.10. Brunei

The following observations can be made from results shown in Table 15 and Fig. 17.

1. GP-CCS is the fossil technology with the highest decarbonization potential as most of the country's power is produced from gas-fired power plants.
2. Solar PV has medium potential but suffers from a low capacity factor of only 10%.
3. Other renewable energies have little impact on decarbonization.
4. It is worth considering nuclear energy if sustainability issues can be managed.

With 89% of its Brunei's power coming from gas in 2019 (Table 5), the decarbonization technology with the highest potential is GP-CCS. Alternatives include importing hydropower from its neighbor.

### 4.11. Discussion

Table 4 shows that the only renewable energy that contributed significantly to ASEAN's electricity generation was hydropower, which generated 14.41% of ASEAN's electricity in 2019. Other forms of renewable energies have insignificant contributions to power generation, e.g., 3.31% by bioenergy, 2.20% by geothermal, 1.15% by solar PV, and 0.52% by wind.

It should be stated that the radar charts Figs. 8–17 are meant for comparison of the pros and cons of different decarbonization technologies within a country. The fact that a technology is ranked high in technology readiness does not mean it is already applied within a country. A high TRL of 9 means a technology is ready to be applied commercially within the industry, and there is no technology showstopper. However, a mature technology may still not be applied in a country due to other reasons such as high cost of capital, lack of investors, government permitting, tax issues or lack of local acceptance, etc. However, a high TRL technology is worth consideration. All ten technologies discussed in this paper are mature with TRL (7–9). Their adoption in any particular country will also depend on the other five other issues (sustainability, security, affordability, relaibility and technology impact) and government policies.

## 5. Issues with renewable energies in ASEAN

### 5.1. Sustainability of hydroelectricity

Fig. 18 shows the history of installed hydropower capacity in ASEAN countries (International Energy Agency (IEA), 2022b). In 2019, hydropower contributed to 14.41% of ASEAN's electricity (Table 4). All ASEAN countries except Singapore and Brunei possess significant amount of hydroelectricity. It is the most dominant source of electricity for Laos (63.2%), Myanmar (46.4%) and Cambodia (46.4%), and second most dominant source for Vietnam (27.8%). These four countries, together with Thailand, are located in the Lower Mekong River Basin. The Mekong River,

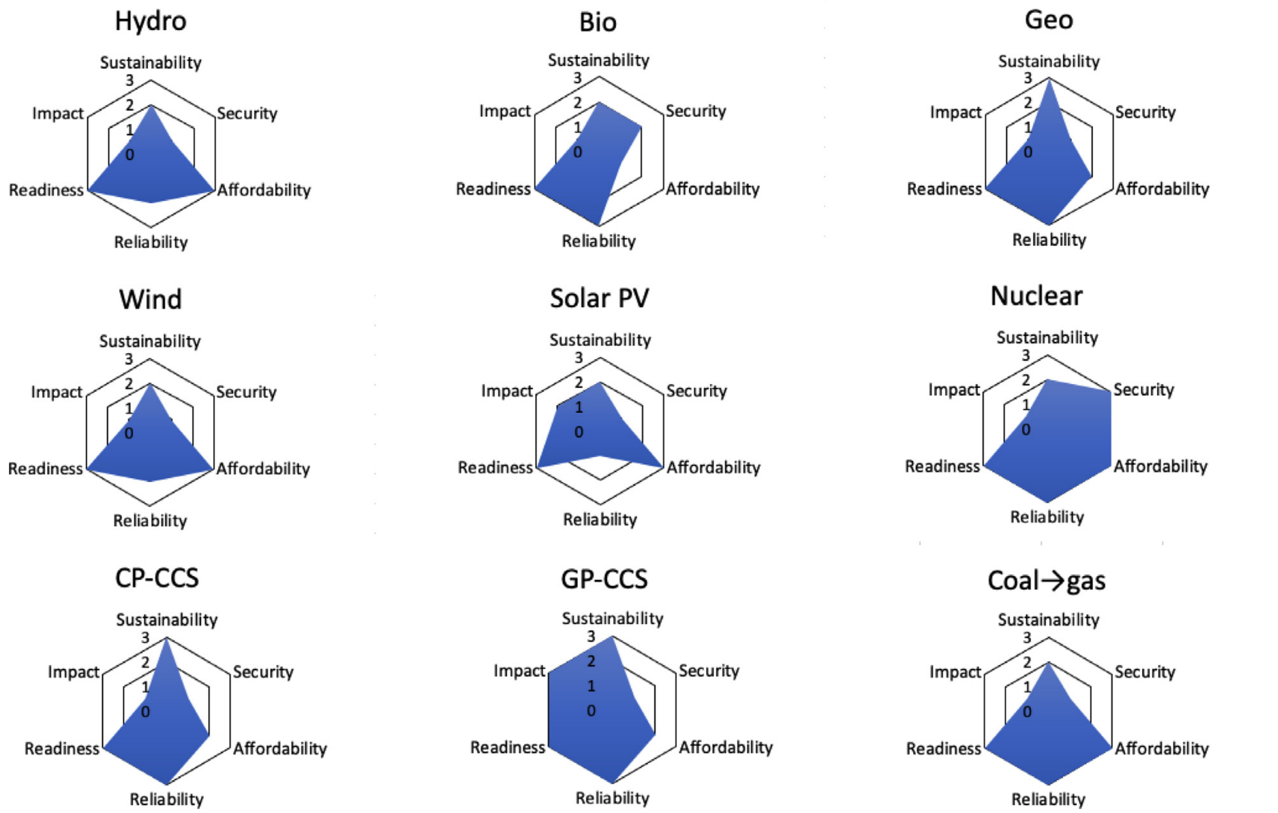


**Fig. 16.** Results of technology screening for Singapore.

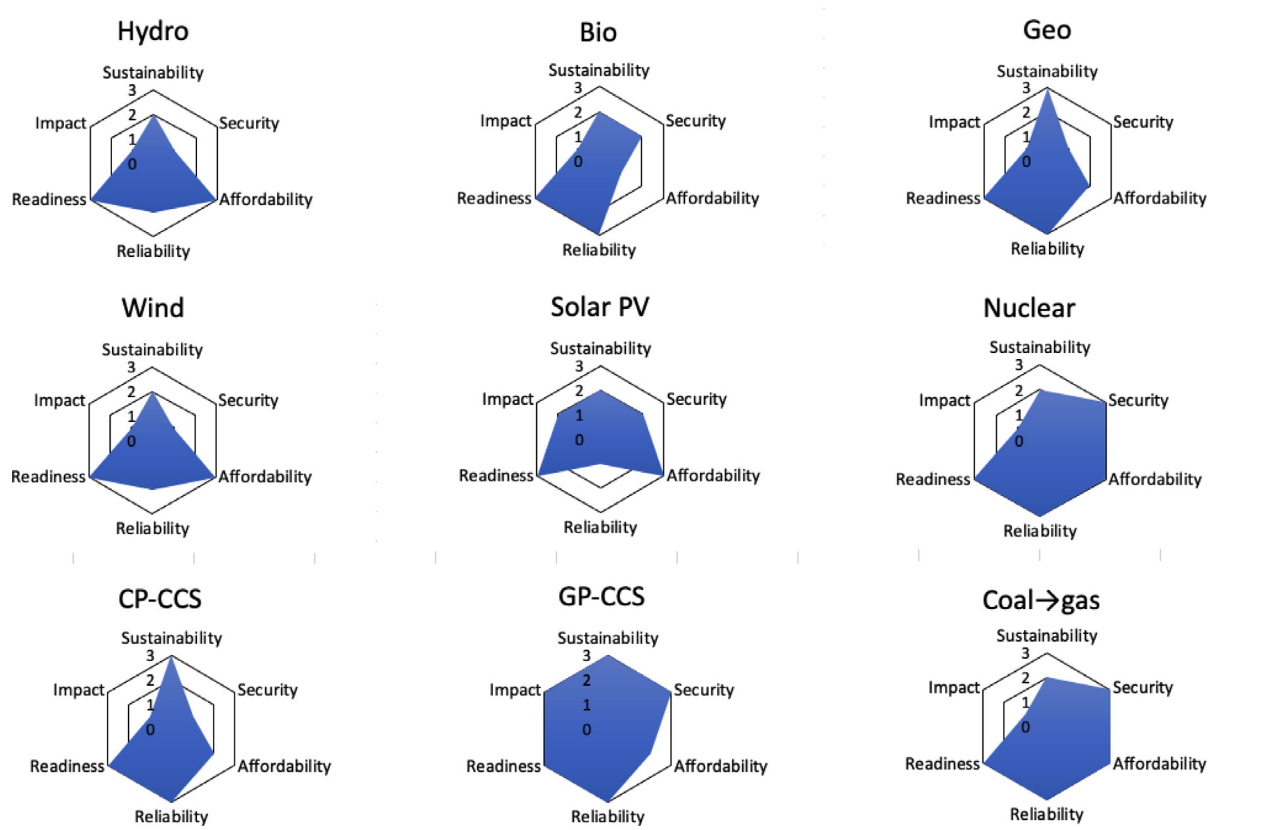


**Fig. 17.** Results of technology screening for Brunei.

**Table 15**
Technology screening for Brunei.

| | Criteria | Hydro | Bio | Geo | Wind | Solar PV | CP-CCS | GP-CCS | Coal → gas | Nuclear |
|---|---|---|---|---|---|---|---|---|---|---|
| Sustainability | Various | Med | Med | High | Med | Med | High | High | Med | Med |
| Security | In-country availability | Low | Med | Low | Low | Med | Low | High | High | High[a] |
| Affordability | LCOE[b] ($/MWh) | 75 | 125 | 100 | 50 | 60 | 120 | 90 | 70 | 70 |
| Reliability | Capacity[c] factor (%) | 39[d] | 47[d] | 59[d] | 27[d] | 10 | 50 | 50 | 50 | 86[e] |
| Readiness | TRL[f] | 9 | 9 | 8 | 9 | 9 | 8 | 8 | 9 | 8 |
| Impact | Potential sector penetration | <5 | <5 | <5 | <5 | 5–10 | <5 | >10 | <5 | <5 |
| Overall assessment on potential in country | | Low | Low | Low | Low | Med | Low | High | Low | Med |

[a]Ranked high because very little uranium is needed to produce a large amount of electricity, and a few years of supply is readily stockpiled. May be regarded as an indigenous energy source.
[b]Data source: Ref. International Energy Agency (IEA) (2020a).
[c]Data source: Ref. International Renewal Energy Agency (IRENA) (2022).
[d]Estimated from ASEAN average.
[e]Data source: Ref. International Atomic Energy Agency (IAEA) (2022).
[f]Data source: Ref. Bui et al. (2018).

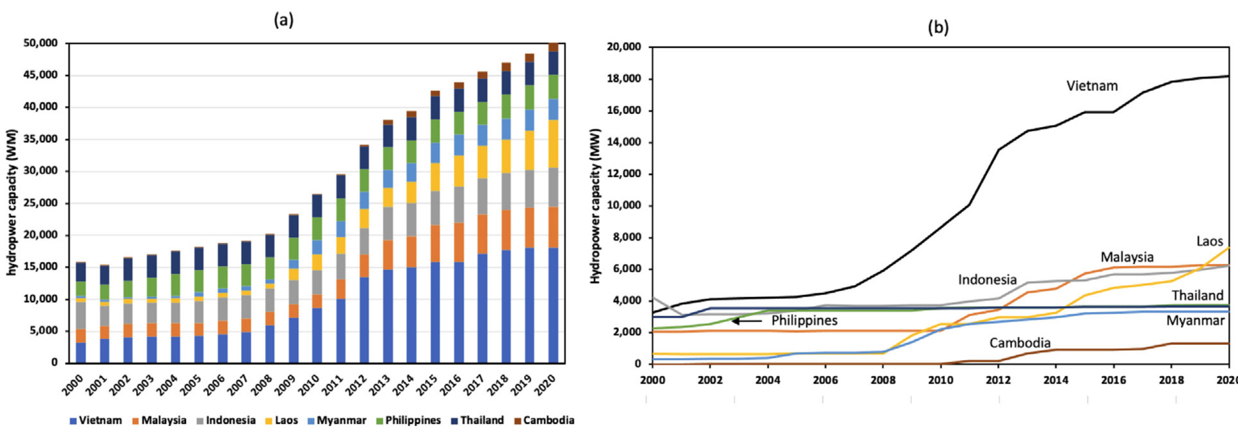


**Fig. 18.** Hydropower capacity in ASEAN (a) cumulatively, and (b) by country (Our World in Data, 2022).

originating in the Qinghai Province of China is one of the biggest rivers in the world. The Lower Mekong Basin is Asia's rice bowl (The Economist, 2022). In 2014, the five lower Mekong countries produced over 100 million tonnes of rice, about 15% of the world's total. The region's fertile soil depends on nutrient-rich sediment carried by the Mekong River during the rainy season from June to October. Over half of the sediment in central Cambodia comes from China. The Mekong River supports the world's largest inland fishery, accounting for one-fourth of the global freshwater catch. Unfortunately, the Mekong is also one of the most heavily dammed rivers in the world. China has already built eleven dams on the Upper Mekong River. Currently, there are two mainstream dams in the Lower Mekong Basin for electricity generation, the Xayaburi dam in Laos and the Don Sahong dam in Cambodia. There are at least seven more mainstream dams planned in Laos. Up to 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 hydropower capacity of 5 GW and 4 GW, respectively, between 2021 and 2030 (International Energy Agency (IEA), 2020c). However, Cambodia has announced the postponement of all dams along the Mekong River until 2030, due to ecological concerns (Kijewski, 2021). Substantial sustainability issues have been raised in all six countries situated along the Mekong River. Research has shown that Mekong River dams affect fish migration, river hydrology, sediment transfers, and negatively impact riparian communities up to 1000 km away (Soukhaphon et al., 2021). 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 (International Centre for Environmental Management (ICEM), 2019). It is uncertain how many of the planned hydropower stations along the Mekong will be actually built due to both sustainability concerns and uncertain international financing (Citowicki, 2020; Kondolf et al., 2014; Weatherby, 2021; Lu and Chua, 2021; Bonnema et al., 2020; Moran et al., 2018). In fact, Fig. 18 shows that except for Laos, addition of hydropower capacity in ASEAN countries has been relatively slow since 2018 (Our World in Data, 2022).

On the other hand, smaller, run-of-the-river hydropower plants (Boyle, 2012), 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 will be beneficial in rural and mountainous areas outside the reach of national grids. It is therefore expected that future growth in ASEAN's hydropower will be in smaller run-of-the-river hydropower plants.

### *5.2. Potential and sustainability of bioenergy for power generation*

With large land masses, and abundant rainfall and sunshine, some ASEAN countries such as Thailand, Indonesia, Malaysia, and the Philipines have medium to high potential for bioenergy, the biomass net primary production (NPP) is 10.5 tC/ha/yr for Indonesia, and the Philippines, 8.5 tC/ha/yr for Malaysia, and 6.5 tC/ha/yr for Thailand, compared to the global average of 3–4 tC/ha/yr (International Energy Agency (IEA), 2022b). According to a recent study by the International Renewable energy Agency (IRENA), direct combustion of agricultural residues for combined heat and power (CHP) generation is the bioenergy pathway that produces the most social and economic benefits ASEAN three countries

**Table 16**
Solar PV potential of ASEAN countries (World Bank Group, 2019).

| Country | Population 2018 | Area ($km^2$) | Average GHI[a] ($kWh/m^2/d$) | PVOUT[b] ($kWh/kW_p/d$) | LCOE ($/kWh) 2018 |
|---|---|---|---|---|---|
| Indonesia | 267,663,435 | 1,811,570 | 4.62 | 3.77 | 0.11 |
| Vietnam | 95,540,395 | 310,070 | 4.25 | 3.55 | 0.12 |
| Thailand | 69,428,524 | 510,890 | 4.93 | 4.06 | 0.10 |
| Malaysia | 31,528,585 | 328,550 | 4.71 | 3.74 | 0.11 |
| Philippines | 106,651,922 | 298,170 | 4.83 | 3.93 | 0.11 |
| Singapore | 5,638,676 | 709 | 449 | 4.06 | 0.10 |
| Laos | 7,061,507 | 230,800 | 4.48 | 3.87 | 0.11 |
| Myanmar | 53,708,395 | 653,080 | 4.69 | 4.14 | 0.10 |
| Cambodia | 16,249,798 | 176,520 | 5.09 | 4.13 | 0.10 |
| Brunei | 428,962 | 5,270 | 4.84 | 3.90 | 0.11 |
| Global average | | | 4.86 | 4.19 | 0.10 |

[a]Global horizontal irradiance.
[b]Photovoltaic power output for utility scale installation, excluding land with physical obstacles.

(International Renewable Energy Agency (IRENA), 2022). In Indonesia, biomass pellets produced from residues of oil palm, rice, sugarcane, rubberwood and acacia may be used to replace coal for CHP plants. In Malaysia, acacia and rubber are potential biomass for CHP plants. In the Philippines, sources of biomass include, agricultural residues, forest residues, agro-industrial waste, and municipal solid waste. In Thailand, agricultural resides from major crops, rubber and teak may be used for CHP plants. In addition, wood processing plants in these countries also produces significant quantity of wood waste which can be used for power generation. Furthermore, waste from food processing industries can be used to generate biogas for power generation. Municipal solid waste in heavily populated urban areas may also be used for power generation. Biomass resources, particularly residues from agricultural crops, forests, wood processing, and food-processing are under-utilized in these southeast Asian countries for commercial heat and power generation.

On the other hand, there is a need for biomass resources for power generation to be certified for sustainability as some ASEAN countries are known to cut down tropical rainforests for wood processing and palm oil plantation. This has created significant sustainability issues such as competition for agricultural land and water resources, food scarcity, loss of biodiversity, deforestation, drainage of peatland, greenhouse gas emission, soil erosion, rural development, social conflicts, and public health issue (Gasparatos and Takeuchi, 2013; Hogan, 2021; Gaveau et al., 2022). These issues need to managed and minimized.

### 5.3. Potential and reliability of solar PV

Table 16 compares the average global horizontal irradiance (GHI), photovoltaic power output (PVOUT) and LOCE of solar PV in ASEAN countries (World Bank Group, 2019). Both GHI and PVOUT measure the solar PV potential of a country. The former measures the irradiance on a horizontal surface, whereas the latter measures the power generated by irradiance on a solar PV panel. It can be seen that the solar PV potential and LCOE of ASEAN countries are close to the global averages. Countries with large land masses (Indonesia, Myanmar, Thailand, Malaysia and Vietnam) have more land available for solar PV installations. On the other hand, Singapore has limited space for solar installation due to its limited land mass and high population density. Overall speaking, solar PV is under-utilized in ASEAN countries and can be further developed. Among ASEAN countries, Vietnam has the largest installed solar PV capacity, all of which was installed in 2019 and 2020.

On the other hand, solar PV in ASEAN countries suffers from a low capacity factor as equatorial countries have higher cloud density and frequent rainfall. Besides, there is no sunshine at night. Table 17 compares the capacity factor of solar PV with other renewable energies in ASEAN. The average capacity factor of solar PV in ASEAN is only 12 compared to 46 for fossil power plants. Therefore, to generate the same amount of electricity as a fossil power plant, 2.8 times more solar PV capacity are needed. In 2019, ASEAN's solar PV has a total installed capacity of 10.3 GW, which was the second highest among renewable energies. However, it only generated 12.9 TWh of electricity, which was the fourth highest among renewable energies in ASEAN, amounting to only 1.1% of total electricity generated (Table 4). Due to the variability of solar PV, energy storage is needed. Battery and pumped storage are two common forms of energy storage. Pumped storage is used commonly in ASEAN countries. However, use of it to store energy generated by solar PV or wind will require the hydropower station to be close to the solar or wind farm. Battery and other storage technologies for solar renewable energies is still in the R&D stage.

Grid improvement will also be needed for further expansion of solar PV, as ASEAN's power cannot handle demand surges. Export of renewable electricity between ASEAN countries will likely require upgrading ASEAN's regional power grid.

Another issue with solar PV is the disposal of used solar panels. Solar panels are designed to last for about 25 years. If the panels contain metals such as lead and cadmium, they are regarded as hazardous waste in the US and must be disposed of accordingly (United States Environmental Protection Agency (EPA), 2022).

### 5.4. Reliability and security issues of wind energy

One major issue with wind energy in ASEAN is that most of Southeast Asia lacks significant wind speed (>7 m/s) for efficient operation of wind turbines (Boyle, 2012). Most of Southeast Asia has an onshore wind speed is less than 4 m/s (Global Wind Atlas, 2021). In fact, Singapore, Brunei, Cambodia, Malaysia, Myanmar, Laos and Thailand have 80 to 100% of their land having wind power density at 100 m of less than 260 $W/m^2$ (International Energy Agency (IEA), 2022b) which is too low for wind turbine operations. However, a 2001 report by the World Bank found that there are locations in the mountains of central and southern Vietnam, central Laos, and central and western Thailand that have good to excellent wind resources (The World Bank, 2001). Also, coastal areas of southern and south-central Vietnam show good promise for wind energy. On a land area basis, approximately, 8.6% of Vietnam, 0.2% of Cambodia, 2.9% of Laos and 0.2% of Thailand have good to excellent winds for large-scale wind generation. Wind energy contributed to only 0.52% of ASEAN electricity generation in 2019 (Table 4). In addition, wind energy also suffers from a low utilization capacity factor of 27% which is the second lowest among renewable energies (Table 17). To remedy this situation, new wind turbine designs for low wind speed power (LWSP) will be needed, but is still in R&D stage (Energy Watch, 2022). ASEAN does not have a wind energy industry which means equipment and material have to be imported,

**Table 17**
Utilization capacity of power plants by fuel type (%) in ASEAN, 2019 (International Energy Agency (IEA), 2022b).

| *Country* | Fossil | Hydro | Bio | Solar PV | Geo | Wind |
|---|---|---|---|---|---|---|
| Indonesia | 48 | 40 | 74 | 9 | 76 | NA |
| Vietnam | 47 | 58 | 12 | 11 | NA | 15 |
| Thailand | 43 | 24 | 86 | 20 | 38 | 28 |
| Malaysia | 61 | 47 | 31 | 6 | NA | NA |
| Philippines | 53 | 28 | 33 | 15 | 63 | 27 |
| Singapore | 48 | NA | 100 | 12 | NA | 40 |
| Laos | 4 | 35 | 13 | 14 | NA | NA |
| Myanmar | 48 | 45 | 51 | 9 | NA | 38 |
| Cambodia | 54 | 35 | 23 | 11 | NA | 14 |
| Brunei | 50 | NA | NA | 10 | NA | NA |
| Average | 46 | 39 | 47 | 12 | 59 | 27 |

adding to transportation cost. Furthermore, used turbine blades are not recyclable and therefore need to be disposed of as solid waste. There is ongoing research to develop recyclable wind turbine blades (Paulsen and Enevoldsen, 2021). Within ASEAN, Thailand, Indonesia, Vietnam and the Philippines have plans to develop more wind power. More supportive government policies and financial incentives will be needed to stimulate wind energy growth in other ASEAN countries.

### *5.5. Availability and affordability of geothermal energy*

In ASEAN, geothermal energy is only available in Indonesia and the Philippines, which are located in the Ring of Fire (Boyle, 2012; National Geographic, 2022; Nasruddin et al., 2016; Fauzi, 2015; Masum and Ali Akbar, 2019; Pambudi, 2018). There has been no addition of geothermal energy in both countries since 2020. The slow addition of geothermal energy in both countries is due to many reasons (Asian Development Bank and World Bank, 2015). A 2015 report on Indonesia's geothermal sector found that many reasons have stymied development of geothermal energy including institutional, regulatory and tariff issues (Asian Development Bank and World Bank, 2015). In the Philippines, the government has limited foreign ownership of assets in this sector, thus discouraging foreign investment. In addition, the high cost of drilling geothermal exploration wells also means that private investors have to bear most of the upfront risks in both countries, thus making investment in geothermal electricity unaffordable. Unless the governments of Indonesia and Philippines create an environment encouraging private investment in geothermal energy, there will be limited growth (Chelminski, 2018; Richter, 2020).

## 6. Issues with fossil and nuclear electricity

### *6.1. Coal*

Within ASEAN, Indonesia and Laos are the only countries which are self-sufficient in coal. Since 2012, Indonesia's coal production has peaked at around 500 million short tons per year (The Global Economy, 2022), making it the fifth largest coal producing country in the world. It consumes 20% and exports 80% of its coal production to China and India. Laos produced 22.5 million short tons of coal in 2019 of which 91% was consumed and 9% was exported. All other ASEAN countries have to import coal. Coal is the largest contributor to electricity generation in Indonesia (59.1%), the Philippines (54.6%), Vietnam (49.9%), Malaysia (45.9%) and the second largest contributor in Cambodia (43.0%) and Laos (36.5%) (Table 4). However, among fossil fuels (coal, oil, and gas), coal emits the most $CO_2$ when combusted. Given coal's dominance in electricity generation in ASEAN and the unlikelihood of its replacement by renewable energies, finding low-carbon coal solutions is a necessity for decarbonizing the electricity sector in ASEAN.

Table 18 shows that coal consumption and production data for ASEAN countries in 2019 (The Global Economy, 2022). Practically speaking, Indonesia is the only ASEAN country that exports coal. In Brunei and Singapore, coal plays no or insignificant part in the energy mix. Myanmar and Laos are mostly self-sufficient in coal. Malaysia, Vietnam, Philippines, Cambodia, and Thailand all have to import significant amount of coal for energy consumption. This suggests that coal is too important a component of the energy mix to be removed. Hence the use of clean coal technologies is a necessity in the decarbonization of ASEAN.

### *6.2. Natural gas*

Natural gas was responsible for 33.65% of ASEAN's electricity generation in 2019, making it the second largest contributor after coal (Table 4). It is the largest contributor to electricity generation in Singapore (95.0%), Brunei (89.2%), Thailand (63.5%), and Myanmar (46.7%) and the second largest in Malaysia (37.1%), Philippines (21.1%), and Indonesia (20.8%). It has no contribution to electricity in Laos and Cambodia. In addition, gas is the cleanest fossil fuel and produced roughly one-half of the $CO_2$ compared to coal when combusted.

Table 19 shows that natural gas production and consumption data for ASEAN countries in 2020 (Fauzi, 2015). Malaysia, Indonesia, Myanmar and Brunei are net exporters of natural gas, whereas Singapore and Thailand are net importers of natural gas. As a region, ASEAN is a net exporter of natural gas in 2020. This suggests that as a region, surplus natural gas can be used to replace coal for electricity generation, if infrastructure to transport natural gas such as LNG terminals or gas pipelines are available.

### *6.3. Oil*

In 2019, oil-fired power plants contributed to only 1.62% of ASEAN's electricity generation (Table 4). Thus, oil plays an insignificant role in power generation in ASEAN. Oil is mostly used as fuels for transportation and as raw material for the petrochemical industries.

### *6.4. Nuclear power*

There is no nuclear power plants in ASEAN. Nonetheless, ASEAN governments have expressed interest in nuclear power plants, although their efforts have been sporadic and not supported by policies. Within ASEAN, Indonesia, Malaysia, Vietnam and the Philippines are more likely to install nuclear power plants by 2030–2035, given their overall readiness (The Diplomat, 2018). However, public acceptance of nuclear power in ASEAN is low, except in Indonesia. ASEAN countries are densely populated making it difficult to build a nuclear power plant far from an urban center. This will magnify the impact on people, animals and environment should an accident occur. Therefore, public engagement is needed to improve public acceptance. Otherwise, the future of nuclear energy in ASEAN will be limited.

**Table 18**
Coal production and consumption data for ASEAN countries in 2019 (The Global Economy, 2022).

| Country | Production ($10^3$ short ton) | Consumption ($10^3$ short ton) | Net import ($10^3$ short ton) |
|---|---|---|---|
| Malaysia | 3812 | 42,860 | 39,048 |
| Indonesia | 679,199 | 152,580 | −526,661 |
| Myanmar | 1572 | 1893 | 321 |
| Brunei | 0 | 0 | 0 |
| Vietnam | 50,361 | 74,810 | 24,449 |
| Cambodia | 0 | 1864 | 1864 |
| Laos | 22,527 | 20,578 | −1949 |
| Philippines | 12,356 | 35,772 | 23,416 |
| Singapore | 0 | 811 | 811 |
| Thailand | 15,518 | 34,047 | 18,529 |
| Total | 785,345 | 365,215 | −420,130 |

**Table 19**
Natural gas production and consumption data for ASEAN countries in 2020 (IndexMundi, 2022).

| Country | Production (bcm) | Consumption (bcm) | Net import (bcm) |
|---|---|---|---|
| Malaysia | 69.49 | 30.44 | −39.05 |
| Indonesia | 72.09 | 42.32 | −29.77 |
| Myanmar | 18.41 | 4.50 | −13.91 |
| Brunei | 12.74 | 3.94 | −8.80 |
| Vietnam | 8.10 | 8.10 | 0 |
| Cambodia | 0 | 0 | 0 |
| Laos | 0 | 0 | 0 |
| Philippines | 3.06 | 3.14 | 0.09 |
| Singapore | 0 | 12.97 | 12.97 |
| Thailand | 38.59 | 52.64 | 14.05 |
| Total | 222.47 | 158.05 | −64.43 |

## 7. Low-carbon fossil electricity

Since coal and natural gas both play an important part in electricity generation in ASEAN, it is only natural that decarbonizing this sector will require low-carbon fossil solutions.

### 7.1. Clean coal technologies

In general, there are at least four types of technologies that can reduce $CO_2$ emissions from coal-fired power plants including: (1) coal upgrading, (2) efficiency improvement in existing plants, (3) advanced technologies and (4) near-zero emissions technologies (International Energy Agency (IEA), 2022a). Together, these are called clean coal technologies (CCT). Coal upgrading includes coal washing, drying and briquetting. Although it is widely used in the world, there is scope for its application in developing countries in Southeast Asia. It can reduce $CO_2$ emission by up to 5%. Efficiency improvement includes converting from sub-critical plants to supercritical (540–560 °C, 25 bar) or ultra-supercritical (>590 °C, >250 bar) plants by using steam of higher temperature and pressure. This can achieve efficiency of up to 45% and reduce $CO_2$ emission up to 22%. Advanced technologies include integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion plants that can reduce $CO_2$ emission up to 25%. Zero-emission technologies include CCS that could reduce $CO_2$ emission close to or near zero. These CCTs should be retrofitted into existing or incorporated into future coal-fired power plants in ASEAN countries.

### 7.2. Switching from coal to gas for power generation

Switching from coal to gas for power generation seems to be a low-hanging fruit for decarbonizing ASEAN's power sector (International Renewal Energy Agency (IRENA), 2022; Asian Development Bank (ADB), 2013; Lau, 2022a). This is especially relevant for ASEAN countries, except Singapore, Brunei and Myanmar where gas is a either the largest or second largest contributor of electricity generation (Table 4). However, with gas production from ASEAN countries declining, investment in LNG terminals will be needed to ensure a stable supply of natural gas from countries outside of ASEAN. Within ASEAN, Indonesia, Malaysia and Brunei export LNG, whereas Thailand, Singapore, Indonesia, and Malaysia import LNG. Vietnam, Philippines, Laos and Cambodia which use a fair amount of coal for electricity generation currently have no LNG import terminals (Table 4), thus making it difficult for them to replace coal by gas for power generation. Investment in LNG infrastructure will therefore be an important part of the energy transition for these countries.

### 7.3. CCS for fossil power plants

The use of CCS to mitigate $CO_2$ emitted from coal- and gas-fired power plants is the main method to decarbonize ASEAN's power sector. As of 2020, there were 28 large-scale CCS project in operation worldwide with a total storage capacity of 41 Mtpa with more in the planning stage (Global CCS Institute, 2022). In the last several years, CCS has picked momentum with a number of significant projects currently being planned. These include the Longship project in Norway storing 0.8–5.0 Mtpa $CO_2$ (Equinor, 2019, 2022), the Porthos project storing 2.5 Mtpa $CO_2$ (Porthos, 2022) and Aramis project storing 2.5 Mtpa $CO_2$ (Aramis, 2022) in the Netherlands, the East Coast Cluster project in UK storing 27 Mtpa $CO_2$ (East Coast Cluster, 2022), and the Houston CCS Alliance project storing 100 Mtpa $CO_2$ (Houston CCS Alliance, 2022). As large-scale implementation of CCS is happening in Europe and US, ASEAN countries should consider CCS seriously as a decarbonization technology, among others.

### 7.4. CCS potential for Southeast Asia

As fossil fuels will continue to be a significant part of the energy mix for power generation in ASEAN in the foreseeable future, it is only reasonable for governments to consider technologies that can mitigate $CO_2$ emission from the burning of fossil fuels for power generation. In fact, it is generally agreed that, without carbon capture, utilization and storage (CCUS) technologies, decarbonization will be more costly and complicated (Baylin-Stern and Berghout, 2021). The International Energy Agency (IEA) concluded that net-zero cannot be achieved without CCUS technologies (International Energy Agency (IEA), 2020b). Carbon capture technologies include pre-combustion, post-combustion, and oxy-fuel combustion (International Energy Agency (IEA), 2020b). Among these, post-combustion is technologically most ready. There are many carbon utilization technologies, such as converting $CO_2$ into chemicals, or using it to proudce other products, such as building materials. However, these processes are energy intensive and often require the use of catalysts. They are also not ready for large-scale implementation (Bui et al., 2018). At present, CCS is the only technology ready for large-scale (million tonnes per year) mitigation of $CO_2$. In CCS, the $CO_2$ captured is compressed and shipped by pipelines or ships to a suitable site for permanent storage in a subsurface reservoir, such gas an oil reservoir, gas reservoir or a saline aquifer. Under suitable reservoir temperature, pressure, and crude composition, $CO_2$ injection into a partially depleted oil or gas reservoir may lead to incremental production. This is commonly known as $CO_2$ enhanced oil recovery ($CO_2$-EOR) or $CO_2$ enhanced gas recovery ($CO_2$-EGR). Some authors classify $CO_2$-EOR and $CO_2$-EGR as CCU technology since the $CO_2$ is utilized to produced incremental oil or gas (Bui et al., 2018). In this paper, they are classified as CCS technology since the injected $CO_2$ can be designed to stay permanently in the reservoir.

In CCS, $CO_2$ can commonly be stored in three types of reservoirs: oil reservoirs, gas reservoirs, and saline aquifers. Recent research has shown that, in general, about 98% of the storage capacity is found in saline aquifers and only 2% is found in oil or gas reservoirs (Lau et al., 2021b). In fact, there is no lack of sedimentary basins in Southeast Asia where these three types of reservoirs are found. Most of the basins in Southeast Asia have been explored for oil and gas development and much is known about their subsurface characteristics. Table 20 gives a summary of $CO_2$ storage capacity in some sedimentary basins in Indonesia, Malaysia, Thailand and Vietnam, based on recently published research results (Lau et al., 2022b; Zhang et al., 2022; Lau and Ramakrishna, 2021; Lau et al., 2021a; Zhang and Lau, 2022a; Lau, 2022a,b). In these basins, a total of 11.0 Gt of $CO_2$ storage space resides in gas reservoirs, 1.07 Gt resides in oil reservoirs and 629 Gt resides in saline aquifers. These basins alone can store almost four centuries of $CO_2$ emission from all ASEAN countries (1.65 Gtpa in 2020).

### 7.5. First mover CCS projects in ASEAN

Table 21 shows eleven first mover CCS projects proposed by the author, based on results of $CO_2$ source–sink mapping exercises (Lau and Ramakrishna, 2021; Lau et al., 2021a; Zhang and Lau, 2022a; Lau et al., 2021b; Bokka and Lau, 2023). Note that some of these projects involve not only the power but also the industry sector. These projects involve five major economies of ASEAN: Singapore, Indonesia, Malaysia, Thailand, and Vietnam. If all these projects are implemented, they will mitigate up to 391 Mtpa $CO_2$, which is 22% of the total $CO_2$ emission from these five countries in 2019. The total storage capacity in these projects is enough to store 180 years of $CO_2$ emission. In addition, 1,759 MMbbl of incremental oil and/or condensate can be produced.

Recently, Zhang and Lau (2022b) have proposed utilizing the high-temperature depleted Arun gas condensate reservoir in Indonesia for the triple purpose of $CO_2$ storage, gas condensate production and geothermal heat mining (Zhang and Lau, 2022b). Their work has shown that $CO_2$ injection into the now depleted Arun gas reservoir can produce 51 MMbbl of condensate over 16 years. Afterwards, continuous $CO_2$ injection without any production over 20 years can allow 1.2 Gt of $CO_2$ to be stored. In addition, subsequent recycling of $CO_2$ can produce substantial amount of geothermal energy for electricity production. The production of geothermal energy in conjunction with CCS in a high-temperature gas reservoir will be a first in the world. This can be an extension of the first CCS project proposed in Table 21.

## 8. Discussion

To achieve net-zero by 2050, decarbonization is an urgent task that needs to be accomplished in the next three decades. In 2019, ASEAN emitted 1.76 Gt of $CO_2$, of which 38% came from the power sector through the burning of fossil fuels. Decarbonization ASEAN's power sector is therefore vital to the overall decarbonization process. In ASEAN's power sector, 78% of power was generated by fossil fuels (43.0% from coal, 1.6% from oil, 33.7 from gas) and 22% from renewable energies in 2019 (International Renewal Energy Agency (IRENA), 2022). ASEAN countries, therefore, need to use all available tools, both fossil and non-fossil, to achieve decarbonization. Non-fossil include renewable energies and nuclear power. Fossil tools include coal → gas, CP-CCS and GP-CCS. All these tools should be considered and each ASEAN country will choose its decarbonization pathways based on availability of fossil and non-fossil energy resources and country-specific priorities such as energy security, affordability, sustainability, etc. The results of the technology screening exercise presented here will provide information to policy makers for devising the optimal country-specific polices for decarbonization.

## 9. Policy implications

A number of policy implications can be derived from this study.

### 9.1. Establishing a credible carbon tax

Establishing a credible carbon tax is a necessary first step for national governments to commit to the energy transition. At present, Singapore is the only ASEAN country that has a carbon tax. It is currently SGD 5/ton $CO_2$(USD 3.7/ton) which will increase to SGD $25/ton (USD 18.3/ton) in 2024. The Singaporean government has announced it will increase the carbon tax to SGD $50–80/ton (USD 36.6–58.5/ton) by 2030 (National Climate Change Secretariat Singapore (NCCS), 2022). A credible carbon tax incentivize companies to reduce or mitigate their $CO_2$ emission. Without either a carbon tax or credit, the energy transition will not take place. A credible carbon tax will also enable national governments to build up a reserve to support R&D in low-carbon solutions. It is no wonder that almost all large scale CCS projects take place in countries that have a substantial carbon tax or credit such gas US, Canada, Norway, and UK (Global CCS Institute, 2022).

### 9.2. Promoting clean coal technologies

Recognizing that coal will remain an important part of the energy mix in the foreseeable future, ASEAN governments should promote the use of clean coal technologies in existing and future coal-fired power plants to increase energy efficiency and reduce $CO_2$ emission. This includes using supercritical, ultra-supercritical technologies, integrated gasification and combined cycles (IGCC) and pressurized fluidized bed combustion plants power plant, etc. (International Energy Agency (IEA), 2022a).

**Table 20**
$CO_2$ storage capacity in selected sedimentary basins in ASEAN.

| Country | Basin | Gas fields (Mt) | | | Oil field (Mt) | | | Saline aquifer (Mt) | | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Low | Mid | High | Low | Mid | High | Low | Mid | High | |
| Indonesia | C. Sumatra | 68 | 73 | 77 | 146 | 156 | 167 | 2,813 | 11,032 | 30,338 | Lau et al. (2021a) |
| | S. Sumatra | 599 | 639 | 678 | 44 | 47 | 51 | 6873 | 26,954 | 74,123 | Lau et al. (2021a) |
| | W. Natuna | 67 | 71 | 1866 | 22 | 23 | 24 | 9755 | 38,255 | 105,202 | Lau et al. (2021a) |
| | N. Sumatra | 1,694 | 1,780 | 156 | 7 | 7 | 8 | 28.557 | 111,900 | 307,973 | Lau et al. (2021a) |
| | NW Java | 138 | 147 | 2461 | 53 | 58 | 62 | 7100 | 27,842 | 76,564 | Lau et al. (2021a) |
| | E. Natuna | 2,171 | 2,316 | 5.314 | 0 | 0 | 0 | 15,286 | 59,944 | 164,846 | Lau et al. (2021a) |
| | Subtotal | 4,737 | 5,026 | 5314 | 271 | 291 | 313 | 70,384 | 275,927 | 759,046 | |
| Malaysia | Malay | 1,381 | 1,448 | 1538 | 158 | 174 | 191 | 19,315 | 75,746 | 208,301 | Lau et al. (2021a) |
| | Pengyu | 0 | 0 | 0 | 8 | 8 | 9 | 7058 | 27,678 | 76,114 | Lau et al. (2021a) |
| | Subtotal | 1,381 | 1,448 | 1538 | 165 | 82 | 200 | 26,373 | 103,424 | 284,415 | |
| Thailand | Khorat | 93 | 104 | 115 | 0 | 0 | 0 | 16,008 | 62,775 | 172,631 | Zhang et al. (2022) |
| | Pattani | 784 | 868 | 953 | 23 | 25 | 27 | 1285 | 5040 | 13,860 | Zhang et al. (2022) |
| | Malay | 691 | 743 | 796 | 0 | 0 | 0 | 874 | 3426 | 9,420 | Zhang et al. (2022) |
| | Fang | 0 | 0 | 0 | 2 | 2 | 2 | 69 | 271 | 746 | Zhang et al. (2022) |
| | Kampaeng Saen | 0 | 0 | 0 | 1 | 0 | 1 | 42 | 164 | 451 | Zhang et al. (2022) |
| | Phetchbun | 0 | 0 | 0 | 0 | 2 | 0 | 83 | 324 | 891 | Zhang et al. (2022) |
| | Philsanulok | 0 | 0 | 0 | 15 | 1 | 1 | 341 | 1337 | 3,675 | Zhang et al. (2022) |
| | Suphan Buri | 0 | 0 | 0 | 0 | 16 | 17 | 100 | 393 | 1,080 | Zhang et al. (2022) |
| | Chumpon | 0 | 0 | 0 | 2 | 0 | 0 | 751 | 2945 | 8,099 | Zhang et al. (2022) |
| | Songkhla | 0 | 0 | 0 | 2 | 2 | 3 | 231 | 907 | 2,495 | Zhang et al. (2022) |
| | Subtotal | 1,567 | 1,715 | 1864 | 45 | 49 | 53 | 19,784 | 77,582 | 213,348 | Zhang et al. (2022) |
| Vietnam | Cuu-Long | 245 | 274 | 303 | 370 | 465 | 560 | 1721 | 6.750 | 18,563 | Bokka and Lau (2023) |
| | Nam Con Son | 541 | 605 | 670 | 39 | 49 | 59 | 6197 | 24,300 | 66,825 | Bokka and Lau (2023) |
| | Song Hong | 1,328 | 1,484 | 1644 | 10 | 12 | 15 | 8262 | 32,400 | 89,100 | Bokka and Lau (2023) |
| | Malay-Tho-Chu | 413 | 461 | 511 | 19 | 24 | 28 | 7343 | 28,796 | 79,188 | Bokka and Lau (2023) |
| | Tu Chinh-Vung May | 0 | 0 | 0 | 0 | 0 | 0 | 1928 | 7500 | 20,790 | Bokka and Lau (2023) |
| | Hong Sa+ Trung Sa | 0 | 0 | 0 | 0 | 0 | 0 | 17,213 | 67,500 | 185,625 | Bokka and Lau (2023) |
| | Phu Khanh | 0 | 0 | 0 | 0 | 0 | 0 | 3856 | 15,120 | 41,580 | Bokka and Lau (2023) |
| | Subtotal | 2,526 | 2,841 | 3128 | 437 | 549 | 662 | 46,520 | 182,426 | 501,671 | |
| Total | | 10,211 | 11,014 | 11,844 | 918 | 1072 | 1227 | 163,061 | 629,061 | 1,758,480 | |

### *9.3. Recognizing and promoting CCS as a low-carbon fossil solution*

Recognizing and promoting CCS as a low-carbon fossil solution in the power section is also important. Governmental promotion of these technologies will be needed for these technologies to attract international financing. The biggest barriers to large scale implementation of CCS is cost and lack of governmental support (Lau et al., 2021b). With the current environmental, social and governance (ESG) screening used by many financial institutions to evaluate their investment portfolio, it is difficult for private investors to obtain the bank loans needed for large-scale CCS projects. However, this will change if CCS gets recognized as a low-carbon energy solution by national governments. A good example is the Northern Lights CCS project in Norway. This multi-billion dollar CCS project is partially funded by the Norwegian government and partially by the private sector (Equinor, 2019, 2022). There are many ways governments can promote large-scale adoption of CCS. This includes increased public engagement, establishing CCS corridors to take advantage of economies of scale, and forming private–public partnership to handle the management and operation of CCS projects (Lau et al., 2021b, 2022a; Lau and Lin, 2022).

**Table 21**
Proposed first mover CCS projects in ASEAN.

| $CO_2$ sink | | | | $CO_2$ source | | | | $CO_2$ transport | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Country | Field & basin | $CO_2$ EOR/EGR (MMbbl) | $CO_2$ 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) | 51 | 1200 | Power, chemical, refinery | Jurong Island | Singapore | 32 | Ship | 890 | Lau and Ramakrishna (2021), Lau et al. (2021a), Zhang and Lau (2022a) and Zhang and Lau (2022b) |
| | | | | Power, cement, refinery | North Sumatra | Indonesia | 10 | Pipeline | 250 | Lau and Ramakrishna (2021), Lau et al. (2021a) and Zhang and Lau (2022a) |
| | Minas oil field, Central Sumatra (onshore) | 767 | 113 | Power, chemical, refinery | Jurong Island | Singapore | 32 | Pipeline | 200 | Lau and Ramakrishna (2021), Lau et al. (2021a) and Zhang and Lau (2022a) |
| | | | | Power, cement, refinery | Central Sumatra | Indonesia | 19 | Pipeline | 250 | Lau and Ramakrishna (2021), Lau et al. (2021a) and Zhang and Lau (2022a) |
| Malaysia | Dulang, Tapis, Seligi oil fields, Malay Basin (offshore) | 303 | 106 | Power, cement, chemical, refinery | Jurong Island | Singapore | 32 | Ship or pipeline | 440 | Lau and Ramakrishna (2021), Lau et al. (2021a) and Zhang and Lau (2022a) |
| | | | | Cement, iron & steel, power, refinery | Peninsular Malaysia | Malaysia | 137 | Pipeline | 250 | Lau and Ramakrishna (2021), Lau et al. (2021a) and Zhang and Lau (2022a) |
| Thailand | Saline aquifers in Phitsanulok, Supan Buri, Phetchabun basins (onshore) | Not applicable | 2053 | Cement in Saraburi, power in Kamphaeng Phet | Saraburi | Thailand | 41 | Pipeline | 20 to 200 | Zhang et al. (2022) |
| | Saline aquifers in Khorat Basin (onshore) | Not applicable | 62,775 | Petrochemical, iron & steel, refinery, power | Bangkok & Rayong | Thailand | 77 | Pipeline | 100 to 200 | Zhang et al. (2022) |
| | Saline aquifers in Chumpon Basin (offshore) | Not applicable | 2945 | Gas processing, cement, power | Nakhon Si, Nakhon Sri Thammart, Surat Thai, Krabi, Phuket | Thailand | 10 | Pipeline | 50 to 200 | Zhang et al. (2022) |

(*continued on next page*)

### *9.4. Switching from coal to gas for power generation*

Switching from coal to gas is a logical next step in decarbonizing ASEAN's power sector. This is especially relevant for countries like Indonesia, Vietnam, Malaysia, Philippines, Laos and Cambodia which rely heavily on coal for power generation (Table 4). However, the construction of LNG import terminals is need for Vietnam, Philippines, Laos and Cambodia. This will require substantial support from national governments and will only happen if national governments recognize the permanence of natural gas in their future energy mix.

### *9.5. Addressing sustainability issues with hydropower*

Although hydropower has been the dominant of renewable energy for power generation in ASEAN, the relentless addition of hydropower capacity has caused a host of sustainability issues

**Table 21** (*continued*).

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Vietnam | Te Glac Trang Oil field | 81 | 45 | Duyen Hai power plant | Ho Chi Minh City | Vietnam | 13 | Pipeline | 180 | Bokka and Lau (2023) |
| | Ken Bau Gas field | 34 | 535 | Formosa Ha Tinh Steel plant | Vung Ang Economic Zone | Vietnam | 14 | Pipeline | 120 | Bokka and Lau (2023) |
| | Back Ho Oil field | 480 | 212 | Vinth Tan power plant | Binh Thuan Province | Vietnam | 31 | Pipeline | 100 | Bokka and Lau (2023) |
| | PM3-CAA Oil field | 40 | 22 | Ca Ma power plant | Ca Mau | Vietnam | 5 | Pipeline | 330 | Bokka and Lau (2023) |
| | Hac Long Gas field | 4 | 135 | Nghi Son steel mill | Thanh Hoa Province | Vietnam | 4 | Pipeline | 90 | Bokka and Lau (2023) |
| Total | | 1759 | 70,141 | | | | 391 | | | |

surrounding over-damming of major rivers, e.g. the Mekong. It is therefore important for ASEAN governments to reassess these issues and recalibrate their plan for the future of hydropower. Adoption of run-of-the-river hydropower stations may be an alternative solution.

### *9.6. Addressing sustainability and affordability of bioenergy*

Bioenergy has medium to high potential and is under-utilized for power generation in Indonesia, Thailand, Malaysia and the Philippines. Government policies are needed to provide financial incentives and encourage the collection and transportation of agricultural residues for combined heat and power generation. In addition, independent certification of the sustainability of biomass will also be needed.

### *9.7. Recognizing reliability issues with solar PV*

Solar PV potential in ASEAN countries is similar to the world average. However, in ASEAN countries with large land masses such as Indonesia, Myanmar, Thailand, Vietnam, Malaysia and the Philippines, solar PV can be further developed. Due to solar PV's variability, grid improvement and energy storage technologies are needed to underpin this development.

### *9.8. Recognizing reliability issues with wind*

Wind energy potential in ASEAN suffers from a low average wind speed, although exceptions can be found. To further develop wind, ASEAN governments should fund R&D in LWSP and offshore wind.

### *9.9. Promoting private sector investment in geothermal energy in Indonesia and the Philippines*

Within ASEAN, geothermal energy is only available in the Philippines and Indonesia. However, it is under-utilized in both countries due to a host of reasons, most of which are non-technical. The key to increased use of geothermal energy is to encourage private investment by reducing and simplifying regulations, promoting risk sharing between governments and companies and allowing private companies to compete with state owned companies. Recent research has also shown that many high-temperature depleted gas reservoirs can be used for both $CO_2$ storage and geothermal heat mining (Lau et al., 2021b). Unleashing the untapped potential of this source of geothermal energy will be important for Indonesia and the Philippines.

## 10. Conclusions

In 2019, 78% of ASEAN's electricity was produced from fossil fuels and 22% from renewable energies. Screening of ten decarbonization technologies for the power sector using a holistic approach according to sustainability, security, affordability, reliability, readiness and impact has resulted in country-specific ranking of these technologies. Overall speaking, the urgency of decarbonization requires ASEAN countries to use both fossil and non-fossil technologies for decarbonization rather than waiting for certain technologies to mature. The main fossil technologies are coal → gas, CP-CCS and GP-CCS. Recent research has shown there is no lack of subsurface $CO_2$ storage capacity in ASEAN for CCS. Consequently, eleven first mover CCS projects are proposed involving Singapore, Indonesia, Malaysia, Thailand and Vietnam. Implementation of these projects will mitigate up to 391 Mtpa $CO_2$ amounting to 22% of energy-related $CO_2$ emission in ASEAN in 2019. On the renewable technology side, hydropower is the dominant form of renewable electricity in ASEAN. However, sustainability issues regarding damming of the Mekong River need to be adequately addressed. Further addition will likely come from smaller run-of-the-river hydropower plants. Biomass for power generation is an under-utilized renewable technology which can be further developed in ASEAN, especially in Indonesia, Thailand, Malaysia and the Philippines. Solar PV has medium potential and further development should focus on improving grid stability and energy storage. In ASEAN, wind energy suffers from low average wind speed but there are exceptions. More R&D is needed for LWSP and offshore wind. Within ASEAN, geothermal resources are found in Indonesia and the Philippines where increased implementation will rely on government policies to incentivize more private investment and streamlining permitting. Energy policies that will promote rapid decarbonization of ASEAN's power sector are also discussed.

## Nomenclature

| | |
|---|---|
| ASEAN | Association of Southeast Asian Nations |
| Bcm | $10^9$ $m^3$ |
| CCS | Carbon capture and storage |

**Table A.1**
Ranking criteria for $CO_2$ emission.

| | Low | Medium | High |
|---|---|---|---|
| $CO_2$ emission (kg/kWh) | <0.37 | 0.37 to 0.45 | >0.45 |

Note: For benchmarking, $CO_2$ emission from US coal, gas and oil fired power plants are 1.011, 0.413, and 0.966 kg/kWh, respectively (United States Energy Information Administration (EIA), 2022).

**Table A.2**
Risk assessment matrix (RAM) for impact on people, animals and environment.

| | Consequence | | | Increasing probability of happening | | |
|---|---|---|---|---|---|---|
| | | | | A | B | C |
| Severity | Impact on people | Impact on animals | Impact on environ. (land & water) | Has occurred in other countries | Has occurred in country | Occurred several times in country |
| 0 | Zero injury | Zero to slight injury | Zero effect | Low | Low | Low |
| 1 | Slight injury | Single to multiple fatalities | Slight effect | Low | Low | Medium |
| 2 | Minor injury | Multiple fatalities to multiple species | Minor effect | Low | Medium | Medium |
| 3 | Major injury | Single fatality to endangered species | Local effect | Medium | Medium | High |
| 4 | Single fatality | Multiple fatalities to endangered species | Major effect | Medium | High | High |
| 5 | Multiple fatalities | Multiple fatalities to multiple endangered species | Massive effect | Medium | High | High |

Color code: Green means low risk, yellow means medium risk, red means high risk.

| | |
|---|---|
| CCT | Clean coal technology |
| CCU | Carbon capture and utilization |
| CCUS | Carbon capture, utilization and storage |
| Coal → gas | Switching from coal to gas for power generation |
| $CO_2$ | Carbon dioxide |
| $CO_2$-EGR | Carbon dioxide enhanced gas recovery |
| $CO_2$-EGR | Carbon dioxide enhanced oil recovery |
| CP-CCS | Coal-fired power plant equipped with CCS |
| ESG | Environmental, social and governance |
| GP-CCS | Gas-fired power plant equipped with CCS |
| Gt | $10^9$ tonnes |
| GWh | $10^9$ Watt-hour |
| IGCC | Integrated gasification combined cycle power plant |
| LNG | Liquified natural gas |
| Mha | $10^6$ hectare |
| MMbbl | $10^6$ barrel |
| Mt | $10^6$ tonnes |
| Mtpa | $10^6$ tonnes per annum |
| MW | $10^6$ Watt |
| SGD | Singapore dollar |
| Solar PV | Solar photovoltaic |
| TWh | $10^{12}$ Watt-hour |
| USD | United States dollar |

## CRediT authorship contribution statement

**Hon Chung Lau:** Idea creation, Execution, Documentation of research project.

## Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

## Appendix

See Tables A.1–A.4.

**Table A.3**
Sustainability ranking of decarbonization technologies for the power sector.

| | $CO_2$ emission (kg/kWh) | Impact on people (RAM) | Impact on animals (RM) | Impact on environ. (RAM) | Overall ranking |
|---|---|---|---|---|---|
| Hydro | 0 | Medium[a] | Medium[a] | Medium[b] | Medium |
| Bio | <0.37 | Medium[c] | Medium[c] | Medium[c] | Medium |
| Geo | <0.37 | Low | Low | Low | High |
| Wind | 0 | Low | Medium[d] | Mediu [e] | Medium |
| Solar PV | 0 | Low | Low | Medium[f] | Medium |
| CP-CCS | <0.37 | Low | Low | Low | High |
| GP-CCS | <0.37 | Low | Low | Low | High |
| Coal→gas | 0.37-0.45 | Low | Low | Low | Medium |
| Nuclear | 0 | Medium[g] | Medium[g] | Medium[g] | Medium |

[a]Teton Dam incident (United States Department of Interior Bureau of Reclamation (USBR), 2022).
[b]Lawn lake incident (Baker, 2022).
[c]Bioenergy is ranked medium in impact on people due to food scarcity, medium in impact on animals due to bio-diversity, and medium in impact on environment due to forest clearing.
[d]Avian death (Boyle, 2012).
[e]Blade waste.
[f]Panel waste.
[g]Fukushima incident (World Nuclear Association, 2022).

**Table A.4**
Classification of technology readiness level (TRL).

| Stage | Research | | | Development | | | Deployment | | |
|---|---|---|---|---|---|---|---|---|---|
| TRL | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Description | Research idea | Technology formulation | Proof of concept | Lab prototype | Lab pilot | Field pilot | Field demonstration | Field refinement | Commercial |

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