"A Study on Decarbonization Roadmaps for ASEAN Countries"

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Abstract

In this study, we applied a liner programming model to the 10 ASEAN countries, and showed cost-optimal results for sectoral CO_2 emissions, primary energy supply, and power generation to decarbonize the region by 2060. We found that, as pointed out in IPCC AR6, (1) energy efficiency and electrification in the final consumption sectors, (2) early decarbonization in the power sectors (by 2040), and (3) utilization of negative emission technologies (DACC, BECCS and natural carbon sink) are also important for the region. In addition, it was confirmed that natural gas will play an important role in the transition period such as 2030 and 2040. Under our standard assumptions, not only renewables such as solar PV, but also thermal power such as natural gas with CCS and hydrogen/ammonia will be essential in many countries. Although decarbonization inevitably leads to an increase in the total cost of the energy system, it is possible to reduce the cost considerably by strengthening resource-sharing within ASEAN (e.g. via the international power grid) and technological innovation including demand-side technologies.
Keywords: ASEAN, decarbonization, roadmap, liner programming model, hydrogen

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1. Introduction

Since COP26, the wave of decarbonization has spread beyond developed nations to emerging and developing countries. Many of the countries in ASEAN have already declared that they will achieve carbon neutrality (CN) by around the middle of this century, including Indonesia by 2060 and Thailand by 2050. Reducing CO_2 emissions in such an ambitious way will require a fundamental transformation of the energy system, but at the same time, energy transition cannot be achieved with a one-size-fits-all approach. First, the existing ASEAN energy systems have a high dependence on fossil fuels: the share of fossil fuels in the primary energy supply of ASEAN as a whole is 80%. Vietnam is one country with a high share of coal, at 50% of primary energy supply. In addition, the potential of solar PV and wind power is unevenly distributed across the ASEAN region. Countries located closer to the equator, such as Indonesia, especially have relatively lower wind resource potential. Moreover, given the remarkable economic growth of ASEAN countries and fast-rising energy demand, it goes without saying that the decarbonization roadmaps of ASEAN countries cannot be realistic unless they fully reflect these circumstances.

Therefore, using a technology selection model that has been proven in analyzing Japan, the authors conducted an analysis aimed at describing cost-optimized decarbonization roadmaps in 10 ASEAN countries. The results of the analysis contributed to one of the five pillars of the Asia Energy Transition Initiative (AETI)[1] founded by then Minister of Economy, Trade and Industry, Hiroshi Kajiyama, "Support for the development of energy transition roadmaps" and were reported to the Asia Green Growth Partnership Ministerial Meeting (AGGPM) Public-Private Forum (March 14, 2022)[2] and ASEAN-Japan Business Week 2022 (May 30 to June 3, 2022)[3]. A research project report[4] was also published on the ERIA website.

Hereafter, charts use the following abbreviations for the names of countries and regions. BRN: Brunei, KHM: Cambodia, IDN: Indonesia, LAO: Laos, MYS: Malaysia, MMR: Myanmar, PHL: Philippines, SGP: Singapore, THA: Thailand, VNM: Vietnam.

2. Methodology

2.1 Model and assumptions

In this study, we applied the linear programming technology selection model[5] - which was used in analyzing Japan and reported in the Strategic Policy Committee[6,7] - to 10 ASEAN countries. This model estimates a combination of technologies that minimizes the discounted total cost of energy systems for the entire target period and region, given the demand for energy services. It should be noted that this is a dynamic optimization across ASEAN as a whole, rather than by country. Data that is necessary in addition to energy service demand includes energy prices, resource endowments, and technical specifications (capital costs, operation and maintenance costs, efficiency). Table 1 shows the framework of the analysis.

Since each of the ASEAN countries is modeled as a single node, energy interchange within ASEAN (such as cross-border transmission lines) is explicitly considered. The model can calculate power supply and demand at up to as often as hourly, but in this analysis it was set to 4-hour intervals to save calculation time. Calculations were also performed at one-hour intervals during model development, but no significant difference was found in the optimal solution (this does not guarantee that there is no difference in the results of the case shown in this analysis). More than 350 technologies were envisioned, with consideration given to renewable energy (solar PV, onshore wind, offshore wind, hydro, geothermal and biomass) and nuclear power (light water reactors), CCUS (CCS, methane synthesis, Fischer-Tropsch (FT) synthesis), hydrogen and ammonia supply technologies (electrolysis, coal gasification, methane reforming, ammonia synthesis, direct importation from outside ASEAN, etc.), consumption technologies (power generation, fuel cell electric vehicles (FCEVs), hydrogen-based direct reduction steelmaking, hydrogen ships and aircraft, industrial heat utilization, etc.), and negative emission technologies (direct air capture with carbon storage (DACCS) and bioenergy with carbon capture and storage (BECCS)). For the use of hydrogen and ammonia in power generation, co-firing technologies were included in addition to single-firing technologies: coal-ammonia co-firing (mixed combustion ratio 20%) and gas-hydrogen co-firing (mixed combustion ratios of 20%, 40%, 60%, 80%)). The final consumption sector was modeled mainly based on the IEA energy balance tables[8], and references were also made to the literature on steel[9] and cement[10].

Table 1. Framework of analysis

Region	10 countries of ASEAN (10 nodes)
Years	2017, 2030, 2040, 2050, 2060
Discount rate	8%
Electricity supply/demand resolution	4-hourly intervals (2,190 hours per year)

Final consumption sector (services)	・ Industry (steel, cement, chemicals, pulp and paper, other industries) ・ Transport (cars, trucks and buses, rail, aviation, shipping, other transport) ・ Residential (lights and appliances, cooling, hot water, cooking) ・ Commercial (lights and appliances, cooling, hot water & cooking) ・ Other (agriculture, other demand)

For the input data, future demand for energy services was set based on the forecasts of ERIA[11] and IEEJ[12]. For future coal and gas prices, current domestic prices (coal: Indonesia, gas: Thailand) were extended with the Sustainable Development Scenario (SDS) in the IEA World Energy Outlook 2020[13]. Imported hydrogen and ammonia prices were based on the Japanese government targets[14] of 25 cents and 17 cents per 1 Nm^3-H_2, respectively in 2040, 20 cents and 16 cents in 2050, and 17.5 cents and 16 cents in 2060. Technical specifications are assumed based on various literature, and technical costs are set for each country where data is available, such as power generation technologies. Table 2 gives one case of assumed technology capital costs.

Table 2. An example of technology capital cost assumptions (Indonesia)

	2017	2030	2040	2050	2060
Solar PV ($/kW) [15]	790	560	485	410	382
Lithium-ion battery ($/kWh) [16]	370 (2020)	208	182	156	135
Direct air capture ($/t$CO_2$/yr) [17]	2,776	1,735	1,041	694	620

Note: Real 2019 prices.

Regarding the main constraints excluding CO_2 emission constraints, the upper limits of solar PV installation (3,513GW for ASEAN), onshore wind installation (313GW for ASEAN) and offshore wind installation (1,241GW for ASEAN) were set taking into account geographical and land use conditions, based on GIS data (Table 3). On solar PV, for example, forested land and land sloping at over 4% were excluded as unsuitable. The upper limit of the geothermal (34GW) and biomass power installation (71GW) were set based on various documents[18]. Here, it is assumed that the power generated by the solar PV, wind and hydro resources located in Indonesian territories outside of Java and Sumatra and Malaysian territories outside of the Malay Peninsula cannot be connected to power grids because these resources are separated from the centers of demand by the sea, but that they can be used for hydrogen production. Although there is significant political uncertainty about the introduction of nuclear power, for the purposes of this analysis, it might be introduced only in Indonesia (up to 35GW after 2050) and the Philippines (up to 0.63GW after 2050). Imports of hydrogen and ammonia from outside ASEAN are allowed from 2040 in our scenario, with import volumes capped at 15% of the total primary energy supply in each country's Baseline scenario (no emissions constraints) (5% in Indonesia) in 2040 and 30% after 2050 (7.5% in Indonesia). Regarding CCS, the annual upper limit of carbon storage for ASEAN as a whole, rather than by country, was set at 10 MtCO_2/year in 2030, 687 MtCO_2/year in 2040 (equivalent to 20% of energy-derived CO_2 emissions in the Baseline scenario), 1,138 MtCO_2/year in 2050 (25% of such emissions), and 1,610 MtCO_2/year in 2060 (30%). One report[19] assesses the cumulative CO_2 storage potential of Indonesia, Malaysia, the Philippines, Thailand and Vietnam combined to be about 75 GtCO_2, with the annual upper limit in 2060 equivalent to 2.1% of the potential. For the international power grid, the optimal installed capacity is determined within the model, but the upper limit was set based on current plans[20] (54GW for ASEAN as a whole). Note that in our standard assumption, electricity exports from Myanmar to Thailand are limited to zero.

Table 3. Upper limits of solar PV, wind and hydro installation (GW)

	BRN	KHM	IDN	LAO	MYS
Solar PV	2	350	1,493 (1,014)	89	195 (117)
Onshore wind	0	14	19 (13)	50	0
Offshore wind	0	2	224 (152)	0	0
Hydro	0	10	75 (55)	26	26 (20)

	MMR	PHL	SGP	THA	VNM
Solar PV	524	287	2	280	291
Onshore wind	1	92	0	70	66
Offshore wind	0	576	0	3	435
Hydro	100	4	0	6	35

Note: Values in parentheses ( ) are assumed usage for hydrogen production

2.2 Emission constraints and scenario setting

Constraints on energy-related CO_2 emissions are set for representative years and countries, with CN to be achieved in 2060 for ASEAN as a whole (Figure 1). Here, constraints on energy-related CO_2 emissions in Indonesia, Malaysia, Myanmar and Thailand were set accounting for CO_2 emissions from land-use change and forestry (LULUCF) (Table 4). Assumed CO_2 emissions in the LULUCF secotr are based on the long-term strategies of each country, NDCs and emissions inventories (for example, Indonesia is assumed to be at -300MtCO_2 from 2050). However, even countries with rich potential absorption resources such as forests have set energy-related CO_2 abatement targets of at least 50% compared to 2017 emissions. While the cost of forestation and reforestation is not zero, they are probably relatively low compared to the cost of reducing energy-related CO_2 emissions, at \$0-240/ tCO_2[21].

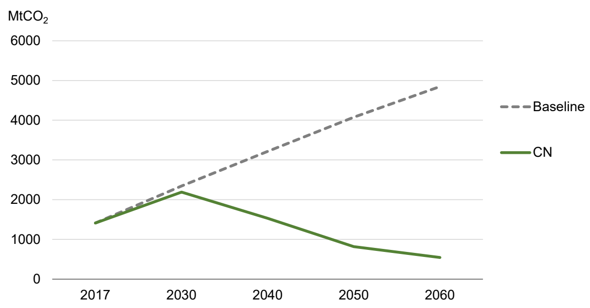

Figure 1. Constrained energy-related CO_2 emissions (ASEAN)

Table 4. Year of CN achievement and energy-related CO_2 abatement targets (against 2017)

	BRN	KHM	IDN	LAO	MYS
CN year	2050	2050	2060	2050	2050
Reduction target	100%	100%	50%	100%	50%
	MMR	**PHL**	**SGP**	**THA**	**VNM**
CN year	2060	2060	2050	2050	2050
Reduction target	60%	100%	100%	50%	70%

The seven calculation scenarios are shown in Table 5. The Baseline scenario has no restrictions on carbon emissions, while the CN scenario does have restrictions. In addition, as a sensitivity analysis for the CN scenario, five scenarios by category (from PowerInov to Combo) are set in which further international cooperation (strengthened power grid across ASEAN) and technological innovations (reduction of various technology costs and raising the upper limit of annual CO_2 storage) are achieved.

Table 5. Scenario setting

Scenario	Salient features
Baseline	No constraints on carbon emissions
CN	Constraints on carbon emissions
PowerInov	・Capital cost of lithium-ion batteries reduced 25% by 2040, 50% from 2050 ・Cost of development of international power grid halved, unlimited development ・Exports from Myanmar to Thailand permitted
CCSInov	・Capital cost of DAC reduced 25% by 2040, 50% from 2050 ・Annual upper limit of CO_2 storage of 2.3GtCO_2/year in 2050, rising to 2.7GtCO_2/year in 2060
H2Inov	・Supply: 25% reduction in the capital cost of coal gasification, methane reforming, electrolysis and hydrogen tanks in 2040, a 50% reduction from 2050 ・Demand: 25% reduction in capital cost of hydrogen-based reduction steelmaking and fuel cell ships in 2040, a 50% reduction from 2050, and capital cost of FCEVs reduced to the same as hybrid electric vehicles in 2060
DemInov	50% reduction in the differential in capital costs between advanced technologies and the existing technologies from 2040 on the demand side (industry, transport, household)
Combo	A combination of PowerInov, CCSInov, H2Inov and DemInov

3. Findings and observations

3.1 Baseline and CN scenarios

As demonstrated in Fig. 2, which shows CO_2 emissions by sector for ASEAN as a whole, these will grow 3.4-fold from 2017 to 2060 in the Baseline scenario, reflecting the rise in energy demand in line with regional economic growth. Above all, emissions from the industry and transport sectors will rocket 4.6-fold and 4.5-fold, respectively. In the CN scenario, which aims for net zero CO_2 emissions across the whole of ASEAN by 2060 by reducing energy-related CO_2 with CO_2 absorption in the LULUCF sector, ASEAN approaches zero emissions from the power generation sector in 2040, and the sector turns into a source of negative emissions after 2050 as a result of BECCS. In addition, with the introduction of DACCS from 2050, BECCS and DACCS will combine to provide negative emissions of over 1GtCO_2 in 2060. Compared to the Baseline scenario, there will also be a large reduction in emissions from final consumption sectors, but the best solution for the remaining emissions, mainly from the transport sector (long-distance transport mainly by heavy-duty vehicles) and industry sector (demand for high-temperature heat) is to offset these with the negative emissions of the abovementioned BECCS, DACCS and the LULUCF sector. As such, the achievement of net zero through offsets with negative emissions while emissions continue from final consumption sectors that are hard to decarbonize is also consistent with the scenario of IPCC AR6.[21]

Under the CN scenario, efficiency and electrification progress in final energy consumption, leading to a 17% reduction in total energy consumption from the Baseline in 2060, with 33% coming from electricity (Fig. 3). Oil consumption is half of Baseline in 2060, due to vehicle electrification, but consumption continues in large vehicles as noted above.

Looking at primary energy supply (Figure 4, nuclear and renewable energy conversion rates in accordance with the IEA Energy Balance Table), the share of renewable energy will reach 38% in 2060 under the CN scenario, while imported hydrogen and ammonia will also account for 14%. If we check the 2060 supply-demand balance for hydrogen and ammonia here, supply is 73% imported, with electrolysis providing 24% and coal gasification 3%. On the demand side, power generation accounts for 85%, industrial heat utilization 9%, and fuel cell ships 4% - so in essence, the imported fuels will be used to generate power. As for natural gas, it is also selected as an important fuel in the power generation and industrial sectors under the CN scenario, and in the transition period of 2030 and 2040, the demand for natural gas will increase more than in the Baseline due to coal replacement. The recent spike in global gas prices is likely to have a significant negative impact on the ASEAN energy transition.

Power generation in the CN scenario is driven by demand from electrification of final consumption sectors and DAC (962TWh in 2060), a significant increase over Baseline and reaching a 6.5-fold increase over 2017 in 2060 (Fig. 5). As a result of efforts to minimize the cost of the overall energy system through optimal installation of batteries and thermal power generation in order to compensate for the intermittency of solar PV and wind power, which are to be adopted at scale (1,628GW in 2060), batteries will be installed on a large scale (1,365GWh in 2060) and the share of thermal power generation will remain at about 40‐50%. Thermal power generation will shift from coal-fired power to gas-fired power and while applying low-carbon technologies such as hydrogen or ammonia co-firing, eventually decarbonizing in stages to gas-fired power with CCS or hydrogen or ammonia single-firing. However, the power supply mix in 2060 will vary greatly by country (Fig. 6). Myanmar, Cambodia and Laos have abundant resources compared to domestic demand, so renewable energy will account for more than 95% of their power generation. In 2060, 18% of Thailand's electricity demand will be covered by imports from Laos, with 65% of Laotian power generation exported to Thailand. In 2050, the capacity of the interconnector between Thailand and Laos will reach the upper development limit of 25GW. On the other hand, Malaysia, the Philippines, Singapore and Brunei will have less than one-third of their power generated by renewables. Malaysia does not benefit from great wind power resources, and most of the solar PV and hydro resources are concentrated on Borneo, where energy demand is low (Table 3). In this analysis, it was assumed that these resources could only be used for hydrogen production, but due to the cost advantage of imported hydrogen and ammonia, there will hardly be any domestic production. Although the Philippines has abundant solar PV and wind resources, based on data supplied by the Philippine government, the cost of introducing wind power generation is higher than that of Indonesia, therefore little wind power is to be installed. In Singapore and Brunei, which have a small land area, gas-fired and hydrogen-fired thermal will be the main power sources.

Regarding the cost of CO_2 abatement, the marginal abatement cost under the CN scenario will be \$348/tCO_2 in 2060 (\$188‐419 by country), and the additional cost from the Baseline case reaching 3.6% of GDP in 2060 (Fig. 7). The marginal abatement cost for ASEAN overall is calculated by applying the weighted average of the primary energy supply to the marginal abatement cost of each country. If we recall the current carbon tax rate in Sweden rate of \$130[22], the world's highest, then the cost burden is going to be significant on the path to CN. IPCC AR6 estimates that the global marginal abatement cost for CO_2 will be \$210 (\$140‐340) in 2050 under the 2°C scenario and \$630 (\$430‐990) (2015 prices) under the 1.5°C scenario, which is largely consistent with our analysis. Moreover, in our analysis, under the CN scenario, it was estimated that the marginal cost of electricity would double in 2060 compared to the base year (simple average of marginal cost over 2,190 hours per year). However, according to the IEA's net zero analysis[23], if the total energy burden of households is considered, electricity bills will increase while gasoline costs will drop to zero (due to the shift to EVs) and that therefore the share of energy-related expenditure in disposable income may not increase. It should be noted that decarbonization is certain to increase the cost of the entire energy system.

3.2 Innovation scenarios

Figure 8 compares the power generation mixes under the CN scenario and the five innovation scenarios in 2060. The share of renewables under the PowerInov scenario maxes out at 76%, higher than the CN scenario (56%), due to higher solar PV and hydro generation. While the share of thermal power decreases, the capacity of batteries installed is 3.1 times higher than under the CN scenario. The removal of upper limits to the expansion of the international power grid allows 45% of power generation in the ASEAN region to be exported, correcting the uneven distribution of renewable energy resources in the region. By contrast, under the CCSInov scenario, the annual CO_2 storage capacity increases, lifting the share of gas-fired power (with CCS) to 36%. In both the PowerInov and CCSInov scenarios, there is less reliance on thermal power using imported hydrogen and ammonia and increased renewables and gas-fired power generation. In the H2Inov and DemInov scenarios, the power consumption of final consumption sectors will decrease due to the shift to hydrogen and efficiency improvements, while the introduction of DACs in electricity also decreases due to the reduction in oil as uptake of FCEV heavy vehicles increases. This means there is roughly 10% less power generated overall than under the CN scenario. In the Combo scenario, which is a combination of the four innovation scenarios, solar PV and gas-fired thermal increase compared to the CN scenario, but hydrogen, ammonia thermal and wind power, which are relatively high-cost, are practically eliminated.

Regarding the cost of CO_2 abatement in 2060 under the innovation scenarios, it is much lower than under the CN and Combo scenarios both in terms of marginal abatement and average abatement costs (Fig. 9). On the other hand, looking at the scenarios other than Combo, CCSInov has the lowest marginal abatement cost, while DemInov has the lowest average abatement cost - they are not the same scenario. For the DemInov scenario, this result may appear obvious as it predicts lower capital costs for a wide range of demand-side technologies from the outset, but it is not just a reduction in demand-side fixed costs for demand-side technology innovation, it also has significant knock-on effects on fuel cost and supply side fixed cost reductions. Given that the model's objective function is the minimization of overall costs, the minimization of overall costs is primarily the most important factor, but on the other hand, reducing marginal costs that are the basis of the market principle is also important. As we have seen here, it is important to remember that the two are not necessarily correlated.

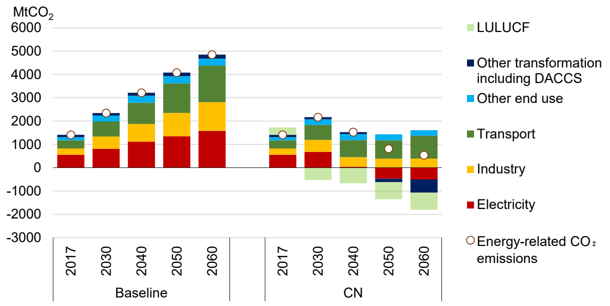

Figure 2. CO_2 emissions by sector (ASEAN)

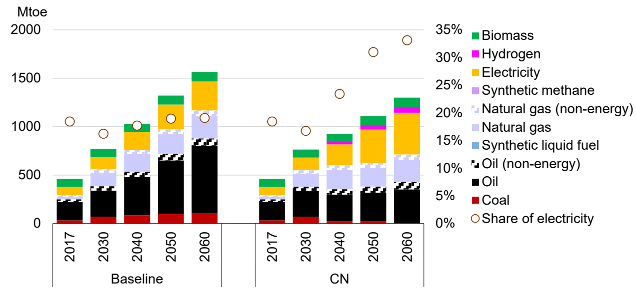

Figure 3. Final energy consumption (ASEAN)

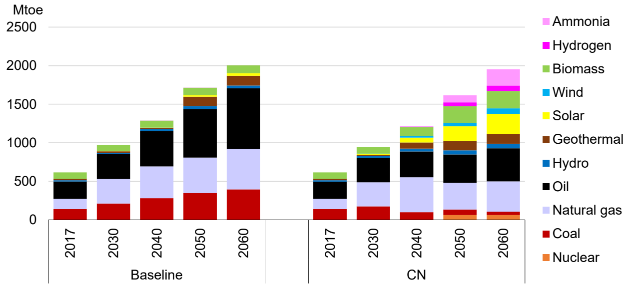

Figure 4. Primary energy supply (ASEAN)

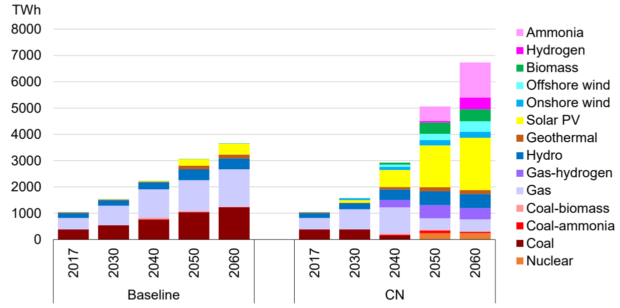

Figure 5. Power generation (ASEAN)

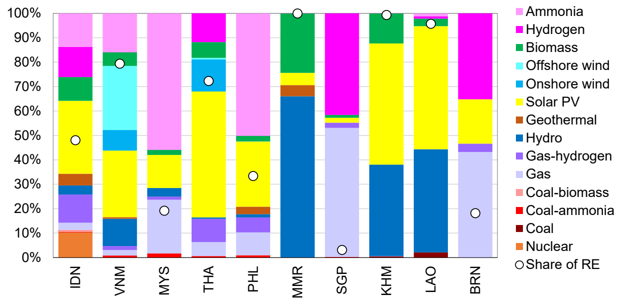

Figure 6. Power generation share (CN, 2060)

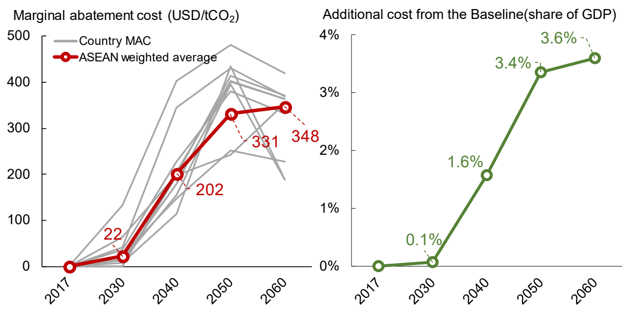

Figure 7. Cost of CO_2 abatement (CN, ASEAN)

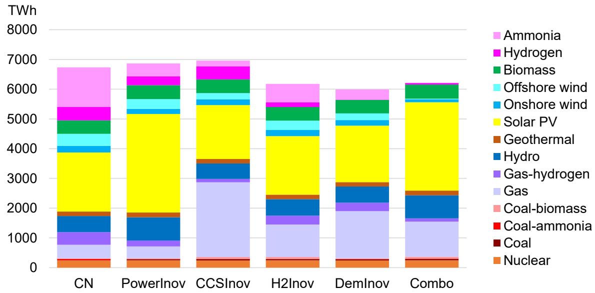

Figure 8. Power generation under Inovation scenarios (ASEAN, 2060)

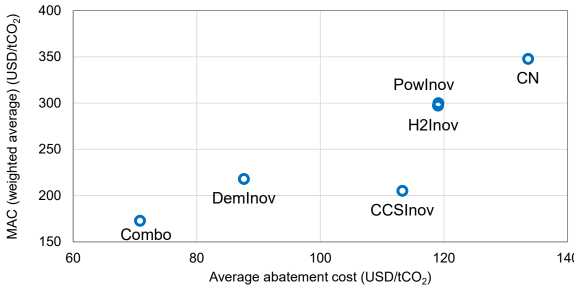

Figure 9. Cost of CO_2 abatement under Innovation scenarios (ASEAN, 2060)

4. Conclusion

In this report on the 10 countries of ASEAN, we applied the linear programming technology selection model to demonstrate the cost-optimal solutions for CO_2 emissions by sector, primary energy supply and power generation mix toward achieving decarbonization. We found that as indicated by IPCC AR6, (1) energy efficiency and electrification in the final consumption sectors, (2) early decarbonization in the power sector (by around 2040), and (3) utilization of negative emission technologies (DACC, BECCS, forest carbon sinks) are also vital for this region. It was also confirmed that natural gas will play an important role in transition periods 2030 and 2040. Regarding the power supply mix, it goes without saying that renewables, especially solar PV, will be important, but gas-fired thermal power with CCS and hydrogen/ammonia-fired thermal power will also be indispensable in many countries. Although it is inevitable that the total cost of the energy system will increase with decarbonization, costs can be reduced considerably by strengthening natural resource sharing within ASEAN via the international power grid and achieving technological innovations, including on the demand side.

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