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Decarbonizing Thailand's Economy: A Proposal

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Abstract: This paper proposes decarbonization pathways for Thailand based on a review of the status of renewable and fossil energies, technology evaluation and scenario studies. Results show that renewable electricity generation needs to grow at a 7.1% average annual growth rate (AAGR) between now and 2050 for the power sector to achieve net-zero by 2050. This would require it to reach 400 TWh, exceeding its technical potential. We propose a more achievable scenario of between 5% and 6% AAGR wherein renewable electricity will grow from 51 TWh to 217–291 TWh between 2020 and 2050. Gas-powered electricity will grow from 127 TWh to 185–111 TWh, requiring carbon capture and storage (CCS) to mitigate 75–45 Mtpa CO_2 by 2050. For the transport sector, electric vehicles have the highest decarbonization potential, but they would add 45 TWh of electricity demand by 2050. For the industry sector, installing CCS in existing plants has the highest decarbonization potential. Overall, CCS is a key decarbonization technology and its large-scale implementation will be needed for Thailand to achieve net-zero by 2050.

Keywords: Thailand; decarbonization; carbon capture and storage; technology screening

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1. Introduction

With a population of 70 million and a GDP of 506 billion dollars in 2021, Thailand is the second largest economy by GDP, fourth largest by per capita GDP, and fourth largest by population, among the ten nations of Southeast Asia, collectively known as ASEAN [1,2]. Thailand's energy consumption has doubled between 2000 and 2020 [3,4]. However, it is vulnerable to global warming and has experienced climate disasters in the last three decades including floods, droughts, storms and extreme temperatures [5]. The Thai government has recently pledged to achieve carbon neutrality by 2050 and net-zero greenhouse gas emission by 2065 [6].

In the last decade, a number of researchers have studied Thailand's energy transition to a low-carbon economy. Phdungsilp and Wuttipornpun (2013) summarized previous scenario studies using different energy models and concluded that Thailand can achieve a low-carbon economy by using all energy options [7]. However, overcoming institutional barriers is critical and will require high-level commitment from the government. Subsequently, the Asian Development Bank (ADB) conducted a study to estimate the theoretical and technical potential of various renewable energies in Thailand [8]. Intelligent Energy Systems (IES) conducted a study on Thailand's power sector in 2016 [9]. It compared the business-as-usual (BAU) scenario with the so-called sustainable energy sector (SES) and advanced sustainable energy sector (ASES) scenarios, through which, by 2050, renewable electricity will contribute to 84% and 100% of total electricity, respectively. The IES study concluded that achieving the SES and ASES targets will require overcoming numerous institutional, financial and technical obstacles. A 2021 study by the International Energy Agency (IEA) concluded that carbon pricing will be needed to enable Thailand to meet its emission goals [10]. However, it has to include state-owned enterprises. A study by Rajbhandari and Limmeechokchai (2021) [11] suggested that achieving Thailand's climate goals will require not only renewable energies but also CCS and carbon-negative technologies, such as bioenergy with CCS. A study by Chaichaloempreecha et al. (2022) [12] concluded that achieving the 2 °C climate target will require Thailand to use all energy options, fossil and renewable. However, the key technology in the power sector is CCS, and the chief policy implication is imposing a carbon tax. A study by Diewvilai and Audomvongseree (2022) [13] proposed blending hydrogen with natural gas for power generation. A recent study by Zhang et al. (2022) [14] estimated that there is a total of 79 Gt of subsurface CO_2 storage capacity in sedimentary basins in Thailand, which is enough to store over 500 years of anthropogenic CO_2 emission. Recently, Lau et al. (2022a) [15] reviewed the status of fossil and renewable energies in ASEAN countries and proposed a set of common decarbonization pathways. Lau (2022a, 2022b) also proposed an integrated assessment tool to evaluate various decarbonization technologies and applied it to ASEAN countries [15,16]. The aforementioned studies show there is an increasing interest in Thailand's energy transition. However, no consensus has been reached as to the optimal pathway.

2. Objective and Methodology

The objective of this study is to propose realistic pathways for decarbonizing Thailand's power, transport and industry sectors by 2050. The methodology used for the power sector has four steps (Figure 1). First, we review the status of fossil and non-fossil energies in Thailand by analyzing the history of total primary energy supply (TPES), electricity generation and CO_2 emission. This enables us to understand the unique energy profile of Thailand from historical data. Second, we subject a set of decarbonization technologies (Table A1) to three evaluations: sustainability, energy quadrilemma, and technology mapping. For sustainability evaluation, we consider not only CO_2 emission, but also a technology's impact on people, animals and the environment. Energy quadrilemma considers the three elements of energy trilemma (sustainability, security and affordability) plus reliability. Technology mapping considers the readiness and impact of a technology. The criteria for evaluation are given in Tables A2–A7. The result is a prioritized list of technologies and key issues to be addressed for their implementation. Third, we propose five scenarios with different AAGR of renewable energies between now and 2050. They include the business-as-usual (BAU) scenario and four low-carbon solution (LCS) scenarios. Fourth, we compared these scenarios with published scenarios and then draw conclusions and policy implications.

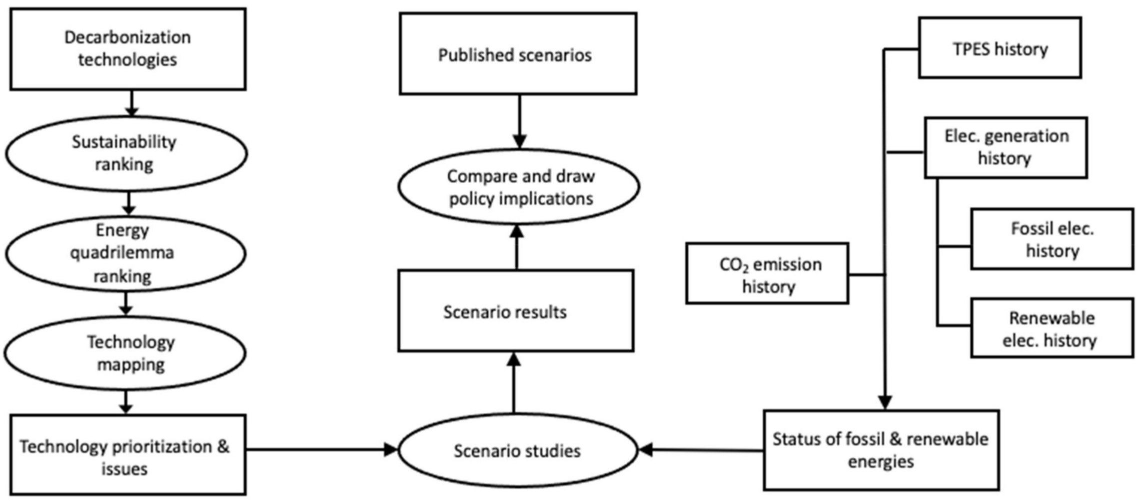

Figure 1. Methodology of the decarbonization study for Thailand's power sector.

The methodology for the transport and industry sectors is given in Figure 2. For the transport sector, decarbonization technologies are evaluated according to CO_2 emission, infrastructure, affordability, technology readiness and technology impact (Figure 2a). For the industry sector, technologies are evaluated according to CO_2 emission, affordability, technology readiness and technology impact (Figure 2b). Criteria for these evaluations are given in Tables A8–A10.

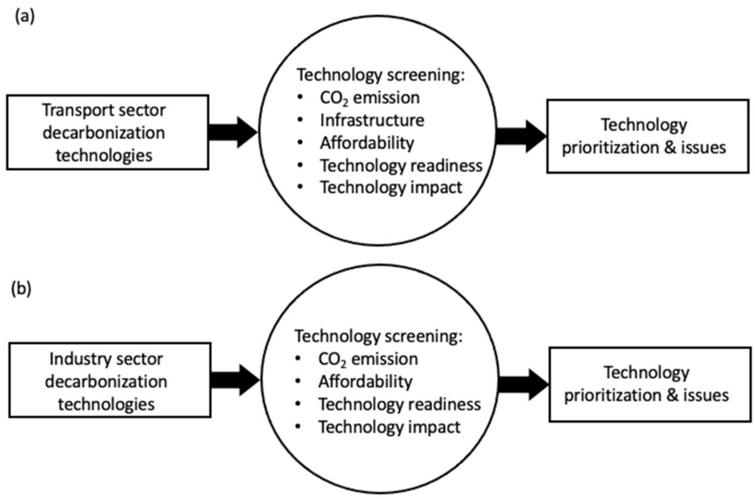

Figure 2. Methodology of the decarbonization study for Thailand's (**a**) transport and (**b**) industry sectors.

The scientific novelty of this study lies in the comprehensiveness and rigor of our technology evaluation. In the power sector, technologies are evaluated according to six categories: sustainability, affordability, security, reliability, readiness and impact. Technology evaluation for the transport and industry sectors encompasses five and four categories, respectively, tailored for these sectors.

3. Status of Fossil and Non-Fossil Energies

3.1. Primary Energy Supply

Figure 3 shows the history of Thailand's TPES by fuel type [17]. Thailand's TPES has been dominated by fossil fuels, with oil and gas being the biggest components. In 2020, fossil fuels contributed to 79% of TPES and renewable energies only 21% (Figure 3b). Renewables' share in Thailand's TPES has stayed around 20% in the last two decades (Figure 4a), with bioenergy contributing up to 95% of renewables in 2019 (Figure 4b). In Thailand, bioenergy consists of biomass, biogas and municipal solid waste used for electricity generation and biofuels (biodiesel and bioethanol) used for transportation fuels.

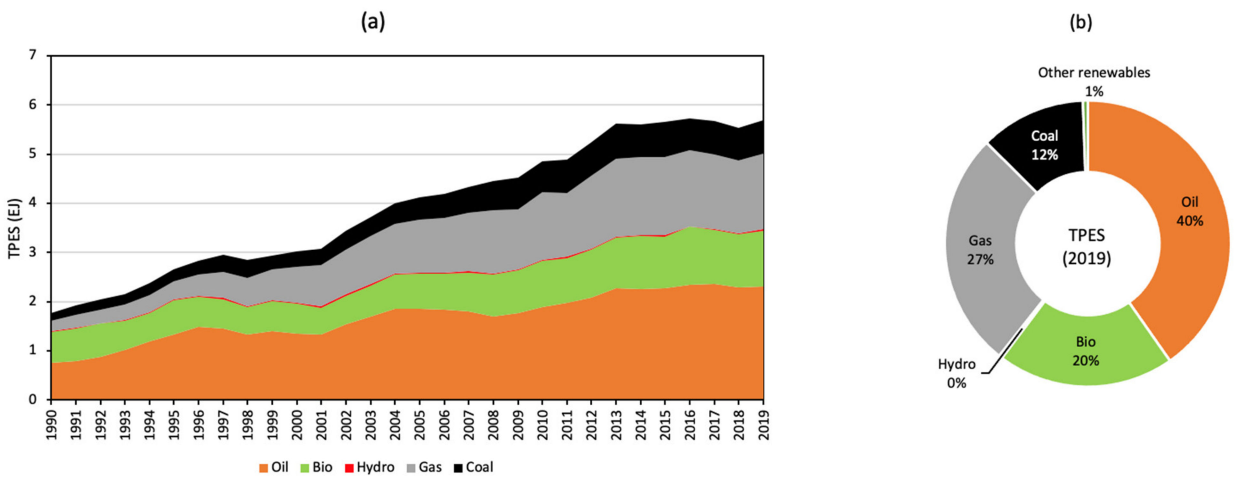

Figure 3. Thailand's (**a**) TPES history by fuel type and (**b**) TPES by fuel type in 2019 (source: Reference [17]).

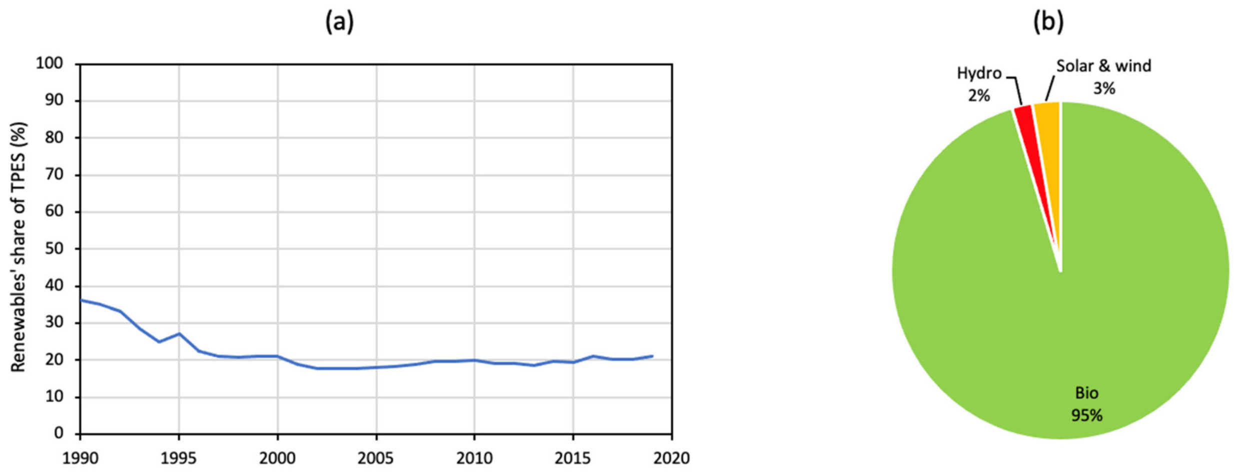

Figure 4. (**a**) History of renewables' share of TPES and (**b**) renewable energies by type in 2019 (Source: Reference [17]).

Figure 5 shows the history of Thailand's TPES, energy production, energy import and export [18]. The slight difference in TPES between Figures 3a and 5a is due to data extracted from different databases. Figure 5 shows that Thailand's TPES in 2018 was 6162 PJ. It has been increasing at an annual rate of 3.7% for the last decade, showing robust growth in Thailand's economy. Energy production reached 3160 PJ in 2018, but it has been decreasing since 2016. Net energy imports rose at 4.7% annually over the last decade, reaching 3200 PJ in 2018, to compensate for the declining domestic production (Figure 5a). Thailand's energy self-sufficiency, defined as (TPES+net energy trade)/TPES, has been trending downwards in the last three decades, from 57% in 1990 to 48% in 2018 (Figure 5b). In 2018, Thailand imported 52% of the energy it consumed. Without new additions of fossil and renewable energy production, Thailand's energy self-sufficiency will keep decreasing, showing its vulnerability to energy insecurity.

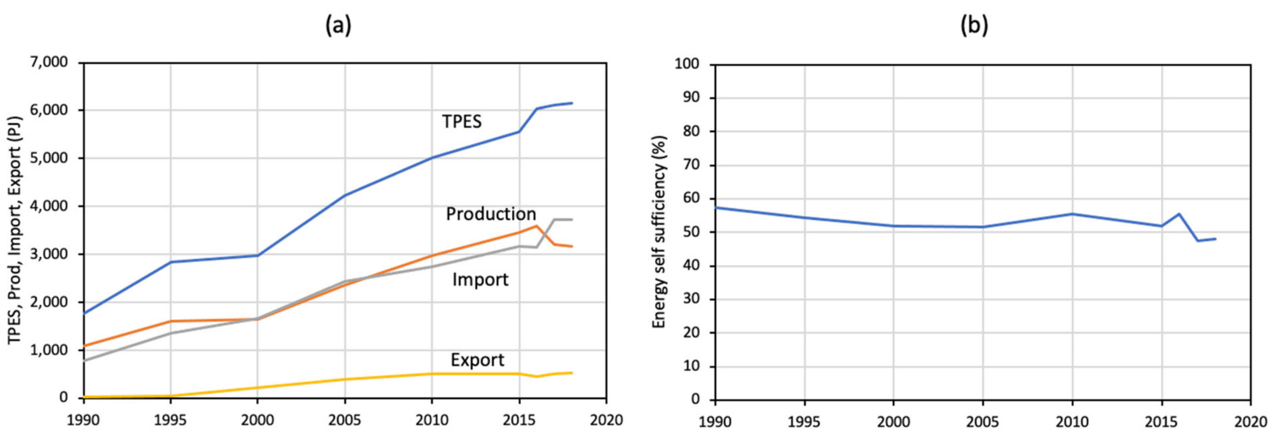

Figure 5. History of Thailand's (**a**) TPES, production, import and export and (**b**) energy self-sufficiency (Source: Reference [18]).

3.1.1. Coal Production and Consumption

Figure 6 shows the history of Thailand's coal production and consumption [19]. Since 1993, Thailand had been consuming more coal than it produces. Consequently, it depended on coal imports to meet its energy demands in the power and industrial sectors. It consumed 42.7 million short tons (MMst) of coal in 2016. It had 1172 MMst of proven coal reserves as of 2016, which was 27.4 times its annual consumption. In 2016, Thailand produced 18.7 MMst of coal and imported 56% of its coal consumption, mostly from Indonesia, Australia and Russia [20]. Thailand's coal reserve consists of lignite to sub-bituminous grade concentrated around two areas: Mae Moh in the north and Krabi in the south. The former is being developed, while development of the latter has been cancelled due to environmental concerns [8,21].

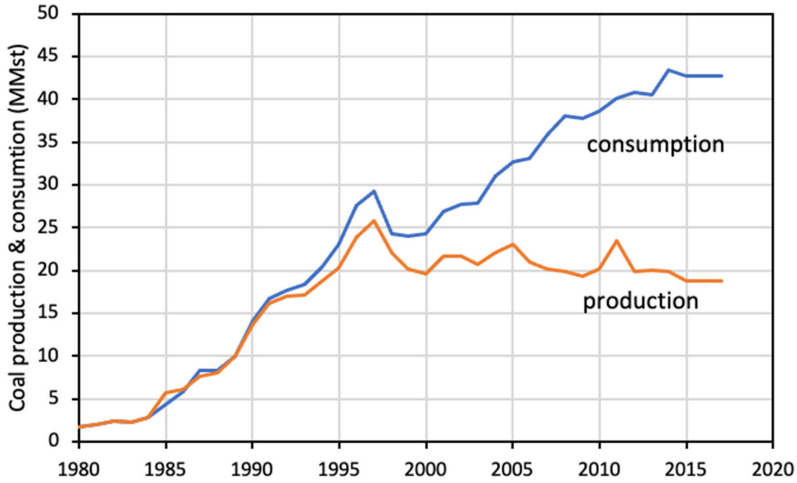

Figure 6. History of Thailand's coal production and consumption (Source: Reference [19]).

3.1.2. Oil Production and Consumption

Figure 7 shows the history of Thailand's oil consumption and production [22]. Oil is used primarily in the transport sector as fuel and secondarily in the petrochemical sector as a raw material. Electricity production by oil is relatively minor in Thailand. In 2016, Thailand consumed 1302 Mbbl/d and produced 531 Mbbl/d. Its oil self-sufficiency was only 41%. Thailand has 404.89 MMbbl of oil reserves, which is less than one year of consumption, making it highly dependent on oil import.

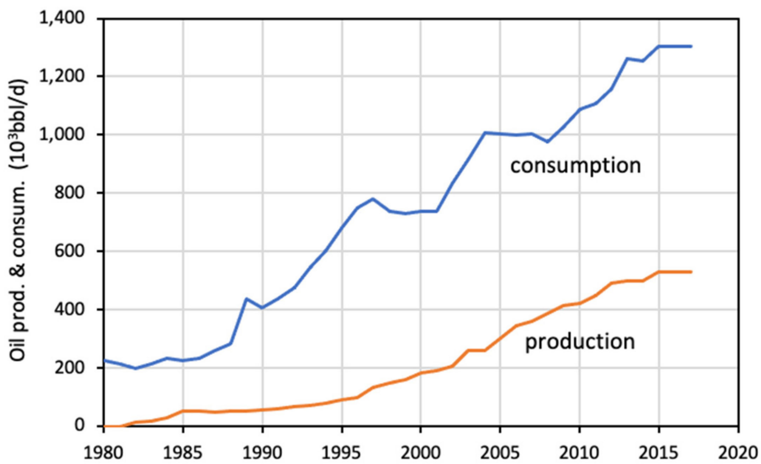

Figure 7. History of Thailand oil production and consumption (Source: Reference [22]).

3.1.3. Gas Production and Consumption

Figure 8 shows the history of Thailand's natural gas consumption, production, and import [4]. As of 2020, Thailand consumed 46.9 bcm of natural gas, produced 32.7 bcm and imported 30% of its natural gas consumption. It has a proven gas reserve of 5.2 Tcf (0.144 Tcm), which is enough to sustain three years of consumption [4]. Currently, gas import by pipeline comes solely from Myanmar, whereas LNG import comes from Qatar (44%), Malaysia (19%), Australia (16%), and other countries. In 2020, Thailand' self-sufficiency in gas was 70%.

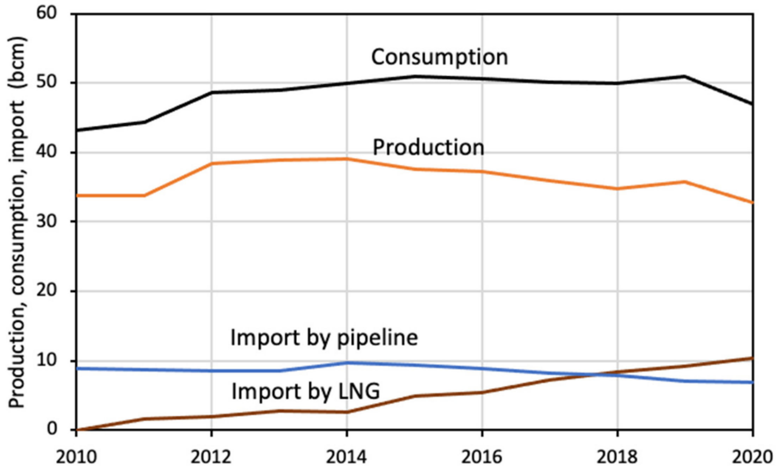

Figure 8. History of Thailand's gas production and consumption (Source: Reference [4]).

The aforementioned discussion shows that Thailand is highly dependent on imported fossil fuels to sustain its energy needs. Without the addition of reserves from new exploration activities, Thailand will soon deplete its oil and gas reserves and become totally dependent on import. This makes Thailand highly vulnerable to energy insecurity, as fossil fuels contributed up to 79% of its TPES in 2019 (Figure 3b).

3.2. CO_2 Emission

Figure 9a shows the history of Thailand's CO_2 emission from the combustion of fossil fuels and production of cement [3]. In 2020, Thailand emitted 258 Mtpa CO_2, with 43% coming from oil, 30% from gas, 21% from coal, and 6% from cement production (Figure 9b). Among ASEAN countries, Thailand is the third largest emitter of CO_2, after Indonesia and Vietnam [3]. Figure 10 shows Thailand's greenhouse gas (GHG) emissions by sector in 2018. The sectors that produced the most GHGs were electricity and heat (23%), road transport (17%), industry (16%) and agriculture (15%) (Figure 10b). Therefore, decarbonizing the electricity, road transport, and industry sectors is key to Thailand's energy transition.

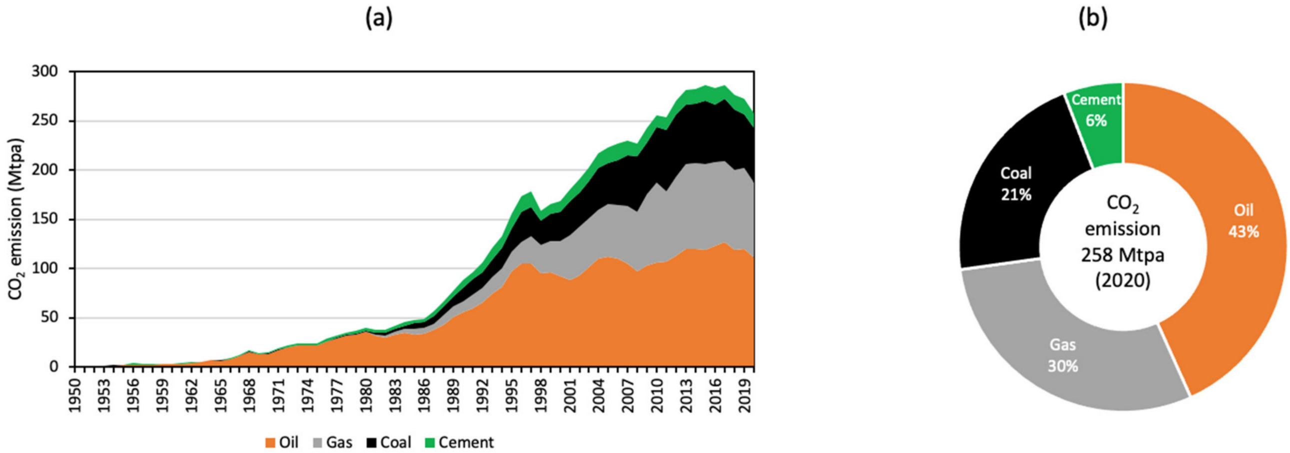

Figure 9. History of Thailand's CO_2 emission (**a**) cumulatively and (**b**) by fuel type (Source: Reference [3]).

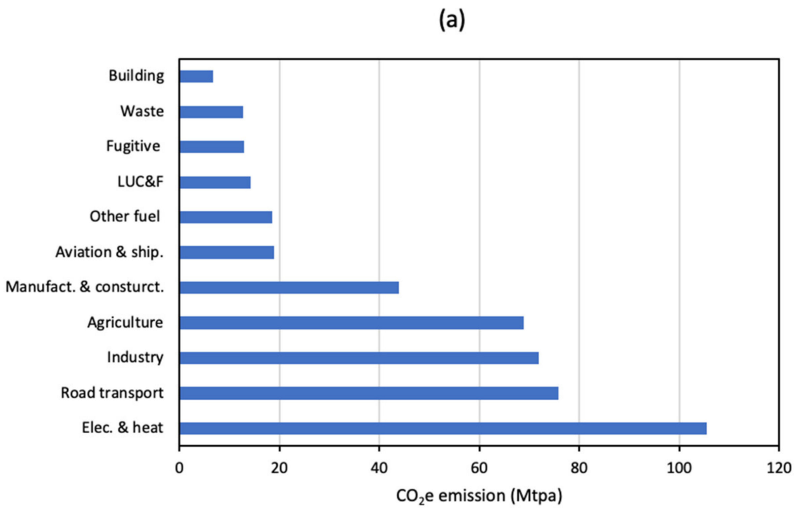

Figure 10. Thailand's sectoral greenhouse gas emissions in 2018 by (**a**) amount and (**b**) percentage (Source: Reference [3]).

3.3. Status of Fossil and Renewable Electricity

Figures 11–13 show the history of Thailand's total and renewable electricity generation and installed capacity, respectively [23]. Thailand's electricity generation has been dominated by gas and coal in the last two decades (Figure 11). In 2019, 25% of Thailand's electricity generation came from renewable energies (Figure 13a) with bioenergy making the largest (16%) contribution (Figure 13a). The other contributors were hydropower (3.5%), solar PV (2.6%) and wind (1.9%). In 2019, 76% of Thailand's installed capacity came from fossil fuels, 8% from bioenergy, 7% from hydropower, 6% from solar PV, and 3% from onshore wind (Figure 13b). Although solar PV contributed to 6% of installed capacity (Figure 13b), it contributed only to 3% of power generation (Figure 13a) because of its low capacity factor of 20% (Table A4). The reverse was true of bioenergy. It contributed to only 8% of the installed capacity (Figure 13b) but 16% of electricity generation (Figure 13a) because of a high capacity factor of 86% (Table A4).

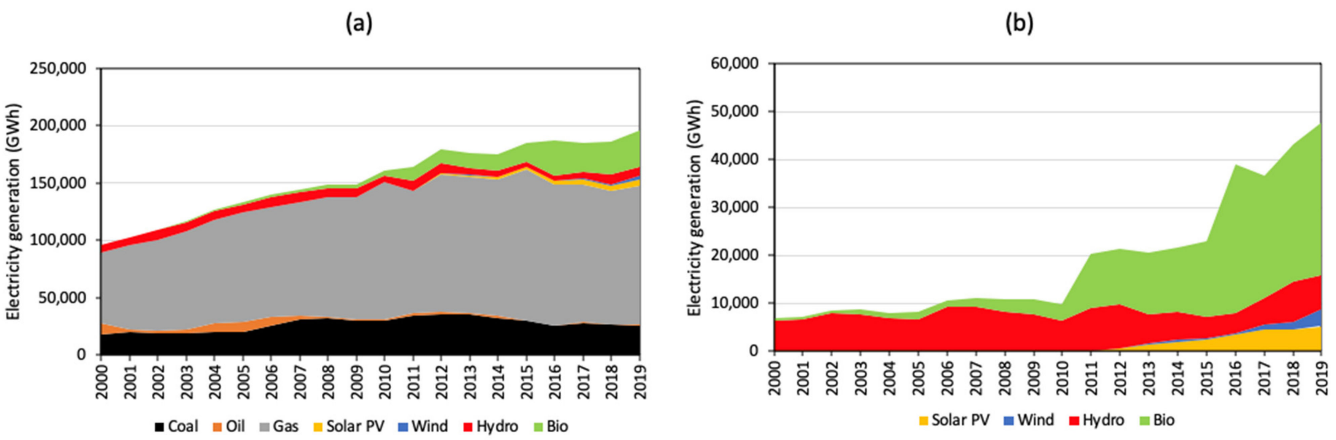

Figure 11. History of Thailand's (**a**) total, and (**b**) renewable electricity generation by fuel type (Source: Reference [23]).

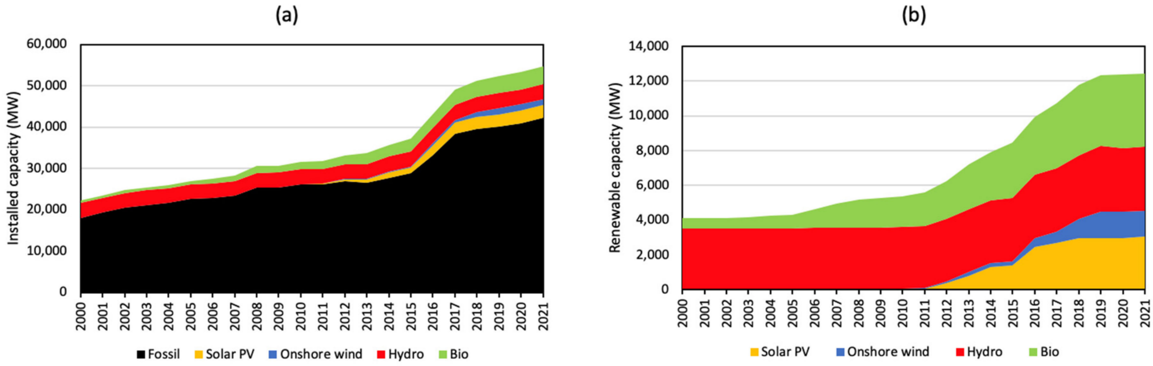

Figure 12. History of Thailand's (**a**) total and (**b**) renewable installed electricity capacity by fuel type (Source: Reference [23]).

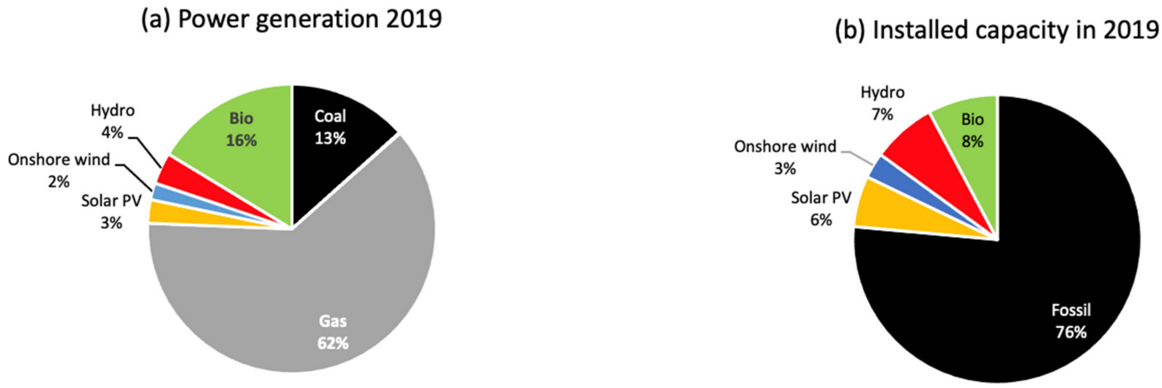

Figure 13. Thailand's (**a**) electricity generation and (**b**) installed capacity by fuel type in 2019 (Source: Reference [23]).

3.3.1. Coal-Fired Electricity

In 2019, 13% of Thailand's electricity (26.2 TWh) came from coal-fired power plants (Figure 13a). As of 2020, there were about half a dozen coal-fired power plants with a total of 25 operating units. They had a combined capacity of 6110 MW [12,24]. However, to achieve net-zero by 2050, Thailand needs to phase out all coal-fired power plants by 2050.

3.3.2. Gas-Fired Electricity

Thailand's electricity generation has been dominated by natural gas (Figure 13a). In 2019, gas-fired power plants produced 121.7 TWh or 62% of the total electricity [23]. In 2020, about 30% of the natural gas consumed in Thailand was imported. In view of Thailand's declining gas production, Thailand will need to import increasing amounts of natural gas.

At present, Thailand has only one LNG import terminal, and two are being developed [25]. The Map Ta Phut LNG terminal, located 180 km southeast of Bangkok, was built in 2011. It has a capacity of 11.5 Mtpa LNG and will be expanded to 16.5 Mtpa by 2025. The second LNG terminal, located in southeast Thailand at Nong Fab with a capacity of 7.5 Mtpa, will be completed in 2022. A third LNG terminal at Surrat Thani in southwest Thailand is being planned and will have a capacity of 3 Mtpa. It is estimated that Thailand's four existing long-term LNG contracts totaling 5.2 Mtpa will be inadequate to meet its growing gas demand after 2022 [25]. More will be needed.

3.3.3. Oil-Fired Electricity

There are several power plants in Thailand which can use either natural gas, bunker oil or diesel for electricity production. In 2019, they supplied 231 GWh of oil-fired electricity [23]. Oil is only a minor form of electricity production in Thailand. It is used mostly as fuel in the transport sector.

3.3.4. Bioelectricity

Bioelectricity consists of biomass, biogas and municipal solid waste used for electricity generation. It contributed up to 16% of power generation in 2019 (Figure 13a). Figure 14 shows the history of installed capacity and electricity generation by bioenergy in Thailand [23]. As of 2019, bioenergy generated 32 TWh of electricity (Figure 11b) with an installed capacity of 4097 MW (Figure 12b). The bulk of bioenergy is solid residue from biomass harvesting and processing, such as sugarcane bagasse, rice husks, empty fruit bunches and others. In most cases, these plants operate in co-generation mode for the production of both electricity and heat. Table 1 shows a list of biomass residues compiled by the Thailand Ministry of Agriculture and Cooperatives (MoAC) [26]. It shows a potential of 80 Mtpa of biomass, enough for 6040 MW of electricity capacity by 2036. Most come from the non-edible parts of food crops and are therefore classified as second-generation biocrop. If indeed 6040 MW is the upper limit of solid biofuels for electricity generation by 2036, then the upper limit of bioelectricity will be around 7500 MW, including biogas and municipal waste. Assuming a capacity factor of 86% (Table A4), the annual bioelectricity generation will be 56.5 TWh by 2036. To achieve 7500 MW of bioelectricity capacity by 2036, the bioenergy capacity has to grow at 3.9% annually between 2021 and 2036. The technical potential of biomass and biogas in Thailand is estimated to be 17,032 MW and 1507 MW, respectively (Table 2) [9].

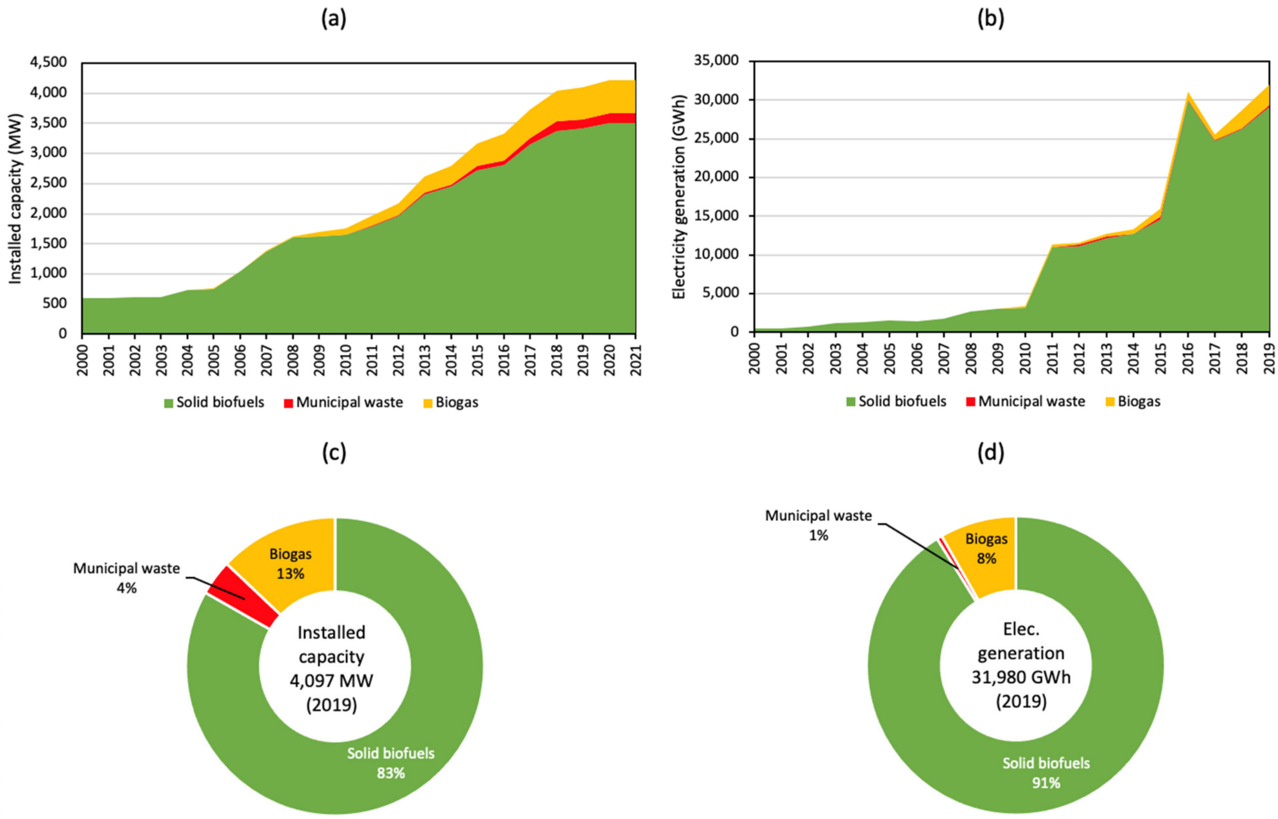

Figure 14. Thailand's bioenergy: (**a**) history of installed capacity, (**b**) history of electricity generation, (**c**) installed capacity by components in 2019, and (**d**) electricity generation by components in 2019 (Source: Reference [23]).

Table 1. Biomass residue potential in Thailand (Source: Reference [26]).

Biomass Type	Available Residues for Power Generation by 2036		
	Ton/Year	Ktoe	Power Potential (MW)
Rice husk	432	0.14	0.05
Rice straw	4,124,630	1204	461
Sugarcane and leaf	5,265,619	1929	738
Bagasse	21,280,000	3712	1421
Corn cob	80,889	18	7
Corn trunk	3,369,690	784	300
Cassava rhizome	3,372,560	439	168
Cassava trunk	2,084,755	769	294
Palm frond	33,586,191	5208	1993
Palm empty fruit bunch	1,402,455	240	92
Palm fiber	2,944,803	795	304
Palm shell	619,959	248	95
Para wood root	1,411,834	287	110
Coconut shell	79,678	31	12
Coconut coir	71,875	27	10
Coconut bunch & frond	249,026	91	35
Total	79,944,394	15,783	6040

3.3.5. Solar PV

Being close to the equator, Thailand has great solar potential, especially in the middle and north-eastern parts of the country which benefit from strong year-round solar radiation levels. Thailand is ranked second among ASEAN countries in solar PV potential, after Cambodia. It has an average theoretical potential (GHI) of 4.935 kWh/m^2/day and an average practical potential (level 1) of 4.065 kWh/TWp/day [27]. The technical potential for solar energy in Thailand has been estimated to be 22 GW (Table 2) [8].

Figure 15 shows the history of Thailand's solar PV installed capacity and electricity generation. Practically, all solar PV installation happened in the last decade. Since 2018, Thailand's solar PV capacity has plateaued at about 3000 MW. Among ASEAN countries, Thailand has the second-largest PV installed capacity, after Vietnam. It plans to increase its solar PV capacity to 6000 MW by 2036 [28,29]. To achieve this, solar PV's capacity needs to grow at 4.6% annually between 2021 and 2036.

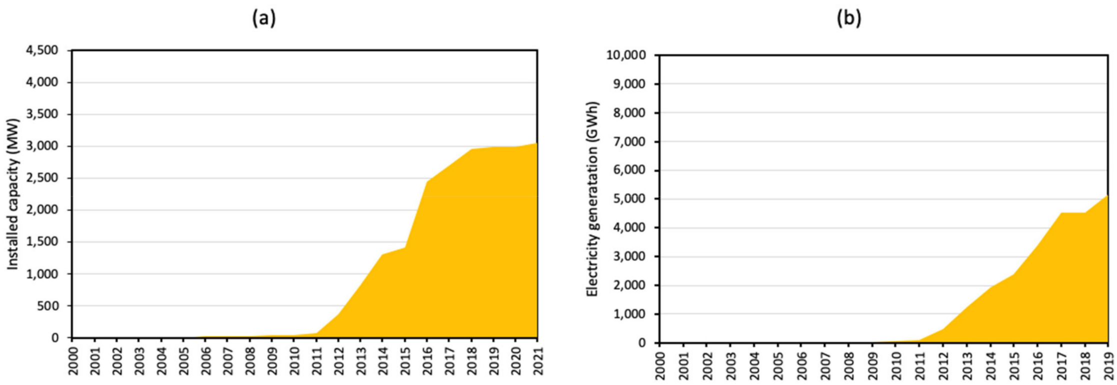

Figure 15. History of Thailand's solar PV (**a**) installed capacity and (**b**) electricity generation (Source: Reference [23]).

3.3.6. Wind Energy

Being close to the equator, Thailand has relatively low average wind speeds of less than 4 m/s at 100 m above sea level. A study conducted in 2001 by The World Bank finds limited potential for large-scale wind power in Thailand [29]. Only 0.2% or 761 km^2 of Thailand land area has a "good to excellent" wind speed (7 to 9.5 m/s) for wind turbines [30]. The area with best wind speeds is the northeast part of Thailand. Figure 16 shows the history of installed wind capacity and electricity generation. As of 2019, Thailand had 1.507 GW of installed onshore wind capacity (Figure 16a) generating 3670 GWh of electricity (Figure 16b). Currently, Thailand has no offshore wind turbines. The total onshore and offshore wind potential in Thailand has been estimated to be 30 GW and 7 GW, respectively (Table 2) [8]. Under the 2015 Alternative Energy Development Plan (AEDP2015), Thailand targets 3.0 GW of wind energy installed by 2036 [30].

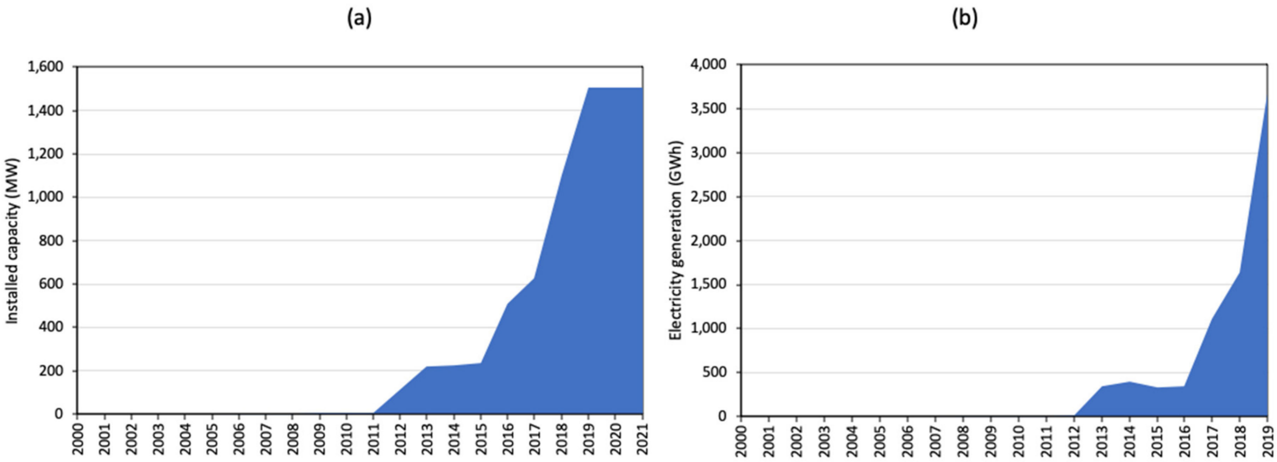

Figure 16. History of Thailand's wind (**a**) installed capacity and (**b**) electricity generation (Source: Reference [23]).

3.3.7. Hydroelectricity

Hydropower is the second most important form of renewable energy in Thailand. Figure 17 shows the history of installed hydropower capacity and electricity generation [23]. Although the installed capacity of hydroelectricity has not changed much in the last two decades, the amount of electricity generated varied significantly from year-to-year. This was partly due to difference in annual and seasonal rainfall. A drought in 2015–2016 caused a significant drop in hydroelectricity in Thailand [30]. Therefore, the capacity factor for hydropower in Thailand was only 24% in 2019 (Table A4) [23].

As of 2021, Thailand had 3107 MW of installed hydroelectricity capacity and 560 MW of pumped storage capacity, giving a total of 3667 MW. The biggest hydroelectric dam in Thailand is the Bhumibol Dam, which has eight turbines with a total capacity of 749 MW. Development of hydropower in Thailand has halted in the last two decades due to environmental concerns [30]. Although the estimated potential of hydropower in Thailand is 15.155 GW or about four times the current capacity [8], the Thai government has no plan to increase large hydropower between now and 2036 [26,31]. However, electricity generation by small-scale run-of-the-river (Hydro ROR) dams is increasing at a modest rate. Hydro ROR has a potential of 1.5 GW in the 25 river systems of Thailand (Table 2) [32].

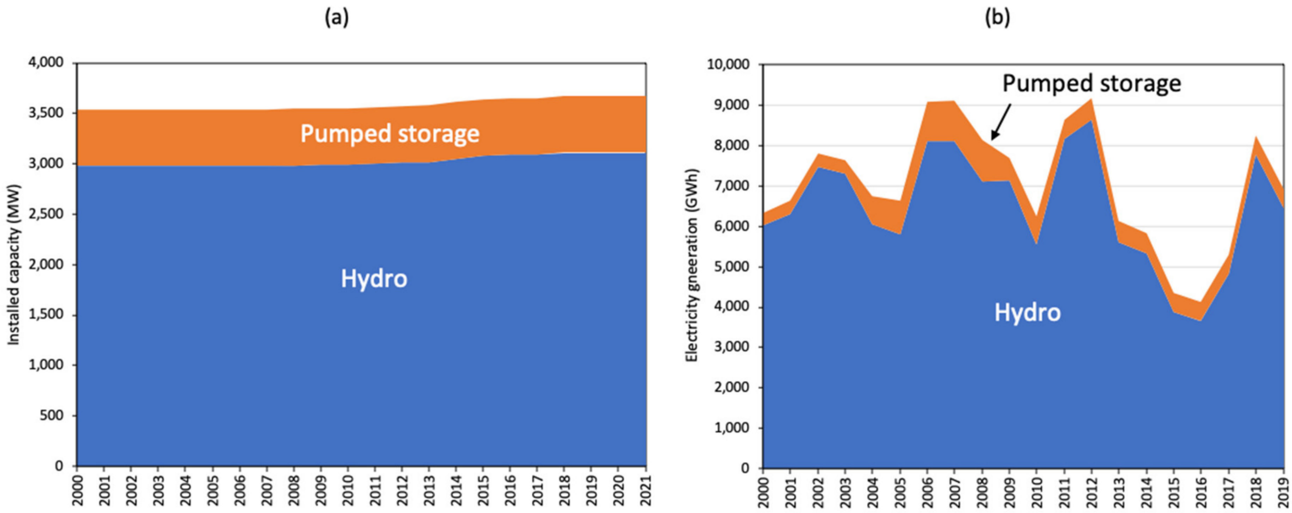

Figure 17. History of Thailand's hydropower (**a**) installed capacity and (**b**) electricity generation (Source: Reference [23]).

3.3.8. Geothermal Energy

Thailand's geothermal potential is estimated to be only 6.6 MW [33]. There are about 64 geothermal resources in Thailand, with the majority being located in the northern part of the country [9]. Currently, there is only one geothermal power plant operating at 300 kW at the Fang District, generating 1.2 GWh/y. The Thai government has no plan to build more geothermal power plants [30].

3.3.9. Nuclear Energy

Thailand has no nuclear power plants. Like the rest of Southeast Asia, Thailand faces low public acceptance of nuclear energy, especially after the Fukushima incident in 2011 [33]. Although the 2015 development plan PDP2015 targets a first production date of 2035 for nuclear power, no concrete plans have been made [34].

3.3.10. Estimated Technical Renewable Electricity Potential

Table 2 gives the estimated technical renewable electricity potential in Thailand. The electricity generation is estimated from the installed capacity using the capacity factors given in Table A4. The maximum technical potential for renewable electricity generation is 317 TWh/y. For all forms of renewable electricity, the installed capacity is much lower than the technical potential.

Table 2. Technical renewable electricity potential in Thailand.

Resource	Potential Capacity (MW)	Potential Generation (TWh/y)	Installed Capacity in 2021 (MW) [23]	Installed/ Potential (%)	Reference for Column 2
Hydropower	15,155	32	1738	11	[32]
Pumped storage	10,807	23	1929	18	[9,35]
Hydro ROR	1500	3	Not available	Not available	[32]
Solar	22,801	40	3044	13	[8]
Onshore wind	30,000	74	1507	5	[9]
Offshore wind	7000	17	0	0	[9]
Biomass	17,032	128	3668	22	[9]
Biogas	1507	11	554	37	[9]
Geothermal	6.6	0.02	0.3	5	[36]
Total	105,809	317			

3.3.11. Comparison of Thailand's Energy Profile with Those of ASEAN Countries

Table 3 compares Thailand's energy profile with those of other ASEAN countries in 2018. Thailand ranked third in CO_2 emission. Its share of renewable energy in TPES was 20%, which was slightly lower than the ASEAN average of 23%. However, it ranked first among ASEAN countries in electricity generation by bioenergy, solar PV and wind.

Table 3. Comparison of Thailand's energy profile with those of ASEAN countries.

Country	CO_2 (Mtpa)	Share in TPES in 2018 (%)				Power Generation in 2018 (GWh)					
		Coal	Oil	Gas	RE	Hydro	Geo	Bio	Solar PV	Wind	Fossil
Thailand	289	13	41	26	20	7783	0	28,705	4537	1641	144,581
Indonesia	625	31	32	15	22	16,828	13,019	636	20	6	235,365
Philippines	154	29	36	6	29	8597	10,435	1105	1249	1153	76,052
Vietnam	311	35	30	11	24	84,984	0	42	101	303	124,197
Malaysia	249	24	32	40	4	27,125	422	0	431	0	139,860
Singapore	53	3	60	35	2	0	0	2002	171	0	49,152
Laos	6.71	68	19	0	13	21,162	0	46	17	0	621
Cambodia	16	8	30	0	62	4737	0	69	41	0	3355
Myanmar	49	2	29	18	51	14,646	0	0	0	0	9486
Brunei	7.27	0	18	82	0	0	0	0	0	0	3852
ASEAN average	176	21	33	23	23	18,586	2388	3261	657	310	78,652
Thai ranking	3rd	6th	2nd	3rd	6th	7th	10th	1st	1st	1st	3rd

4. Results

4.1. Power Sector Decarbonization

4.1.1. Technology Screening for the Power Sector

Ten decarbonizing technologies (Table A1) for the power sector are evaluated according to sustainability, energy quadrilemma and technology mapping.

Concerning sustainability, technologies are ranked according to CO_2 emission, impact on people, impact on animals, and impact on the environment (Table A3). Although all renewable energies rank low in CO_2 emission, some rank medium in other categories. For example, hydropower ranks medium in impact on people, animals and the environment due to well-known incidents in other countries [37,38]. Damming of a large river can adversely impact the river ecosystem, riparian communities and wildlife, as is seen in the Mekong River [39]. However, run-of-the-river hydropower stations avoid these adverse impacts. Solar PV ranks medium in impact on environment because used solar panels are solid waste [40]. Wind energy ranks medium in impact on animals because of avian death caused by wind turbines [41]. It ranks medium on impact on environment because used blades cannot be recycled [42]. Bioenergy ranks medium in impact on people because of competition for agricultural land. It ranks medium in impact on animals because of loss of biodiversity. It also ranks medium in impact on environment due to forest clearing for biocrop plantation.

In technology evaluation for the power sector, we add reliability to the trilemma [43], hence the energy quadrilemma. The criteria for energy quadrilemma ranking are given in Tables A4 and A5. We use the capacity factor as a measure of reliability. It is calculated by dividing the actual electricity generated by the maximum possible output [44]. We take in-country availability as a measure of energy security (Table A5). We use the levelized cost of electricity (LCOE) as a measure of energy affordability [45]. LCOE includes both the capital and operating expense of a power station and is calculated over its lifespan. For the sustainability part of the energy quadrilemma, we carry over the results of the sustainability evaluation.

Technology mapping is a tool commonly used in the field development planning of upstream oil and gas projects [16]. We use the technology readiness level (TRL) first proposed by NASA (Table A6) to measure technology readiness [46]. It should be noted that TRL reflects the readiness of the worldwide industry and not necessarily that in Thailand. The criterion for technology impact is potential sector penetration (Table A7). Technologies that are ranked both high in readiness and impact are likely to be implemented. Those that are ranked high in impact but low in readiness will require more R&D.

Results of energy quadrilemma screening and technology mapping are given in Table 4 and Figure 18. Figure 18 is a radar plot that shows visually how each decarbonization technology ranks in the four areas in energy quadrilemma and two areas in technology mapping.

Table 4. Ranking of decarbonizing technologies for Thailand's power sector.

	Sustainability				**Energy Quadrilemma**				**Tech. Mapping**	
	CO_2	**People**	**Animal**	**Env.**	**Sustain.**	**Reliab.**	**Afford.**	**Security**	**Read.**	**Impact**
	kg/kWh	Risk assess. matrix	Risk assess. matrix	Risk assess. matrix	Combined ranking	Capacity fac. (%) [1]	LCOE ($/MWh) [2]	In-country availability [3]	TRL [4]	Share in elect. (%) [4]
Hydro	0	Teton Dam [5]	Teton Dam [5]	Lawn Lake [6]	Med.	24	75	Med.	9	<5
Hydro ROR	0	Low	Low	Low	High	24	<75	Med.	9	<5
Solar PV	0	Low	Low	Panel waste	Med.	20	60	High	9	5–10
Onshore wind	0	Low	Avian death	Blade waste	Med.	28	50	Med.	9	<5
Offshore wind	0	Low	Avian death	Blade waste	Med.	28	80	Med.	6	<5
Bio	<0.37	Food scarc.	Bio diversity	Forest clearing	Med.	86	125	High	9	>10
Geo	<0.37	Low	Low	Low	High	38	100	Low	8	<5
Coal→gas	0.37–0.45	Low	Low	Low	Med.	43	70	Med.	9	>10
CP-CCS	<0.37	Low	Low	Low	High	43	120	Med.	8	>10
GP-CCS	<0.37	Low	Low	Low	High	43	90	Med.	8	>10

For sustainability, green = low impact; yellow = medium impact; red = high impact. For energy quadrilemma and technology mapping, green = high ranking; yellow = medium ranking; red = low ranking. [1] Reference [23]. [2] Reference [47]. [3] Author's estimate based on Reference [23]. [4] Author's estimate. [5] Reference [37]. [6] Reference [38].

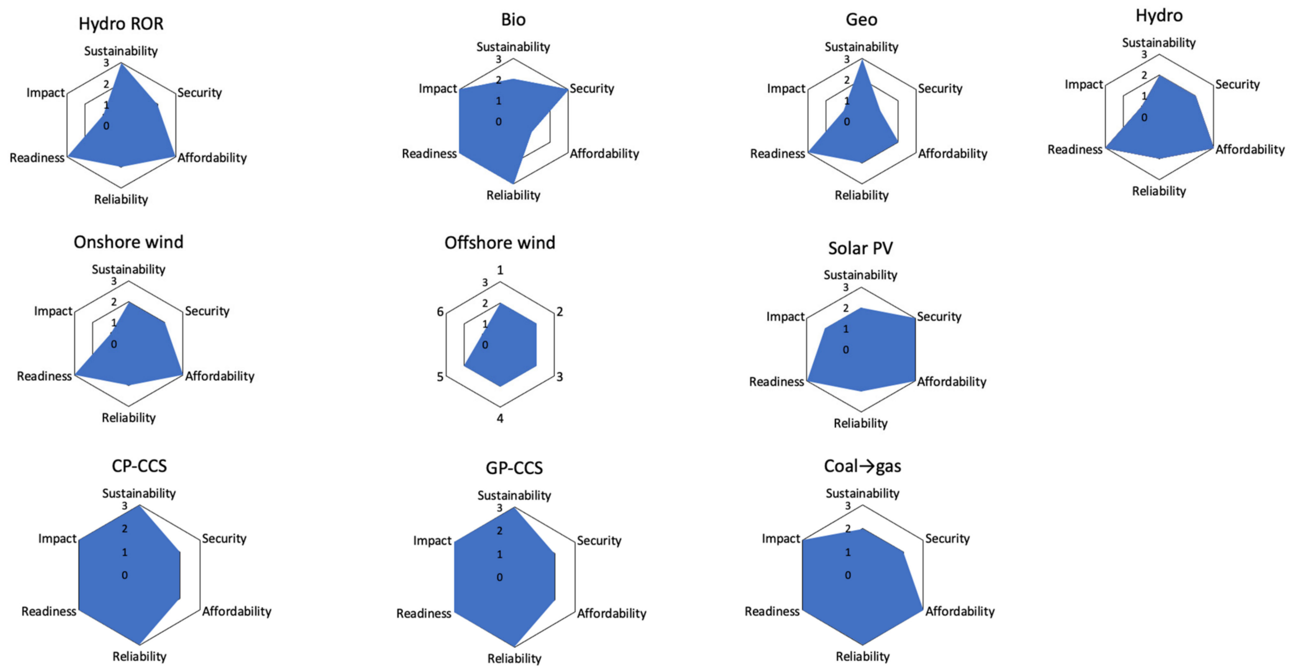

Figure 18. Radar chart for decarbonizing technologies for Thailand's power sector. (Scale: 1 = low; 2 = medium; 3 = high ranking).

We use the numerical ranking of all categories to classify technologies into a tiered system (Table 5). The decarbonization technologies with the highest potential are coal→gas, CP-CCS, and GP-CCS. By switching from coal to gas for power generation (coal→gas), CO_2 emission is reduced by one-half, as the burning of gas produces half the CO_2 compared to coal. In 2020, Thailand produced about 26 Mtpa CO_2 from coal-fired power plants, based on our estimate. A complete switching from coal to gas will avoid about 13 Mtpa of CO_2.

Installing CCS in coal- and gas-fired power plants can reduce up to 90% of the emitted CO_2 [48]. However, the cost of electricity will go up with CCS. In 2019, CO_2 emitted from coal- and gas-fired power plants in Thailand was about 75 Mtpa, by our estimate. Installing CCS in both types of power plant can mitigate up to 90% or 68 Mtpa of CO_2.

The decarbonization technologies with high potential are bio, solar PV, hydro ROR, hydro, and onshore wind. For bioenergy, sustainability issues such as competition with food crop, water resources, clearing of forest for biocrops, and loss of biodiversity need to be resolved before further application. For solar PV, the key issues are disposal of used panels [40] and low capacity factor. A large hydropower power plant has large adverse impacts on people, animals and the environment which need to be adequately resolved. Run-of-the-river hydro avoids these issues, but like large hydro, is affected by variability in annual and seasonal rainfall in Thailand, which results in a low capacity factor. Onshore wind energy faces sustainability issues such as disposal of used wind turbine blades, which are currently not recyclable [42], and avian death [41].

Decarbonization technologies with moderate potential are geothermal and offshore wind. Geothermal suffers from a small resource base in Thailand. Offshore wind suffers from high cost and low wind speed in the Gulf of Thailand.

Table 5. Ranking of decarbonization technologies for Thailand's power sector.

Tier Level	Technology	Key Issues to Be Addressed	Relative Score [1]
Tier 1 (highest potential)	Coal→gas	• Repurpose existing coal-fired power plants for using gas as fuel • Secure long-term pipeline gas and LNG contracts	16
	CP-CCS	• Install CCS in existing coal-fired power plants	16
	GP-CCS	• Install CCS in existing and future gas-fired power plants	16
Tier 2 (high potential)	Bio	• Food scarcity; competition for water resources; biodiversity; clearing of forest	15
	Solar PV	• Used panel is solid waste. • Low capacity factor means more capacity is need per unit of electricity generated compared to other renewables.	15
	Hydro ROR	• Low capacity factor due to variation in rainfall annually and seasonally.	14
	Hydro	• Adverse impact on people, animals and ecology by damming large rivers. • Low capacity factor due to variability in rainfall	13
	Onshore wind	• Avian death • Used blades cannot be recycled	13
Tier 3 (moderate potential)	Geo	• Low geothermal resources	12
	Offshore wind	• Avian death • Used blades cannot be recycled • Inadequate wind speed	11

[1] Summation of numerical score in Figure 18.

4.1.2. Scenario Study for the Power Sector

In 2019, 62% of Thailand's electricity was generated from gas, 13% from coal, and 25% from renewables (Figure 13a). We construct a business-as-usual (BAU) scenario replicating the BAU scenario proposed by IES (2016) [8] which assumes industry developments consistent with current planning in Thailand. The BAU scenario makes the following assumptions: (1) electricity demand grows at an average annual growth rate (AAGR) of 3.5% between 2019 and 2030, 3.2% between 2030–2040, and 2.3% between 2040–2050; (2) renewable electricity grows at an AAGR of 4.7% between 2019 and 2050, (3) coal-based electricity increases by 3.0 GWh/y between 2019 and 2050, and (4) no CCS is implemented. Figure 19 shows the relative contribution of different fuels for the BAU scenario. Total electricity generation will grow from 202 TWh in 2020 to 492 TWh in 2050, with coal, gas and renewable contributing 124, 172, and 196 TWh, respectively (Figure 19b). Total CO_2 emission will be 192 Mtpa in 2050 ((a) in Table 6).

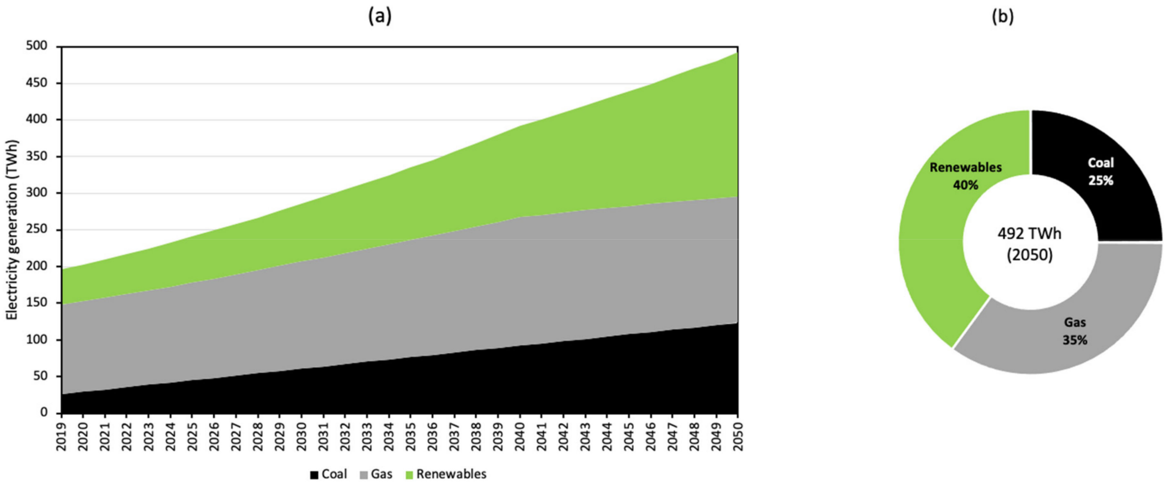

Figure 19. Energy mix for the BAU case in the power sector (**a**) between 2019 and 2050, and (**b**) in 2050.

For comparison with the BAU scenario, we construct four Low Carbon Solution (LCS) scenarios with different AAGR of renewable electricity generation to determine the AAGR for renewable electricity to totally replace fossil electricity by 2050. In these LCS scenarios, we assume replacing 20 million ICEVs in Thailand [49] by EVs by 2050, thus also decarbonizing the road transport sector. By assuming that each EV travels 15,000 km per year and consumes electricity at 15 kWh/100 km, we estimate that the electricity needed will be 45 TWh/y by 2050. The LCS scenarios make the following assumptions: (1) electricity generation will increase at an AAGR of 2.4% between 2019 and 2030 and 1.7% between 2030–2050 due to reduced demand compared to the BAU case, (2) coal will be phased out by 2050, (3) CO_2 emitted from fossil power plants will be mitigated by CCS, and (4) additional electricity demand will increase linearly from zero in 2020 to 45 TWh by 2050 to account for the gradual introduction of EVs. Between now and 2050, electricity generation will be shared by renewable energies and gas with contribution from coal diminishing linearly. The AAGR of renewable electricity will therefore dictate the amount of gas to be used for electricity generation.

Figure 20 shows the relative contribution of coal, gas and renewable energies as a function of AAGR of renewable electricity in the LCS scenarios. It can be seen that if renewable electricity increases at an AAGR of 7.1%, then the power sector can be decarbonized by 2050 with no need for natural gas (Figure 20d). If the AAGR is less than 7.1%, then a substantial amount of natural gas will be needed (Figure 20a–c). To achieve net-zero CO_2 emission by 2050, the CCS capacity should match the CO_2 emission by 2050.

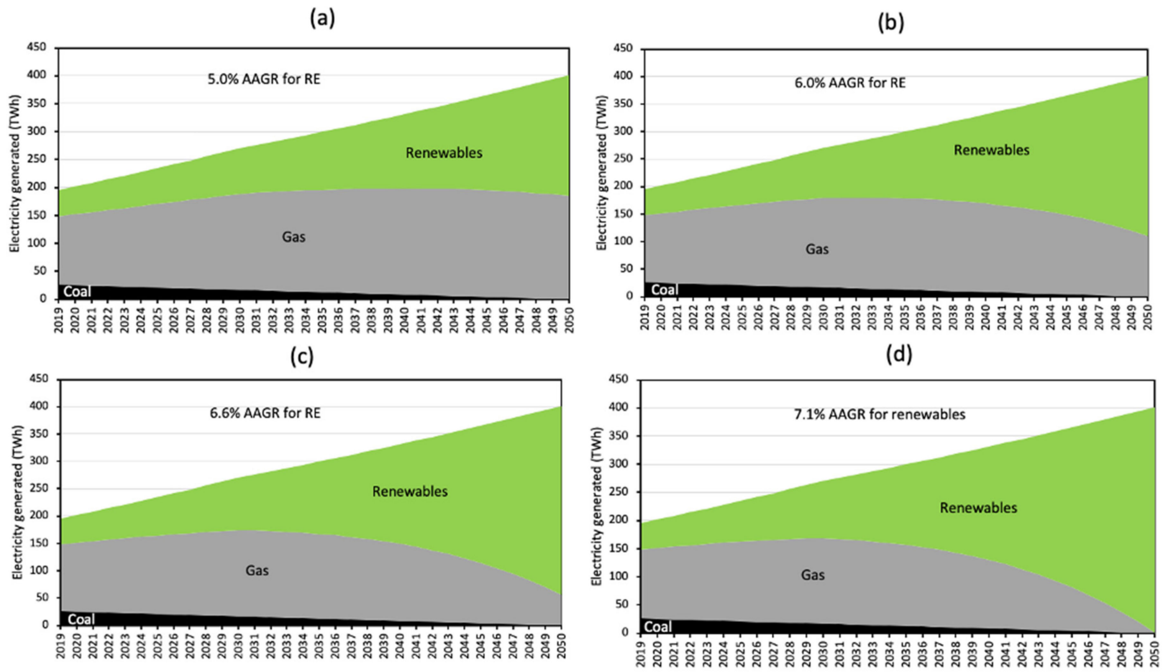

Figure 20. Decarbonization pathways at (**a**) 5% AAGR, (**b**) 6% AAGR, (**c**) 6.6% AAGR, and (**d**) 7.1% AAGR for renewable electricity generation.

Figure 21a compares the relative contribution of natural gas and renewable energies to power generation at different AAGRs of renewable electricity generation. Figure 21b shows the CCS capacity needed in 2050 to mitigate CO_2 emitted from gas-fired power plants. It can be seen that decarbonization depends critically on the AAGR of renewable electricity generation.

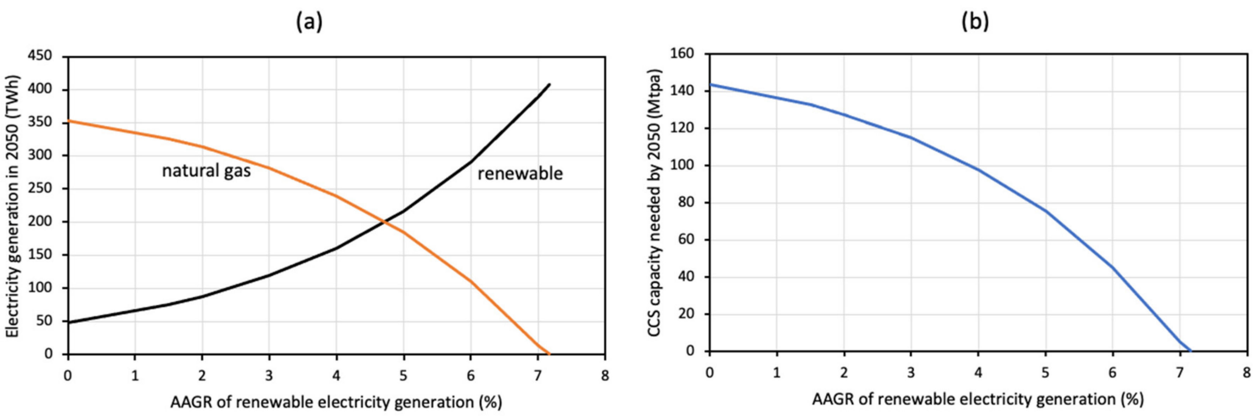

Figure 21. Effect of annual renewable electricity increase on (**a**) CCS capacity and (**b**) gas and renewables electricity generation.

Table 6 compare the results of various scenarios. In the BAU scenario, total electricity supply will grow from 202 TWh in 2020 to 492 TWh by 2050 with renewable electricity contributing to 40%. Renewable electricity will grow at an AAGR of 4.7%. In the LCS scenarios, total electricity will grow to only 401 TWh by 2050 due to increased energy efficiency and reduced demand due to the adoption of a circular economy. However, renewable electricity generation has to grow at an AAGR of 7.1% in order for it to reach 100% of demand. The SES and ASES scenarios proposed by the IES (2016) [9] correspond to the LCS (6.6%) and LCS (7.1%), respectively.

Table 6. (**a**) Comparison between BAU, LCS (5%), and LCS (6%) scenarios. (**b**) Comparison between LCS (6.6%) and LCS (7.1%) scenarios.

(**a**)

	BAU [1]				**LCS (5%)** [2]				**LCS (6%)** [2]			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Coal (TWh)	30	61	92	123	25	16	7	0	25	16	8	0
Gas (TWh)	123	146	175	172	127	172	190	185	127	163	161	111
RE (TWh)	50	79	124	196	51	82	133	217	51	91	162	291
Total (TWh)	202	268	392	492	202	270	331	401	202	270	331	401
RE share (%)	25	28	32	40	25	30	40	54	25	34	49	72
CO_2 (Mtpa)	79	120	162	192	76	86	86	75	76	83	74	45
CCS (Mtpa)	0	0	0	0	0	25	50	75	0	13	30	45

(**b**)

	LCS (6.6%) [2]				**LCS (7.1%)** [2]			
	2020	2030	2040	2050	2020	2030	2040	2050
Coal (TWh)	25	16	8	0	25	16	8	0
Gas (TWh)	126	157	141	56	126	152	122	1
RE (TWh)	51	96	182	345	51	101	202	400
Total (TWh)	202	270	331	401	202	270	331	401
RE share (%)	25	36	55	86	25	38	61	100
CO_2 (Mtpa)	76	80	65	23	76	78	58	0
CCS (Mtpa)	0	8	15	23	0	0	0	0

[1] AAGR of electricity (%): 3.5/3.2/2.3 for 2019–2030/2030–2040/2040–2050; EV electricity included. [2] AAGR of electricity (%): 2.4/1.7/ for 2019–2030/2030–2050; additionally, EV electricity of 0–45 TWh from 2019–2050.

Two important findings are obtained from these results. First, the BAU scenario will not meet the net-zero target by 2050, since no CCS is implemented. Second, in the LCS scenarios, the trade-off is between renewable energies and natural gas for power generation.

Table 7 compares the renewable electricity generation in various scenarios. In the LCS (6.6%) and LCS (7.1%) scenarios, the amount of renewable electricity generated would exceed the technical potential of 317 TWh according to Table 2. Consequently, they are not realistic. In the LCS (6%) scenario, the renewable electricity generated would reach 92% of the technical potential. A scenario where the renewable electricity grows between 5% and 6% is more achievable.

Table 7. Renewable electricity generation by 2050 in various scenarios.

Scenario	**BAU**	**LCS (5%)**	**LCS (6%)**	**LCS (6.6%)**	**LCS (7.1%)**
RE in 2050 (TWh)	196	217	291	345	400
RE in 2050 (% tech. potential *)	62	68	92	109	126

* Table 2.

4.2. Decarbonizing Thailand's Transport Sector

For the transport sector, decarbonization technologies are evaluated according to five categories: CO_2 emission, infrastructure, affordability, technology readiness, and technology impact (Table A8). Technology readiness refers to readiness in the mode of transportation (car, ship and plane) apart from infrastructure readiness. Table 8 and Figure 22 show results. Table 9 lists the technology ranking and issues to be addressed.

In Table 9, technologies are given a score by summing the numerical rankings in all five categories shown in Figure 22.

The technology with the highest decarbonization potential in the road transport sector is electric vehicles (EV) (Table 9). It replaces mobile emission at the tailpipe of vehicles by stationary emission at the power plants. The key issue is the building of infrastructure for EV charging. As of June 2022, there were 18,644 battery-operated electric vehicles (BEV), 37,075 plug-in hybrid electric vehicles (PHEV), and 288,894 hybrid electric vehicles (HEV) in Thailand [50]. There were 855 public charging locations with a total of 2459 charging outlets [50]. As of April 2021, there were 0.07 pieces of public electric vehicle supply equipment (EVSE) or charging outlets per EV in Thailand [51]. The standard set by the European Union is 0.1 EVSE per EV [52]. The Thai government plans for double digit annual growth for EVs up to 2035 [53]. Currently, hydrogen fuel cell vehicles (HFCVs) suffer from a lack of hydrogen infrastructure and the high cost of green or blue hydrogen compared to gasoline.

Use of biofuels, also called sustainable aviation fuel (SAF), for aviation has a high potential in Thailand, as the country is rich in biofuel resources. Currently, the biggest barrier is cost. On average, SAF costs 2.2 times that of petroleum-based aviation fuel [54].

Technologies with moderate potential are HFCV for road transport and hydrogen as fuel for ships (H_2-marine) (Table 9). For both technologies, the major issues are lack of hydrogen infrastructure and the high cost of hydrogen.

Table 8. Ranking of decarbonizing technologies for Thailand's transport sector.

Technology	Sustainability	Infrastructure	Affordability	Technology Readiness	Technology Impact
Criterion	CO_2 emission	Table A8	Table A8	TRL	Potential sector penetration (%)
EV	None	0.07 EVSE/EV	<1.5	9	>10
HFCV	None	sparse	>2.5	6	<5
H_2-marine	None	sparse	>2	6	<5
Bio-aviation	None	None needed	2.2	7	>10

Color code: low–high ranking; green = high ranking; yellow = medium ranking; red = low ranking.

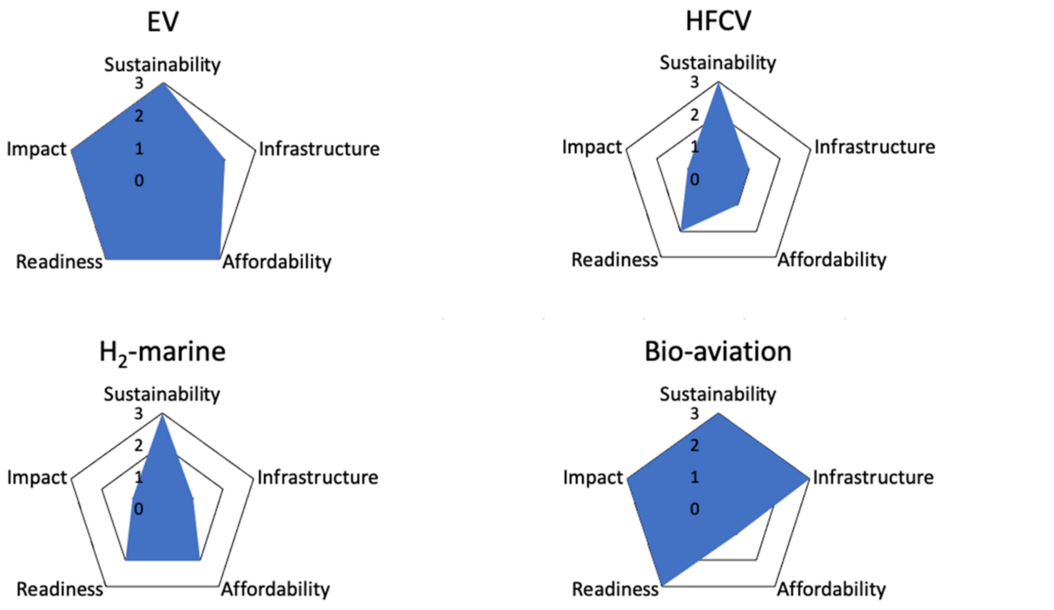

Figure 22. Radar chart of decarbonization technology for Thailand's transport sector (Scale: 1 = low, 2 = medium, 3 = high ranking).

Table 9. Ranking of decarbonization technologies in Thailand's transport sector.

Tier Level	Technology	Key Issues to Be Addressed	Relative Score [1]
Tier 1 (highest potential)	EV	• Infrastructure for EV charging stations	14
Tier 2 (high potential)	Bio-aviation	• Sustainability issues with biofuels production • High cost of biofuels for aviation	13
Tier 3 (moderate potential)	H_2-marine	• Lack of hydrogen bunkering infrastructure • High cost of hydrogen	9
	HFCV	• Lack of hydrogen delivery infrastructure • High cost of hydrogen	8

[1] Summation of numerical score in Figure 22.

4.3. Decarbonizing Thailand's Industry Sector

Three decarbonization technologies, namely, Ind-CCS, Coal→H_2-CCS and Gas→H_2-CCS, are evaluated according to CO_2 emission, affordability, technology readiness and technology impact (Table A9). Ind-CCS is the use of CCS in industry plants to mitigate the CO_2 emitted from the combustion of fossil fuels for high-temperature (>1000 °C) heating, typically used in the cement- and steel-making industries. In cement making, CO_2 is also emitted from the calcination process [54]. Coal→H_2-CCS is the use of hydrogen, produced from coal gasification with CCS, as fuel for industry plants. Gas→H_2-CCS is the use of hydrogen, produced from steam methane reforming with CCS, as fuel for industry plants.

Table 10 and Figure 23 show the results of technology evaluation. Technologies are ranked according to their numerical score in Figure 23. Table 11 gives the results of ranking and key issues to be addressed.

Ind-CCS has the highest decarbonization potential for Thailand's industry sector. The key issue is the cost of implementing CCS, which varies from industry to industry due to different CO_2 concentrations in the flue gas [55]. It is lowest for natural gas processing ($23/t CO_2) and highest for cement factories ($125/t CO_2), which is the biggest CO_2-emitting industry in Thailand (Table A10).

Coal→H_2-CCS and Gas→H_2-CCS have high potential. At present, both suffer from the high cost of blue hydrogen (more than twice) compared to unabated fossil fuel. However, upgrading Thailand's domestic coal to blue hydrogen can contribute significantly to Thailand's decarbonization in the long run. Furthermore, it will generate a new industry with new economic and employment opportunities.

Table 10. Ranking of decarbonization technologies for Thailand's industry sector.

Technology	Sustainability	Affordability	Technology Readiness	Technology Impact
Criterion	CO_2 emission	Table A9	TRL	Potential sector penetration (%)
Coal→H_2-CCS	Low	>2 [1]	5	>10
Gas→H_2-CCS	Low	>2 [1]	5	>10
Ind-CCS	Low	23–125 [2]	8	>10

Color code: low = high ranking, green = high ranking; yellow = medium ranking; red = low ranking. [1] Blue hydrogen cost compared to fossil fuel base [43]. [2] Cost of CO_2 avoided varies with industry, from $23/t to 125/t CO_2 avoided (Source: Reference [56]).

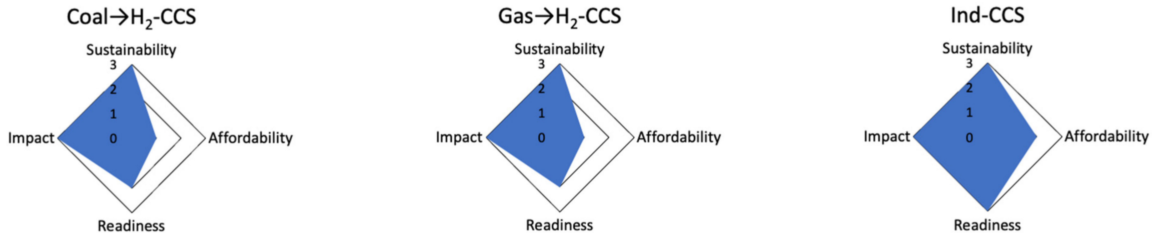

Figure 23. Radar chart for decarbonization technologies for the industry sector (Scale: 1 = low, 2 = medium, 3 = high ranking).

Table 11. Ranking of decarbonization technologies for Thailand's industry sector.

Tier Level	Technology	Key Issues to Be Addressed	Relative Score [1]
Tier 1 (highest potential)	Ind-CCS	• CCS cost varies with industry • High cost of CO_2 avoidance in cement industry	11
Tier 2 (high potential)	Coal→H_2-CCS	• Constructing hydrogen production plant using coal gasification with CCS • High cost of blue hydrogen compared to unabated fossil fuel	9
	Gas→H_2-CCS	• Constructing hydrogen production plant using steam methane reforming or autothermal oxidation with CCS • High cost of blue hydrogen compared to unabated fossil fuel • Securing long-term gas contracts	9

[1] Summation of numerical score in Figure 23.

5. The Role of CCS in Thailand's Energy Transition

Results of our technology evaluation show that CCS will play a critical role in decarbonizing Thailand's power and industry sectors, and indirectly the transport sector by decarbonizing fossil-generated electricity for EVs. In the power sector, CCS will be needed to mitigate CO_2 emitted from gas-fired power plants in three of the four LCS scenarios studied (Table 6) if the AAGR of renewable electricity is below 7.1%. For the transport sector, introduction of EVs will increase electricity demand. By 2050, 45 TWh of electricity will be needed for EV charging. Part of this electricity will be generated by fossil fuels, mostly gas, which needs to be mitigated by CCS. In the industry sector, CCS is the main technology to decarbonize Thailand's industry sector, especially the cement industry. In the long term, the production of blue hydrogen as fuel for HFCV and ships will also require CCS.

A recent study by Zhang et al. (2022) [14] has shown that there is a total of 79 Gt of subsurface storage capacity (mid-case scenario) for CO_2 in Thailand, which is enough to store over five centuries of emission from stationary sources. Of this, 77.6 Gt (98%) resides in saline aquifers, 1.7 Gt (2%) in gas reservoirs, and 0.05 Gt (<1%) in oil reservoirs. Furthermore, six CCS clusters have been proposed as a result of CO_2 source-sink mapping exercise. In each cluster, multiple sources are mapped to a common sink for subsurface storage. By sharing CO_2 transport and injector facilities, these clusters can make use of economies-of-scale to reduce the cost of CCS implementation. In these clusters, the CO_2 transportation distance is less than 200 km, and in some cases less than 100 km.

6. Implications for Energy Policy

The following implications for Thailand's energy policy can be drawn from this study.

6.1. Engaging State-Owned Enterprises in Decarbonization

Most of Thailand's electricity generation is controlled by state-owned enterprises (SOEs). Thailand's electricity-generating capacity and the entire transmission network are owned and operated by stated-owned Electricity Generating Authority of Thailand (EGAT), which sells the power it generates or purchases to the Metropolitan Electricity Authority (MEA) and the Provincial Electricity Authority (PEA). The former has the exclusive rights to distribute and sell power at rates set by the Thai government to consumers in the Bangkok metropolitan area, and the latter in all other areas [57]. Consequently, most of Thailand's CO_2 emission from the power sector comes from EGAT-run power plants. Therefore, it is important for the Thai government to engage EGAT and other SOEs in their decarbonization efforts. As the government is both the owner and key stakeholder in these SOEs, it can influence them to reduce their CO_2 emission. Furthermore, the priority which the Thai government gives to decarbonization relative to other goals is a critical factor in influencing these SOEs [58].

6.2. Promulgating a Credible Carbon Tax

Thailand currently has neither a carbon tax, a carbon credit, nor a carbon cap and trade system. Promulgating a credible carbon tax is probably the single most important step towards incentivizing private companies to reduce their CO_2 emission, especially in the industry sector. Revenue from the carbon tax can be used to fund R&D in low-carbon technologies and CCS projects. Currently, Singapore is the only country in ASEAN that has a carbon tax of $3.6/ton and plans to increase it to $18/ton in 2024 and then to $36–57/ton in 2030 [59].

6.3. Switching from Coal to Gas in Power Generation

In 2019, 13% of Thailand's electricity (26 TWh) came from coal. In the BAU scenario, power generation from coal will increase to 123 TWh or 4.7 times in 2050. To meet this demand, more coal-fired power plants will be built. Switching from the BAU scenario to one of the LCS scenarios will require phasing out coal by 2050. Achieving this will require increasing installed capacity in gas-fired power plants. This can be done by a combination of repurposing existing coal-fired power plants to use gas and building new gas-fired power plants. It will also require securing more long-term LNG contracts from overseas and pipeline gas from Myanmar. This will not be easy as Myanmar's gas export is subject to EU sanction [60] and European countries are looking for LNG supplies to replace Russian gas [61,62]. Also, increasing Thailand's LNG capacity will be important for its decarbonizing.

6.4. Implementing Large-Scale CCS Projects

Implementing large-scale CCS projects will be important to decarbonize Thailand's power and industry sectors. In all LCS scenarios where AAGR is less than 7.1%, CCS will be needed between now and 2050. Recent research has shown that there is ample subsurface CO_2 storage capacity in Thailand's sedimentary basins [14]. However, most of the storage capacity resides in saline aquifers. Detailed subsurface characterization of these basins will be needed to identify the target aquifers for permanent subsurface storage. This effort will require support and funding from the government.

6.5. Addressing Sustainable Issues of Renewable Energies

Bioenergy, wind energy and solar PV all have high decarbonization potential in the power sector in Thailand (Table 5). However, they have sustainability issues to be addressed. The extent to which these renewable energies will contribute to electricity generation in Thailand will depend on future R&D to resolve these issues.

6.6. Formulating a Hydrogen Strategy

Hitherto, Thailand has not announced a hydrogen strategy. Formulating one will be important to guide the nation's direction in the energy transition. With substantial domestic coal resources and CO_2 storage capacity, Thailand can benefit much from producing blue hydrogen by coal gasification, which is a mature technology. Blue hydrogen can be used to decarbonize the transport and industry sectors as well as for export.

7. Discussion

There are two limitations to this study. First, demand-side technologies such as improving energy efficiency, use of less carbon-intensive material, and adoption of a circular economy are excluded. Second, decarbonization technologies with low TRL such as direct air capture, carbon capture and utilization, electricity storage systems, modular nuclear energy, and ocean and tidal energies are also excluded.

Relying totally on renewable energies for power generation is not realistic, as most forms of renewable energies are variable. Solar PV is not available at night and cloudy days. Wind energy depends on wind speed which changes from night to day and across seasons. Hydropower varies with annual and seasonal rainfall. Bioenergy is more stable but the yield of biocrops depends on the climate. Geothermal energy is limited to certain locations. Therefore, the base load of electricity has to be either fossil or nuclear. Since nuclear energy is unavailable in Thailand, the base load will be either coal or gas. Therefore, CCS will still be needed to mitigate the CO_2 emitted from the fossil base load. Currently, Thailand has no ongoing CCS projects. As Thailand's existing oil and gas fields will likely be depleted soon, it is beneficial to inject CO_2 into them to increase oil and gas recovery by enhanced oil recovery (EOR) and enhanced gas recovery (EGR) [14]. In addition, subsurface characterization of saline aquifers will be needed to identify suitable candidates for CO_2 storage. This type of work can be funded by government with revenue from a carbon tax. The experience of Thailand in oil and gas development can be used for CCS projects.

Our study has shown that natural gas will be an important component of Thailand's energy mix in 2050. This means that securing long-term LNG or pipeline gas for the future is important.

This study proposes phasing out coal-fired power plants in Thailand by 2050. However, Thailand's substantial coal resources may be used for blue hydrogen generation for decarbonizing its industry sector. However, CCS will be needed. In addition, Thailand plans to become an LNG hub for southeast Asia [63]. If imported natural gas is converted to hydrogen by steam methane reforming in Thailand, it can be used for domestic consumption and export. Again, CCS will be needed to mitigate the CO_2 produced during hydrogen production. Therefore, developing CCS capacity, especially in the Gulf of Thailand, will be important to create a blue hydrogen industry with concomitant economic benefits.

8. Conclusions

The following may be concluded from this study.

1. For the power sector, technologies with the highest decarbonization potential are coal→gas, CP-CCS and GP-CCS. Next in potential are hydro ROR, hydro, bioenergy, solar PV and onshore wind. Except for hydro ROR, these renewable energies have sustainability issues that need to be addressed.
2. Renewable electricity has to grow at an AAGR of 7.1% between now and 2050 in order to replace all fossil fuels by 2050. It will, however, reach 400 TWh exceeding the technical potential for Thailand. A more achievable goal is a AAGR between 5% and 6%. In this case, natural gas will be needed for power generation and a CCS capacity of 45–75 Mtpa will be needed to decarbonize the power sector.
3. Replacing ICEVs with EVs has the highest decarbonization potential for road transport. Next is bio-aviation for aviation transport. In the long term, H_2-marine for marine transport also holds potential.

4. For the industry sector, Ind-CCS has the highest decarbonization potential. Next is coal→H_2-CCS, as Thailand's coal reserves can be used to produce blue hydrogen. Also, gas→H_2-CCS has the potential to decarbonize Thailand's industry sector and enable it to become a regional hub for hydrogen.
5. CCS as a critical technology to decarbonize Thailand's power and industry sectors, and indirectly the transport sector. Since Thailand has enough subsurface CO_2 storage capacity for several centuries of CO_2 emission, large-scale implementation of CCS will enable Thailand to achieve net-zero by 2050.

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Nomenclature

AAGR	Average annual growth rate
ADB	Asia Development Bank
ASEAN	Association of Southeast Asian Nations
ASES	Advanced sustainable energy sector
BAU	Business-as-usual
BEV	Battery electric vehicle
Bio	Bioenergy
Bio-aviation	Biofuels for aviation
Blue hydrogen	Hydrogen produced from fossil fuels with CCS
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
Coal→gas	Replacing coal by gas for power generation
Coal→H_2-CCS	Hydrogen production by coal gasification with CCS
CO_2-EOR	CO_2 enhanced oil recovery
CO_2-EGR	CO_2 enhanced gas recovery
CP-CCS	Coal-fired power plant with CCS
EGAT	Electricity Generating Authority of Thailand
EV	Electric vehicle
EVSE	Public electric vehicle supply equipment (charging outlet)
Gas→H_2-CCS	Hydrogen production by methane steam reforming or similar processes with CCS
Geo	Geothermal energy
Green hydrogen	Hydrogen produced from electrolysis with renewable electricity
Gt	10^9 ton
GWh	10^9 Wh
H_2-marine	Hydrogen as fuel for ships
HEV	Hybrid electric vehicle
HFCV	Hydrogen fuel cell vehicle
Hydro	Hydropower plant
Hydro ROR	Run-of-the-river hydropower plant
ICEV	Internal combustion engine vehicle
Ind-CCS	Industrial plant equipped with CCS
LCOE	Levelized cost of electricity
LCS	Low carbon solution
Mbbl/d	10^3 bbl/d
MMbbl	10^6 bbl
MEA	Metropolitan Electricity Authority
MMst	10^6 short ton
Mtpa	10^6 ton per annum
MW	10^6 W
Offshore wind	Offshore wind energy
Onshore wind	Onshore wind energy
PEA	Provincial Electricity Authority
PHEV	Plug-in hybrid electric vehicle

R&D	Research and development
RAM	Risk assessment matrix
RE	Renewable energy
SAF	Sustainable aviation fuel
SES	Sustainable energy sector
SOE	State-owned enterprise
Solar PV	Solar photovoltaic
TPES	Total primary energy supply
TRL	Technology readiness level
TWh	10^{12} Wh

Appendix A

Table A1. Description of sector-specific decarbonization technologies.

Sector	Decarbonization Technology	Description
Power	Hydro	Large hydropower plant
	Hydro ROR	Run-of-the-river hydropower plant
	Solar PV	Solar photovoltaic
	Bio	Bioenergy for power generation
	Onshore wind	Onshore wind turbine for power generation
	Offshore wind	Offshore wind turbine for power generation
	Geothermal	Geothermal power plant
	Coal→gas	Switching from coal to gas for thermal power generation
	CP-CCS	Using CCS to capture and store CO_2 emitted from coal-fired power plant
	GP-CCS	Using CCS to capture and store CO_2 emitted from gas-fired power plant
Transport	EV	Electric vehicles
	HFCV	Hydrogen fuel cell vehicles
	H_2-marine	Hydrogen as fuel for ships
	Bio-aviation	Biofuels as fuel for planes
Industry	Ind-CCS	Using CCS to capture and store CO_2 emitted from industrial plant
	Coal→H_2-CCS	Blue hydrogen generated from coal gasification (with CCS) for use in industry heating and raw material
	Gas→H_2-CCS	Blue hydrogen generated from methane steam reforming (with CCS) for use in industy heating and raw material

Table A2. Ranking criteria for CO_2 emission.

CO_2 emission (kg/kWh)	Low	Medium	High
	<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 [64].

Table A3. Risk assessment matrix (RAM) for impact on people, animals and the environment.

	Consequence			Increasing Probability of Happening		
				A	B	C
Severity	Impact on people	Impact on animals	Impact on environ. (land & water)	Has occurred outside countries	Has occurred in Thailand	Occurred several times in Thailand
0	Zero injury	Zero to slight injury	Zero effect			
1	Slight injury	Single to multiple fatalities	Slight effect			
2	Minor injury	Multiple fatalities to multiple species	Minor effect			
3	Major injury	Single fatality to endangered species	Local effect			
4	Single fatality	Multiple fatalities to endangered species	Major effect			
5	Multiple fatalities	Multiple fatalities to multiple endangered species	Massive effect			

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

Table A4. Utilization capacity factor for power generation in Thailand (Source: Reference [23]).

Fossil	Hydro	Wind	Solar PV	Bio	Geothermal
43	24	28	20	86	38

Note: Based on 2019 data.

Table A5. Ranking criteria for energy quadrilemma for the power sector.

Category\Ranking	Criteria	Low	Medium	High
Sustainability	CO_2 emission, impact on people, animals, and environment	Ranked high in one or more sustainability categories	Ranked medium in any sustainability category. No high ranking	Ranked low in all sustainability categories
Security	In-country availability	Unavailable in country	Available in limited quantiity	Readily available in adequate quantity
Affordability	LCOE (USD/MWh)	>120	80–120	<80
Reliability	Capacity factor (%)	<20	20–40	>40

Table A6. Technology readiness level (TRL) classification.

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

Table A7. Ranking criteria for technology mapping.

	Criterion	Low	Medium	High
Technology readiness	TRL	1 to 3	4 to 6	7 to 9
Technology impact	Potential sector penetration (%)	<5	5 to 10	>10

Table A8. Ranking criteria for decarbonization technologies in the transport sector.

Category	Criterion	Low	Medium	High
Sustainability	CO_2 emission	None	Some	Some
Infrastructure (EV)	EVSE/EV	<0.05	0.05 to 0.10	>0.10
Infrastructure (HFCV, ship, plane)	Availability of refueling stations	Sparse	Inadequate	Adequate
Affordability (EV, HFCV)	Vehicle cost compared to ICEV	<1.5	1.5 to 2.5	>2.5
Affordability (ship & plane)	Fuel cost compared to fossil fuel	<1	1 to 2	>2
Technology readiness	TRL	1 to 3	4 to 6	7 to 9
Technology impact	Potential sector penetration (%)	<5	5 to 10	>10

Table A9. Ranking criteria for decarbonizing technologies in the industry sector.

	Criterion	Low	Medium	High
Sustainability	CO_2 emission by fuel used for heating	Non-fossil	Fossil	Fossil
Affordability (coal→H_2-CCS or gas→H_2-CCS)	Fuel cost compared to fossil fuel	<1	1 to 2	>2
Affordability (Ind-CCS)	CCS cost ($/t CO_2)	<30	30 to 90	>90
Technology readiness	TRL	1 to 3	4 to 6	7 to 9
Technology impact	Potential sector penetration (%)	<5	5 to 10	>10

Table A10. Cost of CO_2 avoided ($/t CO_2) for first-of-a-kind installation (Source: Reference [56]).

	Iron & Steel	Cement	Nat. Gas Processing	Fertilizer	Biomass to Ethanol
Indonesia	76	125	22.8	26.9	22.8

Note: Data for Indonesia are treated as proxy for Thailand.

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