Myanmar's Power Mix and International Interconnection: Cost Minimization Model

Ryohei Ikarii*, Yumiko Iino**, Yuji Matsuo***

Abstract

In Myanmar, it is unclear how long the political turmoil caused by the military coup will last. However, one of the keys to sustainable economic development of the country and living standard improvement of the people continues to be tackling the increasing demand for electricity. This requires Myanmar's government to construct an electricity supply system based on long-term planning and to consider the installation of international interconnection lines under the situation where many countries are starting to go forward to decarbonization. Therefore, this paper illustrates the preferable energy mix for Myanmar in 2050 from the perspective of the 3Es (economic efficiency, environmental sustainability and energy security) in multiple scenarios, setting different carbon prices and hydropower potentials for Myanmar. In conclusion, Myanmar should strongly promote hydropower development, including large-scale power plants, which will contribute to ensuring the 3Es, and also promote the development of international interconnection lines with neighboring Thailand, which will improve the fiscal revenue from the electricity export.

Key words: Myanmar, Power mix, International interconnection, Cost minimization

1. Introduction

In Myanmar, the National League for Democracy (NLD) led by Aung San Suu Kyi remained in power from 2016 to February 2021 when the national military forces staged a coup and took power amid the COVID-19 pandemic. However, many people have participated in an anti-government movement in pursuit of democratization, continuing armed conflicts with the military government. While how long the turmoil's adverse political and economic impacts would last is uncertain, one of the keys to the sustainable development of the Myanmar economy and the improvement of living standards for citizens is to respond to growing electricity demand. The Ministry of Electricity and Energy (MOEE) achieved power grid access for 50% of all households in December 2019 and has enhanced electricity supply. Efforts to achieve the electrification rate of 100% are continuing. The development and enhancement of power plants and power transmission/distribution networks may take a long lead time and installed facilities may remain in service for at least 25 to 40 years. Therefore, it is important to develop an overall electricity supply system based on long-term planning. Electricity exports to neighboring countries may also benefit the Myanmar economy. Given the global decarbonization trend, Myanmar may be required to reduce electricity generated from fossil fuels. This study considers the optimum power generation mix and international interconnection lines for Myanmar in 2050 and argues that the Myanmar government should focus on hydropower development and consider electricity exports through international interconnection lines to neighboring Thailand.

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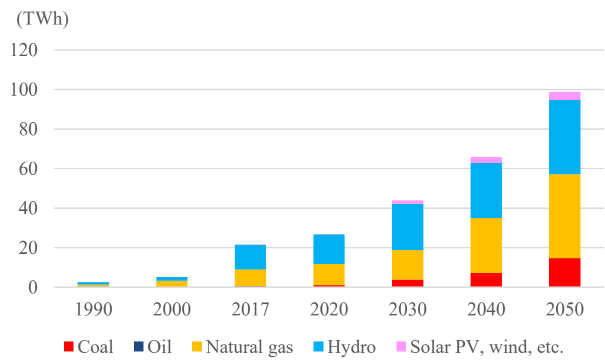
2. Literature review

2.1 Electricity demand outlook

Power generation in Myanmar quintupled from only 5 TWh in 2000 to 25 TWh in 2018 (IEA, 2021a[1]). According to Myint (2021)[2], power generation in 2050 is expected to nearly quadruple to 99 TWh (Figure 1). IEEJ (2021)[3] predicts Myanmar's power generation to nearly sextuple from 2019 to 137 TWh in 2050. Both predictions are based on an econometric approach, indicating a relatively wide gap between 99 TWh and 137 TWh.



(Source) Myint, 2021[2)]

Figure 1 Power generation results and outlook in Myanmar

Power generation mix shares estimated for 2050 by Myint (2021)[2] are 43% for natural gas, 38% for hydro, 15% for coal and 4% for variable renewable energy (VRE). The IEEJ (2021)[3] projects the respective shares for 2050 at 60%, 15%, 21% and 4%.

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Their power generation mix projections also differ from each other.

2.2 Power generation outlook by source

(1) Gas-fired power generation

Gas has replaced hydro as Myanmar's largest power source. According to the IEA (2021a)[1)], gas-fired power generation totaled only 1.8 TWh against 6.2 TWh in hydropower generation in 2010 and surpassed 10.5 TWh in hydropower generation to 11.3 TWh in 2019. The literature[1)] indicates that gas' share of total power generation rose from 20.4% in 2010 to 46.7% in 2019.

Myanmar has so far used domestically produced natural gas for power generation. As domestic gas fields are being depleted, however, the country is required to expand liquefied natural gas (LNG) imports in the future. In 2014, Myanmar consumed 20% of its domestic gas production, totaling about 1,900 million standard cubic feet per day (mmscfd), and exported the remaining 80% to Thailand and China (Nippon Koei Co., etc., 2016[4)]). In 2040, however, domestic production will decline to about 810 mmscfd, while domestic demand increases to 1,142 mmscfd. In this way, Myanmar will fail to cover its gas demand with domestic production even if it discontinues all exports (Kobayashi & Phoumin, 2018[5)]). The NLD explored new gas fields but failed to find any large ones (Kobayashi & Phoumin, 2018[5)]), indicating that Myanmar will transition from a natural gas exporter to an LNG importer. It launched LNG imports in May 2020 (Yep, 2020a[6)]). The MOEE minister has indicated that a project has started to increase LNG power generation capacity by 4,000 MW (Yep, 2020b[7)]).

Given that gas for power generation is expected to account for about 80% of gas demand in 2040 (Kobayashi & Phoumin, 2018[5)]), Myanmar will have to further promote domestic gas field exploration and development and predict the gas consumption required for power generation.

(2) Coal-fired power generation

The government has considered developing coal-fired power plants as a new power source to meet growing electricity demand. Due to opposition from local residents and the absence of coal distribution networks, however, the development has been stalled.

The 120 MW Tigyit coal-fired power plant is Myanmar's only existing coal power generation facility (Emmerton et al., 2015[8)]), accounting for 9.3% of its total power generation as of 2019 (IEA, 2021a[1)]). The government has considered developing coal-fired power plants at some locations. However, the development has stagnated in the face of opposition from local residents who are concerned about such plants' environmental and social impacts (Myanmar Times, 2018[9)]). Myanmar's Nationally Determined Contribution (NDC) updated in July 2021 sets coal-fired power plants' share of total power generation capacity in 2030 at 20% for an unconditional target with its own efforts and 11% for a conditional target with international cooperation, indicating that the country plans to suppress coal-fired power generation through international cooperation (Myanmar, 2021[10)]).

Major coal deposits have been confirmed in northwestern and central eastern regions that are far away from Yangon as the demand center (Emmerton et al., 2015[8)]). Railway transportation capacity is insufficient. Rivers are sufficiently deep in the rainy season but shallow in the dry season, failing to be suitable for barge transportation (ERIA, 2020[11)]). Deposits are not so large in any coalmine. Coalmines that can stably supply coal for large coal-fired power plants are extremely limited (ERIA, 2020[11)]). At present, constraints exist on domestic coal supply, meaning that Myanmar may have to depend on imported coal.

If Myanmar were to use coal-fired power generation to help meet growing electricity demand, its government would have to get local residents' understanding and develop supply chains for domestic and imported coal while considering environmental and social impacts.

(3) Hydropower

Myanmar, though rich with water resources, has stagnated their development in consideration of environmental and social impacts and water shortages in the dry season. Its technologically feasible hydropower potential is estimated by IFC (2020)[12)] and Tang et al. (2019)[13)] at 40-50 GW. The MOEE's Aye (2017)[14)] claims that the potential reaches 100 GW. Due to insufficient considerations given to local residents regarding past dam development and concern about negative impacts on the ecosystem, however, there is particular opposition to large-scale hydropower development (Dapice, 2015[15)]). While sufficient water must be stored in reservoirs during the rainy season to secure full hydropower operation even during the dry season, output declines or stands at zero at some hydropower plants during the dry season (Dapice, 2015[15)]). Given such conditions, Schmitt et al. (2021)[17)] asserts that the hydropower potential should be regarded as 6.7-10.3 GW. In its updated NDC given in July 2021, however, the Myanmar government projects the hydropower potential in 2030 at 22.8 GW including large-scale hydropower plants (Myanmar, 2021[10)]). As a long lead time around 20 years is required for large-scale hydropower plant development (Dapice, 2015[15)]), long-term development plans must be formulated.

Regarding the stagnant hydropower development in Myanmar, IFC (2020) [12] supports the formulation of economic and social impact assessment standards to identify suitable locations for hydropower development. The IEA (2021b)[18] concludes that the value of hydropower must be reaffirmed globally, proposing to combine hydropower and solar photovoltaics facilities during water shortages in the dry season. In the context of Myanmar, ERIA (2020)[11] indicates that Myanmar could take advantage of its long sunshine hours to combine solar PV and hydropower during the dry season to help stabilize electricity supply. The IEA (2021b) [18] notes that the long lead time for hydropower plant construction may be shortened through the rationalization of the approval process and that large-scale hydropower plants feature long-term revenue predictability that is useful for lowering fundraising costs and improving the feasibility of development projects.

(4) Renewable energy (excluding hydropower)

Myanmar has embarked on renewable energy development, launching its first commercial solar PV power generation in 2019. However, its government has yet to specify goals or roadmaps for each renewable energy source.

The government has traditionally promoted the electrification of rural areas through solar PV power generation, introducing solar home systems and solar mini-grids under support from various international organizations (SolarPower Europe, 2019[19]). Myanmar's solar PV potential is relatively high in the Association of Southeast Asian Nations (ASEAN), estimated at about 40 TWh per year (ADB, 2016[20]). Regarding renewable energy development, its NDC updated in July 2021 specifies solar PV capacity in operation at 40 MW, such capacity under construction at 8.25 MW, such capacity in auction processes at 1,060 MW and wind power generation capacity under feasibility study at 30 MW, indicating that Myanmar gives development priority to solar PV among renewables. The updated NDC projects a power generation capacity mix share for renewables (excluding hydro) at 11% for an unconditional target with Myanmar's own efforts and 17% for a conditional target with international cooperation, indicating that the country plans to promote renewables under international support.

To further develop solar PV capacity, the Myanmar government should clarify its policy and strategy on renewable energy development and establish adequate law and regulation frameworks, as indicated by Aung et al. (2018) [21].

2.3 ASEAN Power Grid (Myanmar-Thailand international interconnection lines)

ASEAN is promoting the ASEAN Power Grid (APG) initiative to develop interconnected grid systems to efficiently use and share regional resources and improve energy security (ACE, 2015[22]). Total AGP capacity stood at 5,502 MW as of January 2019. Myanmar, though having its power distribution lines with Thailand and Laos to link local areas (IEA, 2019a[23]), has no international interconnection lines. For the future, Myanmar is considering developing international interconnection lines with capacity totaling 26,680 to 30,150 MW. In particular, potential capacity for international interconnection lines between Myanmar and Thailand is estimated at as much as 11,709 to 14,859 MW (IEA, 2019 b[24]). As noted by IEA (2019a)[23], international interconnection lines may improve the flexibility of electricity supply and demand in the ASEAN region and contribute to reducing the intermittency of VRE expected to spread in the future.

2.4 Comparison with similar studies

This study is similar to ERIA (2020)[11] and ERIA (2021) [25] that analyzes Myanmar's optimum power generation mix.

ERIA (2020)[11] assumes Myanmar's total power generation in 2040 at a level in the Alternative Policy Scenario of ERIA Outlook 2018 and sets hydropower and VRE power generation in reference to Emmerton et al. (2015)[8], without using any optimization or econometric model. Then, it sets a fossil-fired power generation mix, giving priority to economic efficiency, environmental sustainability and energy security. Electricity exports are assumed to remain at the level for 2016.

ERIA (2020) [11] projects a power generation mix for 2040, while this study illustrates one for 2050. Given the lead time for power plant construction, this study gives the Myanmar government more time to formulate and implement a power development plan. While ERIA (2020) [11] uses no optimization or econometric model, this study uses an optimization model to project a power generation mix and electricity exports.

Meanwhile, ERIA (2021) [25] uses an optimization model to indicate cost changes accompanying the presence or absence of international interconnection lines and changes in the solar PV share for eight ASEAN countries, including Myanmar, and the ASEAN region in 2040. As a reference, it indicates a cost optimum power mix, including minimum shares for fossil fuels, and electricity exports for the case of a carbon price at US$50/t-$CO_2$.

In line with the ERIA (2021) [25] approach, this study uses an optimization model to minimize costs. Unlike ERIA (2021) [25], however, this study focuses on Myanmar and Thailand, uses the latest power generation cost data and projects a power generation mix for 2050 without setting minimum shares for fossil fuels. While ERIA (2021) [25] focuses on solar PV share changes as an issue for the entire ASEAN region, this study pays attention to and deepens discussions on hydropower potential as an issue peculiar to Myanmar. Furthermore, this study quantitatively assesses each scenario.

3. Methodology

3.1 Total power demand settings

As the prolongation of the current turmoil in Myanmar is expected to exert downward pressure on energy demand, we adopt a conservative projection of total power demand for 2050 in Myint (2021)[2) 1]. On an assumption that power supply will meet the projected demand, we seek a power generation mix to minimize costs, without considering standby power. Although the impact of COVID-19 is not reflected in Myint (2021)[2)], we adopt the projection on an assumption that the COVID-19 pandemic's long-term impact on total power demand will be small (IEEJ, 2020a[27)]; Kimura et al., 2021[28)]).

3.2 Optimization model

To determine an optimum power generation mix in Myanmar, we use a cost-minimization model for Myanmar and neighboring Thailand. The model assumes one year as 8,760 hours and determines a power generation mix to minimize total power generation costs for the electricity system in the two countries. The cost minimization logic is that the power generation mix is determined when power generation marginal costs for all energy sources become equal[2]. The power generation costs include annual construction, operation and maintenance & management costs for each power generation technology, each power storage system and international interconnection lines. When total power generation exceeds total power demand due to an increase in VRE power generation, the utilization of power storage systems or the suppression of output from VRE power facilities will be chosen. Given high power storage costs, the output suppression will be chosen more frequently.

3.3 Assumptions

(1) Power generation costs

As projected power generation costs (construction, operation and maintenance & management costs) in 2050 for gas-fired, coal-fired, hydrogen-fired, hydro, geothermal, biomass, solar PV, onshore wind and offshore wind power plants in Myanmar and Thailand were difficult to collect, we adopt such projected costs in 2050 in Indonesia as another ASEAN member (DEN, 2021[29)]). As for power generation costs for gas-fired power plants with carbon capture and storage (CCS) and nuclear power plants on which data in DEN (2021)[29)] are insufficient, we estimate the costs based on projections in IEA (2020)[30)]. We set fuel costs in line with international energy price assumptions (for Reference Scenario) in IEEJ (2020b)[34)], based on Indonesian coal prices (PLN, 2019[31)]) and average gas prices for Indonesia, Malaysia and Thailand (PLN, 2019[31)]; EGAT, 2019[32)]; Energy Commission, 2021[33)]). As a result, the levelized cost of electricity (LCOE) for each energy source in 2019 dollars is set for the carbon price of zero, as shown in Table 1.

Table 1 LCOE in Myanmar and Thailand

Coal	Gas	Gas+CCS	Hydrogen	Nuclear	Hydro
4.2	4.8	7.3	11.5	5.7	5.0

Geothermal	Biomass	Solar PV	Onshore wind	Offshore wind
3.8	8.2	3.7/4.4	12.5/9.4	12.8/21.1

(Unit: US cents/kWh in 2019 dollars)
(Note) Left values for solar PV and onshore/offshore wind are for Myanmar and right values for Thailand.

(2) Renewable energy potential

We estimate solar PV and wind potential out of renewable energy power generation potential by using geographic information system data to consider land-use classification and land gradients. We also use data in Renewalbes.ninja (Staffell & Pfenninge, 2016[35)]; Pfenninge & Staffell, 2016[36)]) to find solar PV and wind output patterns.

Table 2 Renewable energy potential in Myanmar and Thailand

	Solar PV	Wind	Hydro	Geothermal	Biomass
Myanmar	524	1	49	1	12
Thailand	1,120	73	6	0	7

(Unit: GW)

We set hydropower potential at 49 GW for Myanmar in line with IFC (2020)[12)] and at 6 GW for Thailand in line with Huber et al. (2015)[37)]. Geothermal potential is set at 1 GW for Myanmar according to Huber et al. (2015)[37)]. Biomass potential is set at 12 GW for Myanmar and at 7 GW for Thailand according to Tun et al. (2019)[38)].

(3) International interconnection line costs

Although there is no international interconnection line between Myanmar and Thailand as noted in Section 2.3, we assume their

[1] For Thailand, we adopt an outlook in Kamalad (2021)[26)] that is in the same book as Myint (2021)[2)].

[2] When maximum and minimum constraints are imposed, marginal costs for energy sources subject to the constraints may become higher or lower than for other sources. For details, see ERIA (2021)[25].

future interconnection potential at 14.9 GW (IEA, 2019b[24]).

We set construction costs and a power transmission loss rate for international interconnection lines according to Kutani & Li (2014)[39]. As for power transmission costs, we first set a unit cost per kilometer for transmission lines and computed costs according to the transmission distance. Then, we add electric power substation (switching station) construction costs according to the number of substations required for the interconnection lines. Specifically, we set a unit price for power transmission lines at US$0.9 million/km/2 circuits, based on past construction cost data for neighboring countries. As for electric power substation (switching station) construction costs, we set a fixed cost at US$20 million per substation and an additional cost at US$10 million per circuit. Furthermore, we assume operation and maintenance & management costs at around 0.3% per year of total construction costs. We assume the power transmission loss rate at 1% per 100 km. Based on these assumptions, we estimate costs for international interconnection lines between Myanmar and Thailand at US$24 million/GVA/year and the power transmission loss rate at 5.4%.

3.4 Scenarios

(1) Scenarios regarding international interconnection lines

We assume the scenarios with and without international interconnection lines between Myanmar and Thailand in 2050.

(2) Base scenario

In the base scenario, we assume the carbon price at zero in Myanmar and Thailand and Myanmar's hydropower generation potential at 49 GW.

(3) Scenario for the carbon price at US$50/ t-$CO_2$

In this scenario, we assume that the carbon price will rise to US$50/t-$CO_2$ in 2050. The carbon price may not necessarily be realized as a carbon tax. It may be regarded as a carbon avoidance cost.

(4) Scenario for hydropower potential at 23 GW

In this scenario, we assume that Myanmar's hydropower potential in 2050 will be lower than 49 GW and limited to 23 GW as given in the updated NDC for 2030.

(5) Scenario for the carbon price at US$25/t-$CO_2$ for Myanmar (US$50/t-$CO_2$ for Thailand) plus hydropower potential at 23 GW

In this scenario, we assume Myanmar's hydropower potential at 23 GW and the carbon price at US$50/t-$CO_2$ for Thailand and at US$25/t-$CO_2$ for Myanmar in consideration of economic gaps between the two countries.

3.5 Assessment standards

(1) Assessment of scenarios

To consider which scenario is favorable for Myanmar, we set specific assessment standards for this study from the perspective of the 3Es (economic efficiency, environmental sustainability and energy security) and assess each scenario.

(2) Economic efficiency

As a standard to assess the economic efficiency of each scenario, we use costs per MWh that we determine by dividing total costs in US dollars by total power generation (MWh) in Myanmar and Thailand.

(3) Environmental sustainability

As a standard to assess the environmental sustainability of each scenario, we use CO_2 emissions per MWh that we determine by dividing total CO_2 emissions (t-CO_2) by total power generation (MWh) in Myanmar and Thailand.

(4) Energy security

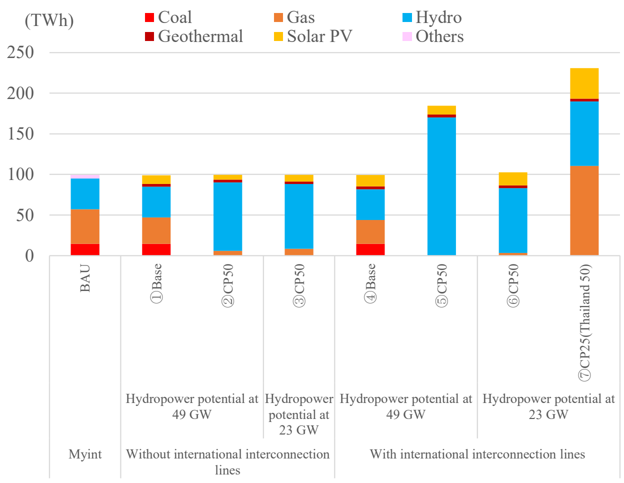
As it is conceivable that Myanmar will deplete domestic fossil fuels and import natural gas and coal in the future, we use fossil fuel input per MWh that we determine by dividing total fossil fuel input (toe) by total power generation (MWh) in Myanmar and Thailand to assess the energy security of each scenario.

4. Scenario results

4.1 Optimum power generation mix for each scenario

(1) Overview

Of the scenario estimation results based on the assumptions, the Myint BAU scenario at the left edge of Figure 2 indicates a business as usual scenario in Myint (2021)[2]. Indicated next are three scenarios without international interconnection lines: ① Base (hydropower potential at 49 GW) as the base scenario, ② Hydropower 49 GW + CP50 for the carbon price at US$50/t-$CO_2$ and ③ Hydropower 23 GW + CP50 for the carbon price at US$50/t-$CO_2$ and hydropower potential at 23 GW. In addition to the three scenarios (④-⑥) with international interconnection lines for the respective assumptions, the figure indicates the ⑦ Hydropower 23 GW + CP25 (Thailand 50) scenario that assumes different carbon prices reflecting an economic gap between Myanmar and Thailand – the carbon price at US$25/t-$CO_2$ for Myanmar (the carbon price at US$50/t-$CO_2$ for Thailand) and hydropower potential at 23 GW.



(Note) "Others" for Myint BAU means solar PV, wind, etc.

Figure 2 Myanmar's optimum power generation mix in 2050 for each scenario

(2) Scenarios without international interconnection lines

In the scenarios without international interconnection lines, there will be no electricity trade between Myanmar and Thailand. In the ① Base (hydropower 49 GW) scenario close to the Myint BAU scenario, the minimum-cost power generation mix for total power generation of 99 TWh will consist of hydropower (38%), gas-fired power (33%), coal-fired power (15%), solar PV (11%) and geothermal power (4%)[3].

In the ② Hydropower 49 GW + CP50 scenario, the carbon price will raise fuel costs for coal and gas, while low-cost hydropower increases. Hydropower will account for 85% of the cost optimum power generation mix to generate 99 TWh in electricity. Gas-fired power and solar PV each will capture 6% and geothermal power 3%[4].

In the ③ Hydropower 23 GW + CP50 scenario, the carbon price will have a similar impact, with hydropower generation falling slightly in line with the hydropower potential drop. The optimum mix for power generation totaling 99 TWh will consist of hydropower (80%), gas-fired power (9%), solar PV (8%) and geothermal power (3%)[5].

(3) Scenarios with international interconnection lines

In the scenarios with international interconnection lines, electricity trade between Myanmar and Thailand will help lower power generation costs. Exports from Myanmar to Thailand will dominate bilateral trade because Myanmar's electricity costs, even if including those for international interconnection lines, will be cheap for Thailand. However, optimum electricity imports and exports will differ by scenario.

In the ④ Base (hydropower potential at 49 GW) scenario, coal- and gas-fired power generation will cost less than renewable energy power generation including hydropower because of the carbon price at zero. The optimum power mix in this scenario will be almost the same as in the base scenario without international interconnection lines. Myanmar's optimum power generation will be the same as 99 TWh in the base scenario without interconnection lines. The optimum power mix will consist of hydropower (38%), gas-fired power (30%), coal-fired power (15%), solar PV (14%) and geothermal power (3%). Myanmar's power generation costs will be minimized when Myanmar exports a small volume of electricity generated from solar PV and imports the same volume generated from Thai gas-fired power plants[6].

In the ⑤ hydropower 49 GW + CP50 scenario with international interconnection lines, massive hydropower electricity consumption in the two countries will optimize Myanmar's power generation costs from the perspective of hydropower costs and potential. The best solution for the two countries is for Myanmar to export surplus electricity after satisfying domestic demand. Myanmar's power generation will increase to 185 TWh. Myanmar's cost optimum power generation mix will consist of hydropower (92%), solar PV (6%) and geothermal power (2%), with exports to Thailand totaling 83 TWh[7].

In the ⑥ hydropower 23 GW + CP50 scenario with international interconnection lines, power generation costs will be optimized, with Myanmar's exports to Thailand being limited to only 5 TWh, as Myanmar's smaller hydropower potential is used primarily to satisfy domestic demand. The optimum power generation mix will consist of hydropower (78%), solar PV (16%), geothermal power (3%) and gas-fired power (3%), with power generation totaling 103 TWh[8].

In the ⑦ hydropower 23 GW + CP25 (50 for Thailand) scenario, Myanmar's hydropower potential will be used to satisfy

[3] In the ① scenario, Thailand's power generation will total 402 TWh, of which gas-fired power will account for 74%, coal-fired power for 22%, hydropower for 3% and solar PV for 2%.

[4] In the ② scenario, Thailand's power generation will total 402 TWh, of which gas-fired power will account for 71%, coal-fired power for 23%, hydropower for 6% and solar PV for 1%.

[5] In the ③ scenario, Thailand's power generation and its mix will be the same as in the ② scenario.

[6] In the ④ scenario, Thailand's power generation will total 401 TWh, of which gas-fired power will account for 75%, coal-fired power for 22% and hydropower for 3%.

[7] In the ⑤ scenario, Thailand's power generation will total 321 TWh, of which gas-fired power will account for 70%, solar PV for 22%, hydropower for 7% and coal-fired power for 1%.

[8] In the ⑥ scenario, Thailand's power generation will total 399 TWh, of which gas-fired power will account for 71%, solar PV for 22%, hydropower for 6% and coal-fired power for 1%.

domestic demand while 128 TWh in electricity generated from solar PV and gas-fired power plants that cost less than in Thailand is exported. The optimum power generation mix for Myanmar's power generation totaling 231 TWh will include gas-fired power (48%), hydropower (34%), solar PV (16%), geothermal power (1%) and coal-fired power (a little)[9].

(5) Summary

In scenarios with and without international interconnection lines, solar PV that features the lowest LCOE is adopted first at optimum points. As the solar PV share's rise is accompanied by a rapid increase in the marginal integration cost, however, massive solar PV diffusion is not cost optimal. Geothermal power is adopted next, but its potential is small. As far as the carbon price is zero, therefore, the optimum solution is the massive diffusion of coal- and gas-fired power generation that features the third lowest LCOE after solar PV and geothermal power.

As the carbon price rises in the absence of international interconnection lines, however, raising the hydropower share after adopting solar PV and geothermal energy contributes to minimizing costs. Hydropower costs less than coal- and gas-fired power generation on which the carbon price is imposed. Even in the case where hydropower potential is limited to 23 GW, therefore, hydropower should be expanded to the maximum extent to minimize costs.

In the ⑤ hydropower 49 GW + CP50 and ⑥ hydropower 23 GW + CP50 scenarios with interconnection lines, exporting electricity to Thailand will be cost optimal. However, the export volume will differ between the two scenarios. The export volume in the ⑤ scenario will stand at 83 TWh against only 5 TWh in the ⑥ scenario. In the ⑤ scenario, the large hydropower potential of 49 GW will allow cheap hydropower electricity to be consumed in Myanmar and Thailand to minimize power generation costs in the two countries. In the ⑥ scenario where hydropower potential will be limited to 23 GW, however, all cheap hydropower electricity will be consumed in Myanmar alone. This means that whether massive electricity will be exported from Myanmar to Thailand depends on hydropower development in Myanmar.

In the ⑦ hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines in which the carbon price in Myanmar will be lower than in Thailand due to an income level gap, massive electricity exports from gas-fired power plants in Myanmar to Thailand will be the optimum solution, even if hydropower potential is limited to 23 GW. This is because importing electricity from Myanmar will cost less than domestic gas-fired power generation for Thailand due to the carbon price gap.

4.2 Scenario assessment

(1) Assessment overview

Table 3 indicates assessment results for each scenario based on the assessment standards set in Section 3.5.

Table 3 Scenario assessment

International inter-connection lines	Scenario	Economic efficiency USD/MWh	Environmental sustainability t-CO_2/MWh	Energy security toe/MWh
Absent	① Base (hydropower 49 GW)	48.21	0.203	0.139
	② Hydropower 49 GW + CP50	61.32	0.118	0.086
	③ Hydropower 23 GW + CP50	61.36	0.120	0.086
Present	④ Base (Hydropower 49 GW)	48.08	0.204	0.140
	⑤ Hydropower 49 GW + CP50	59.34	0.091	0.066
	⑥ Hydropower 23 GW + CP50	61.18	0.118	0.085
	⑦ Hydropower 23 GW + CP25 (Thailand 50)	59.62	0.119	0.086

(2) Economic efficiency

The unit cost per MWh in Myanmar and Thailand will generally increase in line with a carbon price rise, irrespective of whether international interconnection lines will exist.

The unit cost in the ④ Base (hydropower 49 GW) scenario with interconnection lines will be US$0.13/MWh lower than in the ① Base (hydropower 49 GW) scenario. The unit cost in the ⑥ Hydropower 23 GW + CP50 scenario with international interconnection lines will be US$0.18/MWh lower than in the ③ Hydropower 23 GW + CP50 scenario. These suggest that economic efficiency has only slight differences among the scenarios with or without international interconnection lines.

However, the unit cost in the ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines will be US$1.98/MWh lower than in the ② Hydropower 49 GW + CP50 scenario, indicating a large economic efficiency gap between the two scenarios.

The unit cost in the ⑦ Hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines will be

[9] In the ⑦ scenario, Thailand's power generation will total 277 TWh, of which gas-fired power will account for 67%, solar PV for 24%, hydropower for 8% and coal-fired power for 1%.

US$1.56/MWh lower than in the ⑥ Hydropower 23 GW + CP50 scenario with interconnection lines, showing a clear economic efficiency difference.

Therefore, economic efficiency, though deteriorating under the carbon price imposition, will improve substantially if hydropower generation capacity increases to 49 GW to realize massive electricity exports. If the carbon price is US$50/t-$CO_2$ in Myanmar and Thailand, with Myanmar's hydropower capacity limited to 23 GW, economic efficiency may not improve even with international interconnection lines. If the carbon price in Myanmar is lower than in Thailand, however, economic efficiency may slightly improve through electricity trade.

(3) Environmental sustainability

CO_2 emissions per MWh in Myanmar and Thailand will decrease in line with a carbon price increase, irrespective of whether international interconnection lines will exist.

The unit CO_2 emissions in the ④ Base (hydropower 49 GW) scenario with interconnection lines will be only 0.001 t-CO_2/MWh more than in the ① Base (hydropower 49 GW) scenario. The unit CO_2 emissions in the ⑥ Hydropower 23 GW + CP50 scenario with international interconnection lines will be only 0.002 t-CO_2/MWh less than in the ③ Hydropower 23 GW + CP50 scenario as electricity exports are limited. These suggest that environmental sustainability has little difference among the scenarios with or without international interconnection lines.

However, the unit CO_2 emissions in the ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines will be 0.027 t-CO_2/MWh less than in the ② Hydropower 49 GW + CP50 scenario, indicating a large environmental sustainability gap between the two scenarios.

The unit CO_2 emissions in the ⑦ Hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines will be only 0.001 t-CO_2/MWh more than in the ⑥ Hydropower 23 GW + CP50 scenario with interconnection lines, indicating a small environmental sustainability gap in contrast to the clear economic efficiency gap.

If the carbon price is imposed, with massive electricity from hydropower being exported from Myanmar to Thailand, environmental sustainability will improve remarkably. Between other scenarios, however, the environmental sustainability gap will be small. Even if the carbon price in Myanmar is lower than in Thailand, with massive electricity from gas-fired power plants being exported from Myanmar to Thailand, environmental sustainability will change little from a scenario for Myanmar's hydropower potential limited to 23 GW and the two countries' carbon price at US$50/t-$CO_2$ as gas-fired power generation declines in Thailand. This is because gas consumption will increase in Myanmar while decreasing in Thailand.

(4) Energy security

Fossil fuel input per MWh in Myanmar and Thailand will generally decline in line with a carbon price hike, irrespective of whether international interconnection lines will exist.

The unit fossil fuel input in the ④ Base (hydropower 49 GW) scenario with interconnection lines will be only 0.001 toe/MWh more than in the ① Base (hydropower 49 GW) scenario. The unit fossil fuel input in the ⑥ Hydropower 23 GW + CP50 scenario with international interconnection lines will be only 0.001 toe/MWh less than in the ③ Hydropower 23 GW + CP50 scenario as electricity exports are limited. These suggest that energy security has only slight differences among scenarios with or without international interconnection lines.

However, the unit fossil fuel input in the ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines will be 0.020 toe/MWh less than in the ② Hydropower 49 GW + CP50 scenario, indicating a major improvement in energy security.

The unit fossil fuel input in the ⑦ Hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines will be only 0.001 toe/MWh more than in the ⑥ Hydropower 23 GW + CP50 scenario with interconnection lines, indicating a small energy security gap. This is because gas consumption will increase in Myanmar while decreasing in Thailand.

If the carbon price is imposed, with massive electricity from hydropower being exported from Myanmar to Thailand, energy security as well as environmental sustainability will improve remarkably. Between other scenarios, however, the energy security gap will be small. Even if the carbon price in Myanmar is lower than in Thailand, with massive electricity from gas-fired power plants being exported from Myanmar to Thailand, energy security will change little from a scenario for Myanmar's hydropower potential limited to 23 GW as gas-fired power generation declines in Thailand.

(5) Scenario assessment

If priority is given only to economic efficiency, base scenarios with the lowest unit cost, including the ④ Base (hydropower 49 GW) scenario with interconnection lines, will be optimal.

If the carbon price is assumed to be introduced in some form, however, the ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines is the most preferable for economic efficiency, environmental sustainability and energy security. This scenario features greater economic efficiency even than the ⑦ Hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines that includes a lower carbon price for

Myanmar and more electricity exports.

5. Discussion: Benefits from investment in international interconnection lines

In the previous chapter, we have found that investment in international interconnection lines has an economic advantage from the perspective of the unit cost per MWh. In this chapter, we compute total costs for investment in international interconnection lines for each scenario and determine benefits from the investment as a cost decrease through investment in interconnection lines.

Table 4 shows electricity exports from Myanmar to Thailand through international interconnection lines and changes in total costs through investment in interconnection lines in 2050 for three scenarios: ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines, ⑥ Hydropower 23 GW + CP50 scenario with interconnection lines and ⑦ Hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines. The total costs cover costs for the construction of international interconnection lines in Myanmar and Thailand and almost all power generation costs (including fuel costs) in the two countries. However, the total costs do not include costs for investment in domestic power transmission and distribution networks, which are required irrespective of international interconnection lines and offset when the benefits are measured. The total costs do not include environmental or social costs.

Table 4 Changes in total costs through investment in international interconnection lines (US$ million per year)

Scenario	Impact of investment in international interconnection lines	
	Export volume (TWh)	Change in total costs
⑤ Hydropower 49 GW + CP50	83	-740
⑥ Hydropower 23 GW + CP50	5	-60
⑦ Hydropower 23 GW + CP25 (Thailand 50)	128	-390

The table indicates that the total costs will decrease thanks to investment in international interconnection lines in all three scenarios.

In the ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines, massive electricity from hydropower plants in Myanmar will be exported to Thailand, contributing to increasing hydropower generation and interconnection line costs in Myanmar and to decreasing fossil-fired power generation costs (including fuel costs) in Thailand. As a result, the total costs will decline by US$740 million. In the ⑥ Hydropower 23 GW + CP50 scenario with interconnection lines, a decline in the total costs will be far smaller as electricity exports are limited. In the ⑦ Hydropower 23 GW + CP25 (50 for Thailand) scenario with interconnection lines, the carbon price gap between the two countries will lead massive electricity from gas-fired power plants in Myanmar to be exported to Thailand, contributing to increasing interconnection line costs and to decreasing fossil-fired power generation costs (including fuel costs) in Thailand. As a result, the total costs will decline by US$390 million.

We here estimate economic benefits in Myanmar. If the total costs are simply divided by 2, the benefits are US$30-370 million. If the total costs are allocated in proportion to the ratio of power generation in Myanmar to that in Thailand, the benefits are US$10-270 million. Government final consumption expenditure's share of gross domestic product (GDP) at 18%[40] in 2018 is applied to real GDP assumed by Myint (2021)[2] at US$511 billion for 2050, and government spending for 2050 is estimated at US$92 billion. The benefits in the ⑤ Hydropower 49 GW + CP50 scenario with interconnection lines will cover around 0.3% of government spending in 2050. If environmental sustainability such as CO_2 emission cuts and energy security like electricity imports from Thailand during a severe drought are incorporated into economic efficiency, the benefits may increase further. However, accurate economic or financial benefits may be determined through negotiations between Myanmar and Thai governments on matters such as how to share costs for constructing international interconnection lines between the two countries and their electricity sales contracts.

Myanmar's benefits from investment in international interconnection lines in the highest benefit case (⑤ Hydropower 49 GW + CP50 scenario with interconnection lines) will come to US$270-370 million. The value may not be so much compared with GDP or government spending in 2050. However, the benefits may represent stable annual income from a foreign country. As pointed out in Section 2.2, gas resources in Myanmar are expected to be depleted, leading to a decline in foreign currency income from natural gas exports. Then, foreign currency income from electricity exports to Thailand will undoubtedly support government finance in Myanmar over the long term.

6. Conclusion

Amid the global decarbonization trend, Myanmar's promotion of hydropower development including large-scale power plant construction and of the installation of international interconnection lines with neighboring Thailand will contribute to ensuring the power sector's economic efficiency, environmental sustainability and energy security. If hydropower generation capacity reaches 49 GW in Myanmar in 2050, with the carbon price of US$50/t-$CO_2$ being imposed in Myanmar and Thailand, Myanmar's power generation mix will become cost optimal when hydropower accounts for 92% of total power generation at 185 TWh, solar PV for 6% and geothermal power for 2%, with electricity exports to Thailand standing at 83 TWh. Benefits from investment in international interconnection lines are estimated at about US$270-470 million per year. Electricity exports will become a precious foreign currency income source for Myanmar expected to see a decline in future natural gas exports.

However, Myanmar has many challenges regarding hydropower development. The Myanmar government should take leadership in continuing and deepening discussions on whether to give top priority to environmental sustainability (IFC, 2020[12]) or tolerate some economic rationality (IEA, 2021b[18]).

While Myanmar is now plagued with a domestic armed conflict, it is hoped that the Myanmar government will discuss hydropower potential and carbon prices and accelerate the formulation and implementation of energy policy to realize a power generation mix giving consideration to economic efficiency, environmental sustainability and energy security, to implement electricity exports and to promote the country's economic development and the improvement of citizens' living standards.

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