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Analyses on Transitions to Net-Zero Emissions in Asian Countries

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ABSTRACT

Asian countries have a large share in energy-intensive industry sectors and are key to achieving deep emissions reduction in the world including the transition stages toward net-zero emissions. This study develops the energy transition scenarios to meet the Paris long-term climate goals both in energy supply and end-use sectors in some key Asian countries, using a global energy systems model with high regional and technology resolutions. There are different pathways among Asian countries even for the 2℃ and 1.5℃ targets. For example, Japan shows a relatively large share of imported hydrogen-based energy sources, such as hydrogen, ammonia, e-methane, and e-fuels. Meanwhile, large amounts of CCS contributions in China are observed as well as renewables. Meanwhile, hydrogen-based energy sources will be also important after around 2040, and the cooperation for the energy supply chains among Asian countries is also important. While it is also important for seeking coordination in the carbon price, different pathways and different roles exist among Asian countries.

1. INTRODUCTION

The Paris Agreement has long-term goals of limiting global warming below 2 °C or 1.5 °C, compared to pre-industrial levels, and achieving net-zero emissions of global greenhouse gases (GHGs) during the latter half of this century [1]. However, there is a large emission gap between the current emissions or the emission reduction targets submitted by each country in their Nationally Determined Contributions (NDCs) for 2030 and those long-term goals [2]. To move forward with the emissions reduction actions, it is important to provide emission pathways and countermeasure scenarios for each country and each sector quantitatively, having the consistency with the global temperature rise targets, including transition periods such as 2030 and 2040. The Asian region has a large share of the manufacturing industry including hard-to-abate sectors, such as iron and steel, and chemical, in the world, and exports the products to the world including developed countries. The shares in China, Korea, and Japan are approximately 30%, 29%, and 21%, respectively, in 2023, while those in the US, UK, and France are around 10% [3]. The energy transition scenarios particularly in Asian countries are significant for achieving the long-term goals. With this background, we have developed sectoral transition roadmaps to achieve the 2°C and 1.5°C goals using the global energy and climate change mitigation assessment model DNE21+. This study provides the scenarios on energy transition in some Asian countries to meet the 2°C or 1.5°C goals.

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2. LITERATURE REVIEWS

It is necessary to strengthen measures in each sector to achieve the 2°C and 1.5°C long-term goals and net-zero emissions. For achieving even net-zero emissions, various possibilities have been presented such as in the 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [4], including scenarios with high dependence on negative emissions through carbon dioxide removal (CDR) and scenarios with low dependence on negative emissions through the realization of a low energy demand society. Furthermore, transition pathways to net-zero emissions will vary widely across countries and sectors due to different potentials in economic growth, different potentials in renewable energy and accesses, different lifetimes of existing infrastructure, and the like. Uniform reductions for all countries and sectors may increase the cost of countermeasures and make emission reductions more difficult.

However, the emission reduction targets and measures in countries and industries at a slower rate than the linear reduction one toward net-zero emissions might be criticized. In addition, financial institutions and evaluation agencies do not necessarily have a sufficient understanding of the pathways for emission reductions that are consistent with the energy system as a whole, so quantitative information to make judgments about the appropriateness of investments is needed. Therefore, the Network for Greening the Financial System (NGFS) and other organizations are developing emission reduction scenarios using integrated assessment models that enable quantitative analysis [5]. On the other hand, these do not provide sufficient information on sectoral emission reduction pathways. The International Energy Agency (IEA) has also presented, but not enough information by country [6]. Likewise, the report by the International Capital Market Association (ICMA) [7] also has issues regarding the consideration of regional and industrial characteristics. The Government of Japan has developed a transition roadmap in Japan to provide a specific direction for the transition toward achieving carbon neutrality, and to use this roadmap in transition finance [8]. The roadmaps also provide useful information, but they were developed on a sector-by-sector basis, therefore, there is a need to further improve the accountability for consistency with the overall 2 °C and 1.5 °C emission reduction pathways, as well as consistency among sectors. There are several scenario studies also in other Asian countries, such as Korea [9], China [10], [11], India [12], Thailand [13]. However, there are few existing studies on whole energy systems including industries having global consistency.

Therefore, we developed emission reduction scenarios by sector, that are consistent with the 2 °C and 1.5 °C targets globally and with economic rationality while taking into account the differences among countries and sectors, using a global energy and climate change mitigation model. This study focuses on the energy transition in Asian countries with their comparisons. This study provides a new contribution through the energy transition scenarios including the decarbonized energy sources such as hydrogen-based energy sources not only for energy supply but also for demand sectors in Asian countries, considering the equilibrium of amounts of energy and the prices, and the scenarios.

3. MODEL

3.1 Model Overview

The Dynamic New Earth 21+ (DNE21+) model [14]-[16] is an intertemporal linear programming model for the assessment of global energy systems and global warming mitigation, in which the worldwide costs are minimized. The model represents regional differences and assesses detailed energy-related CO_2 emissions reduction technologies up to the year 2100. The representative time points are 2005, 2010, 2015, 2020, 2025, 2030, 2040, 2050, 2070, and 2100, and the linear interpolation between the time points are assumed. The results until 2015 are calibrated by using historical data. The objective function is the net present value of total system cost between 2000 and 2100 as shown in Equation 1.

$$Minimize$$

$$\sum_{t=1}^{T}\left\{\int_{year_{t-1}}^{year_t}\frac{C_{t-1}\times(year_t-\tau)+C_t\times(\tau-year_{t-1})}{year_t-year_{t-1}}e^{-\gamma(\tau-year_0)}d\tau\right\} \quad (1)$$

where γ: discount rate for time preference (5%/yr), C_t: total system cost (fuel, operation and maintenance, and annualized facility costs) in t-th time point, $Year_t$: year in t-th time point.

When any emissions restriction (e.g., an upper limit for emissions, emission reduction targets, targets for energy or emission intensity improvements, or carbon taxes) is applied, the model specifies the energy systems in which costs are minimized, meeting all the assumed requirements, including assumed production for industries, such as iron and steel, cement, and paper and pulp, transportation by passenger cars, buses, and trucks, international marine bunkers, and other energy demands. The energy supply sectors are hard-linked with the energy end-use sectors, including energy exporting and importing, and the lifetimes of facilities are taken into account, so that assessments are made with complete consistency maintained over the energy systems. Salient features of the model include; (1) analysis of regional differences between 54 world regions (for some countries, each country is further disaggregated, totaling 77 world regions) while maintaining common assumptions and interrelationships, (2) a detailed evaluation of global warming response measures for about 500 specific technologies that help suppress global warming, and (3) explicit facility replacement considerations over the entire time period. Based on the plausible ranges derived from the relevant literature, the model assumes energy efficiency improvements in several kinds of technologies and cost reductions of renewable energies, CO_2 capture, utilization and storage (CCUS), among others. The obtained energy systems optimized within the model are basically determined by the total systems costs including the considerations of facility vintages, but two assumptions exist: 1) nuclear power constraints depending on the policies of each nation, and 2) the expansion speed constraints on CO_2 storage. A non-CO_2 GHG emissions model and a land-use model are soft-liked with the DNE21+.

The socioeconomic assumptions of population and GDP are based on the Shared Socioeconomic Pathway (SSP) 2 [17]. The productions of iron and steel, cement, and chemical (ethylene and propylene) in the world are assumed to be 2.07, 4.34, and 0.37 billion ton/yr in 2050, respectively; those in China are 0.74, 1.53, and 0.10 billion ton/yr, respectively.

For the economic decisions for investments, greatly different discount rates (implicit discount rates) are observed across countries and sectors, due to different conditions on investments considering the investment risks including depreciation rates, opportunities of expected return of other investments *etc*. [18] The discount rates for investments are assumed to be different across countries, sectors, and technologies as shown in Table I. Under the lower discount rates, facilities or products having higher initial costs and lower CO_2 emissions are selected compared with under the higher rates.

3.2 Scenario Assumptions

For assuming scenarios for quantitative analyses using DNE21+, the NGFS scenarios [5] are basically referred to. The NGFS develops Orderly scenarios and Disorderly scenarios, based on whether the transition will proceed orderly or not. Complying with this, we have developed our Orderly scenarios and Disorderly scenarios, as well as an additional scenario similar to

Net Zero by 2050 (NZE) [6] by IEA. Outlines of the scenarios and assumptions for model analyses with the DNE21+ are shown in Table II. In terms of temperature rises, two scenarios that are consistent with a 2 °C target, and three scenarios consistent with a 1.5 °C target are assumed. Global CO_2 emissions scenarios are assumed as shown in Figure 1. Orderly scenarios assume the coordination of carbon prices across countries, while Disorderly scenarios assume delayed actions on emissions reduction and greatly different carbon prices. Thus, while Orderly scenarios provide the globally least-cost measures, Disorderly scenarios provide the scenarios considering the existing emission targets by each country and the different development stages among countries. All the scenarios, except Orderly Below 2°C, assume net-zero emissions by 2050 in the USA, UK, EU, and Japan. The specific assumptions on CO_2 capture and storage (CCS) and carbon dioxide removal (CDR) including CO_2 storage potentials, renewables, and passenger cars (EV batteries) are shown in Tables III, IV, and V, respectively.

Table I. Assumed discount rates for investments.

		Upper range	Bottom range
Power		8%	20%
Other energy conversion		15%	25%
Energy-intensive industries		15%	25%
Transport	Passenger cars	30%	45%
	(Environmentally friendly consumers or early adopters)	10%	
	Trucks, buses, and others	20%	35%
Building (Commercial)	Co-generation	15%	25%
Building (Residential)	Water heater, air-conditioning, and heating appliances, *etc*.	20%	35%
	Refrigerator, lighting, *etc*.	25%	40%

Note: The specific assumptions on the discount rates are determined with in the ranges depending on the scenarios of per-capita GDP.

Table II. Assumed scenarios.

Scenarios	Global average temp. increase	Policy speed	CCS/CDR contribution	RE and BEV	Differences in policy intensity among regions	Relation to other scenarios: IPCC AR6 (IPCC 2022)	Relation to other scenarios: IEA
Disorderly Below 2 °C	1.7 °C in 2100 (peak:1.8 °C)	Gradual (NDCs in 2030)	Medium	Medium cost red.	Large (major developed countries: CN by 2050)	C3b	APS (WEO2022)
Orderly Below 2 °C	1.7 °C	Rapid	Small	Rapid cost red.	Small (equal MAC among countries)	C3a	SDS (WEO 2021)
Disorderly 1.5 °C	1.4 °C in 2100 (peak:1.7 °C)	Gradual (NDCs in 2030)	Large	Medium cost red.	Large (major developed countries: CN by 2050)	C2	
Orderly 1.5 °C	1.4 °C in 2100 (peak:1.6 °C)	Rapid	Medium	Rapid cost red.	Medium (major developed countries: CN by 2050)	C1	
1.5C-CO_2_CN	Approx. below 1.5 °C	Rapid	Small (Near-zero of CO_2 by sector)	Rapid cost red.	Large (major developed countries: CN by 2050)	C1	NZE

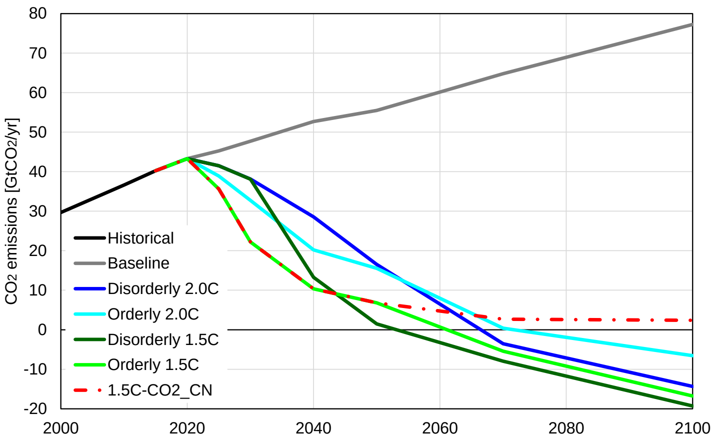


Fig. 1. Global CO_2 emissions pathways.

Table III. Assumed scenarios on CCS/CDR.

Technology scenario	Specific constraints on annual maximum CO_2 storage into a deep saline aquifer
Standard	The maximum annual increase rate which is 0.01% and 0.02% by 2030 and thereafter, respectively, of the total capacities of CO_2 geological storage by each disaggregated region, in order to avoid the rapid occupations of CO_2 reservoirs. The maximum annual uses of storage are 14 Gt CO_2/yr in 2050 in the world.
Higher barriers to CCS/CDR	The maximum annual increase rate which is 0.004% of the total capacities of CO_2 geological storage by each disaggregated region. They correspond to the maximum CO_2 storage of 3 Gt CO_2/yr in 2050 in the world.

Table IV. Assumed scenarios on renewables.

	Technology scenario	Cost category	Potentials (TWh/yr)	Costs (USD/MWh)		
				2020	2050	2100
Solar PV	Medium	Low	75,105	74 – 118	44 – 60	40 – 53
		Middle	1,052,869	116 – 234	60 – 120	43 – 102
		High	140,820	180 – 411	120 – 247	76 – 224
	Rapid cost reductions	Low	70,170	74 – 119	16 – 20	8 – 13
		Middle	473,470	80 – 404	20 – 50	12 – 33
		High	725,155	138 – 411	50 – 176	26 - 118
Wind power	Medium	Low	1,579	58 – 89	48 – 60	39 – 43
		Middle	10,459	73 – 209	60 – 160	42 – 109
		High	1,800	204 – 282	160 – 190	94 – 151
	Rapid cost reductions	Low	1,563	58 – 83	35 – 40	30 – 33
		Middle	10,402	73 – 202	40 – 100	30 – 68
		High	1,872	204 – 282	100 – 152	53 – 105

Table V. Assumed scenarios on passenger cars (small cars).

	Technology scenario	2015	2020	2030	2050
Conventional ICEV (gasoline)	Medium	15.5	15.5	16.4	16.8
	Rapid cost reductions		15.5	16.4	16.8
HEV (gasoline)	Medium	19.1	19.0	18.4	18.3
	Rapid cost reductions		18.9	18.3	18.3
PHEV (gasoline)	Standard	24.5	22.5	19.9	19.1
	Rapid cost reductions		22.2	19.1	18.6
BEV	Standard	28.3	27.7	24.1	20.5
	Rapid cost reductions		25.9	19.1	18.6
FCEV	Standard	54.4	46.7	35.3	22.2
	Rapid cost reductions		37.5	22.2	18.6

Unit: thousand USD/vehicle.

4. RESULTING SCENARIOS

This section shows the developed scenarios by using the DNE21+ model with the assumptions shown in the previous section. The first sub-section shows some of the key results compared with the IPCC scenarios. The following sub-sections show the transition scenarios meeting the Paris long-term goals in Asian countries.

4.1 World

Figure 2 shows the comparison of global CO_2 emissions by sector with those by IPCC. The sectoral CO_2 emissions in DNE21+ scenario analyses are almost consistent with those in IPCC and encompass their upper and lower limits, with a few exceptions of exceeding their ranges in the transport and the residential and commercial sectors. Comparisons of CO_2 marginal abatement costs (MACs) with scenarios in the IPCC report are shown in Figure 3. The MACs vary widely across countries particularly in Disorderly scenarios. In Disorderly Below 2C, the MACs in 2040 are 298 and 80 USD/tCO_2 in Japan and other Asian countries, respectively; in Disorderly 1.5C, those are 456 and 291 USD/tCO_2, respectively. Many models in the IPCC report estimate them under the condition of MACs being globally equalized. MACs in DNE21+ scenarios are consistent with those in the IPCC report. While many IPCC scenarios do not assume DACCS, DNE21+ does assume DACCS, thus leading to slightly lower MACs in 2050 compared to those in the C1 scenario in IPCC. Thus, the scenarios in this study are consistent with both sectoral emissions and the MACs of the IPCC scenarios and cover the uncertain ranges in sectoral emissions in the world, and provide the energy transition in Asian countries with the global consistency.

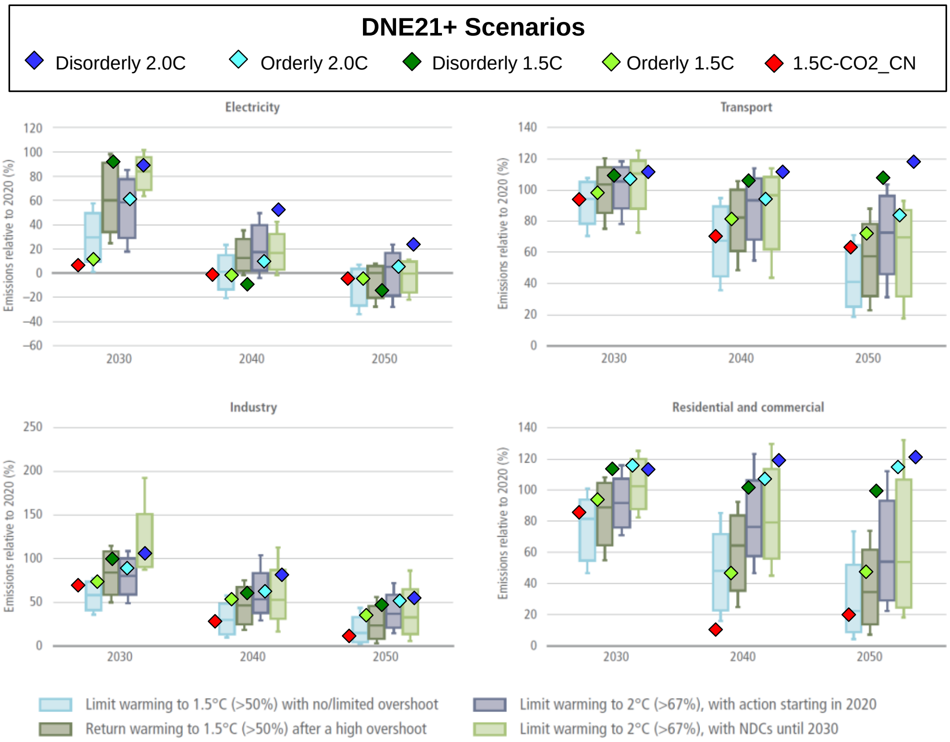
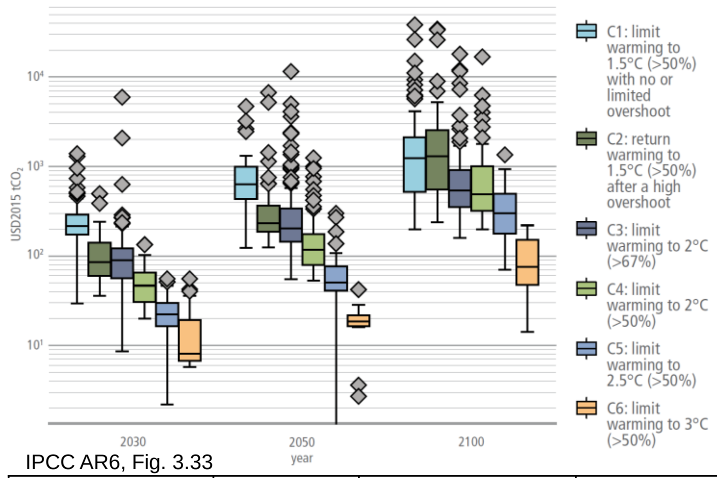


Fig. 2. Comparison with global CO_2 emission scenarios of IPCC.

4.2 Sectoral Emissions in Asian Countries

Figure 4 shows GHG emissions by sector in 2040 and 2050 in some Asian countries, i.e., Japan, Korea, China, India, Malaysia and Singapore, and Thailand. The total amounts of emissions in 2040 are required to be reduced by 53–82% and 22–64% in Japan and China, respectively, compared with in 2015, for the assumed global emission pathways meeting the Paris long-term goals. The emissions in India are from +58% to -16% according to the five different scenarios. The potential emissions in China and India are significantly large toward 2050, making their reductions crucial for achieving deep emissions reduction in the world. Even for the 2 °C or 1.5 °C targets, the residual emissions from the transport sector in China and India are relatively large even in 2050, due to high costs in freight transport, as well as non-CO_2 GHG emissions. Reforestation (land-use changes) in Malaysia and Singapore, and Thailand will contribute to reducing emissions.

The emissions reduction rates among sectors for the least cost measures are also different like those across countries. The emissions from the power sector in China are needed to be nearly zero emissions by 2040 except in Disorderly Below 2C scenario. Meanwhile, those in 2040 from iron and steel sector, one of the hard-to-abate sectors, are almost the same levels as in 2015, except 1.5C- CO_2_CN scenario, while the energy savings are required from Baseline. For example, the emissions reduction rates of the iron and steel sector in Japan are 10–17% by 2040 (relative to 2015) for the assumed scenarios except 1.5C- CO_2_CN scenario.



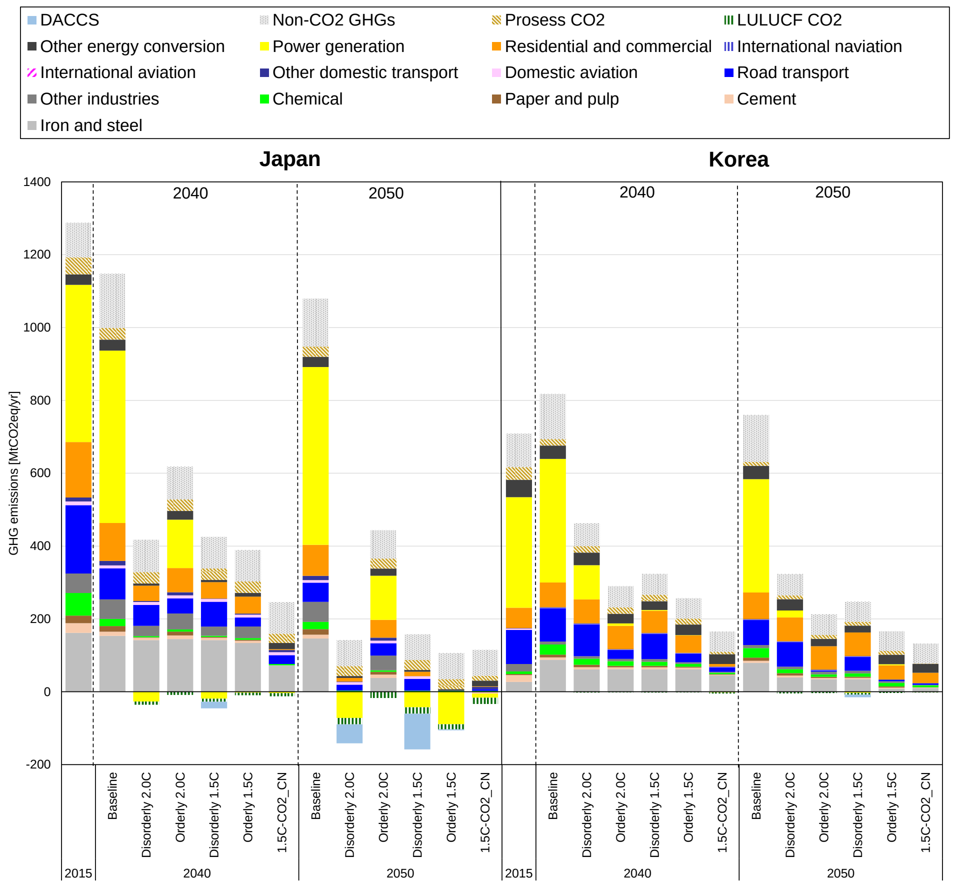
IPCC AR6, Fig. 3.33

	DNE21+	IPCC (25-75 percentile, approximately)		IEA WEO2022: NZE
Disorderly 2.0C	119–500	C3	150–350	n.a.
Orderly 2.0C	158	C3		n.a.
Disorderly 1.5C	268–685	C2	200–350	n.a.
Orderly 1.5C	268–465	C1	450–1000	n.a.
1.5C-CO2_CN	293–351	C1		180–250

Unit: USD/tCO2eq

Note) The MAC having the ranges of DNE21+ are differences across countries.

Fig. 3. CO_2 marginal abatement costs compared with IPCC.



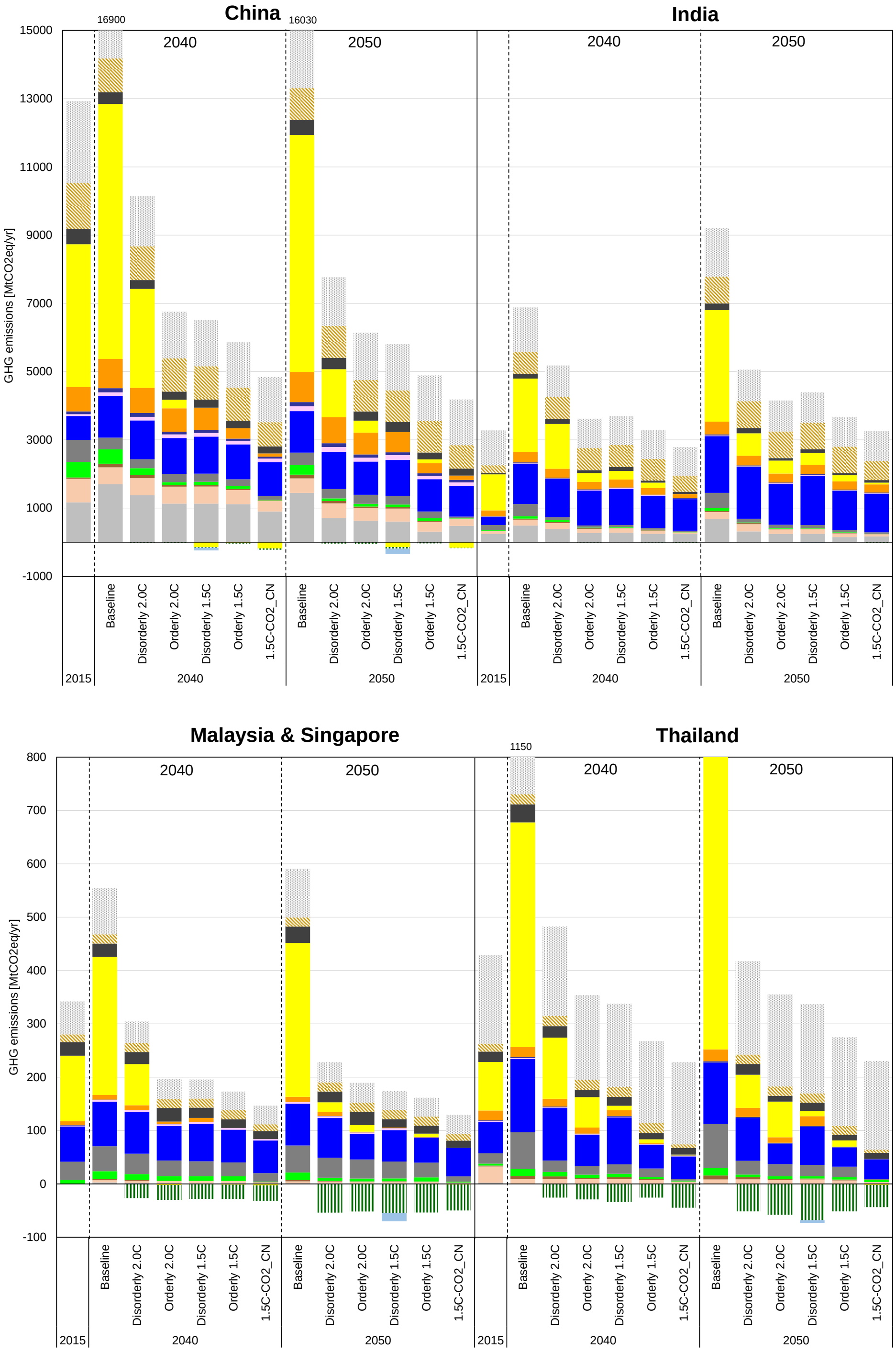


Fig. 4. GHG emissions by sector in 2040 and 2050.

4.3 Primary Energy in Asian Countries

Figure 5 shows the primary energy supply in 2040. The total amounts of energy supply in Japan and Korea will decrease compared to 2015, whereas those in China, India, Malaysia and Singapore, and Thailand will increase. Japan shows a relatively large share of imported hydrogen-based energy sources including e-methane, ascribed to deeper emissions reduction targets along with limited measures for net-zero emissions, like renewables and CO_2 storage potentials. Most imported hydrogen and hydrogen-based energy sources will be CCS-based ones in 2040. For example, in the 1.5C-CO_2_CN scenario, those energy sources are supplied mainly from Indonesia, the U.S., some Sub-Saharan African countries, and Canada to Japan, while renewable origins increase in 2050. The energy supply in Korea is a similar to Japan, but the share of hydrogen-based energy sources is smaller than in Japan, because Korea can be expected to be a higher share of nuclear power than in Japan, so far. Meanwhile, large amounts of CCS contributions in China are observed as well as renewables. Oil supply in Malaysia and Singapore will increase to 2040 even under the 2°C and 1.5°C scenarios. These two countries import ammonia from Australia and some Sub-Saharan African countries in the 1.5C-CO_2_CN scenario.

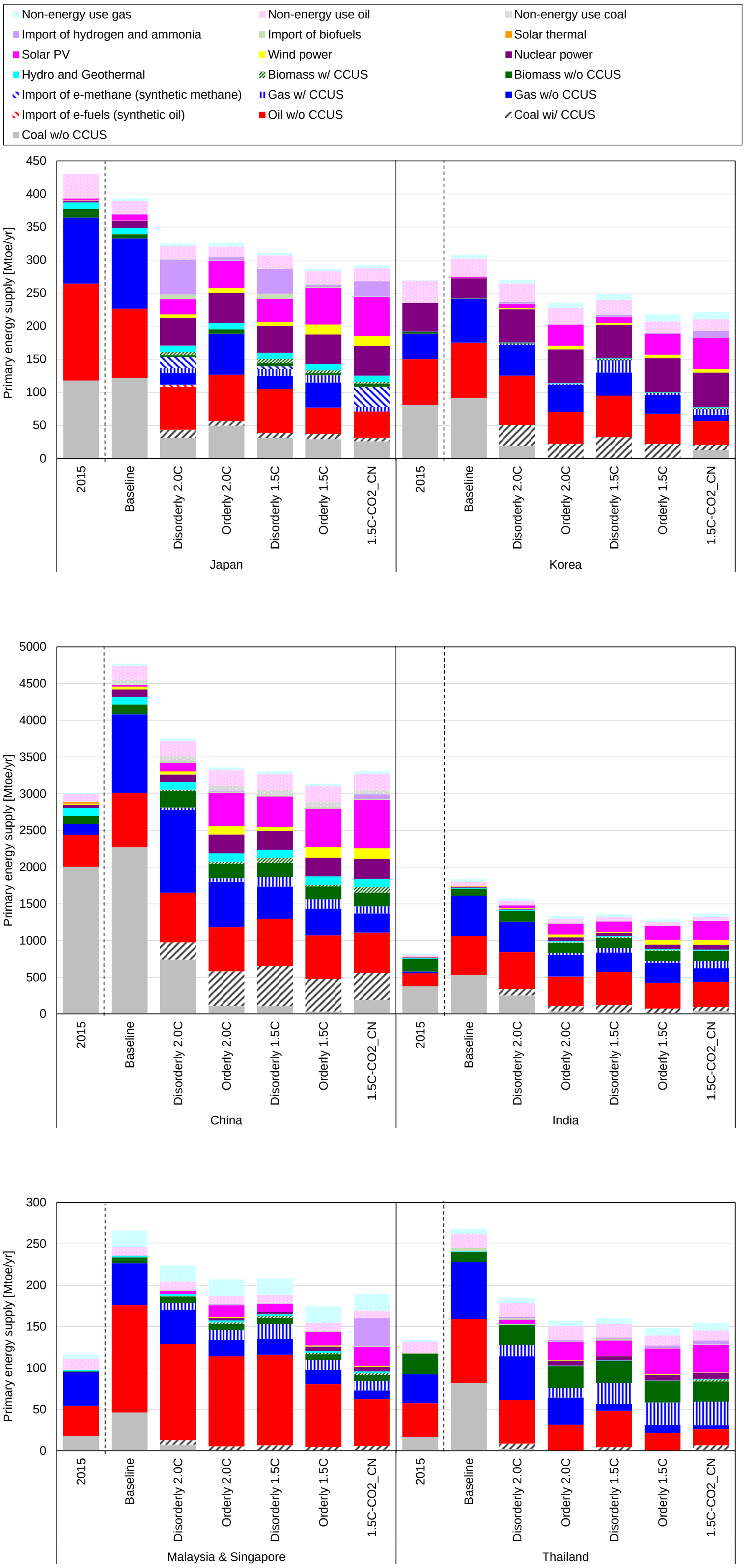


Fig. 5. Primary energy supply in 2040.

4.4 Final Energy in Industry in Asian Countries

Figure 6 shows the final energy consumption in industry in 2040. All the countries will increase their industry electrification ratios to meet the Paris long-term goals. There are relatively large consumptions of hydrogen-based energy sources, such as hydrogen, ammonia, and e-methane, even in 2040 in the 1.5C- CO_2_CN scenario which requires nearly net-zero emissions in each sector. Hydrogen-based iron and steel processes will be important in some scenarios. The share will also increase toward 2050. However, the usage of natural gas as a substitute for coal and oil will also be increased in most of the countries, thanks to CDR contributions in the world as well as Asian countries. However, substantial consumption of oil and gas for non-energy uses will remain in Malaysia, Singapore, and Thailand even in 2040, while the alternative renewable energy-based options exist but they are costly.

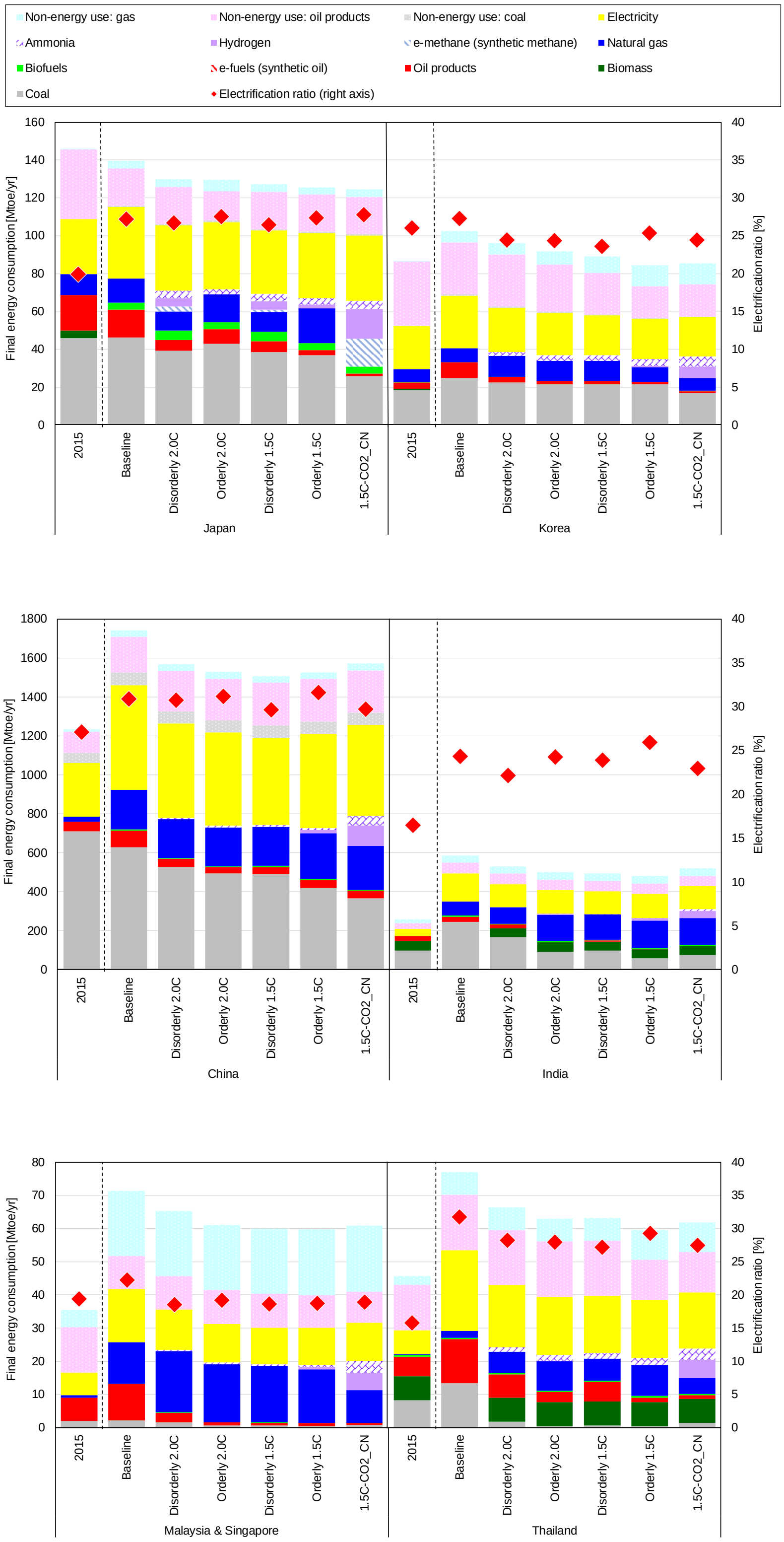


Fig. 6. Final energy consumption in industry in 2040.

Tables VI and VII show the technological measures in the iron and steel, and cement sectors (for clinker production), respectively, in Japan, China, India, and Thailand. The cost-efficient measures are different among countries in the transition periods even for the 2°C or 1.5°C targets, according to the differences not only in energy supply systems which are determined simultaneously within the model but also in development stages which are considered in the discount rates for investment shown in Table I. Blast furnace (BF) and basic oxygen furnace (BOF) of Internal hydrogen-use which are high efficiency and CCS are the cost-efficient measures in 2040. In addition to the methods, hydrogen-based direct reduced iron (DRI) is the cost-efficient to achieve net-zero emissions in 2050 in many of the countries. Under 1.5C_ CO_2_CN scenario, CCS is an important option also in the cement sector in many countries; however, under the other scenarios, improving energy efficiency for clinker productions without CCS is cost-efficiency measures thanks to CDR.

Table VI. Technological measures in iron and steel sector.

	2015	2040					2050				
		DO 2.0C	O 2.0C	DO 1.5C	O 1.5C	1.5 C-CN	DO 2.0C	O 2.0C	DO 1.5C	O 1.5C	1.5 C-CN
Japan											
BF-BOF, low efficiency	0	0	0	0	0	0	0	0	0	0	0
BF-BOF, middle efficiency	0	0	0	0	0	0	0	0	0	0	0
BF-BOF, high efficiency	81	53	48	53	44	0	0	0	0	0	0
BF-BOF, next-gene. coke oven	0	0	8	0	0	0	0	8	0	0	0
Internal hydrogen use + CCS	0	14	11	14	14	0	0	11	0	0	0
Hydrogen use from other sectors + CCS	0	0	0	0	9	67	0	0	0	0	0
Hydrogen-based DRI	0	0	0	0	0	0	68	48	68	68	68
Scrap-based EAF, low efficiency	0	0	0	0	0	0	0	0	0	0	0
Scrap-based EAF, middle efficiency	6	0	0	0	0	0	0	0	0	0	0
Scrap-based EAF, high efficiency	18	25	25	25	25	25	26	26	26	26	26
Korea											
BF-BOF, low efficiency	0	0	0	0	0	0	0	0	0	0	0
BF-BOF, middle efficiency	8	0	0	0	0	0	0	0	0	0	8
BF-BOF, high efficiency	40	0	0	0	0	0	0	0	0	0	40
BF-BOF, next-gene. coke oven	0	0	0	0	0	0	0	0	0	0	0
Internal hydrogen use + CCS	0	37	37	37	37	8	23	20	20	4	0
Hydrogen use from other sectors + CCS	0	0	0	0	0	28	0	0	0	0	0
Hydrogen-based DRI	0	0	0	0	0	0	10	13	13	30	0
Scrap-based EAF, low efficiency	18	8	8	8	0	0	0	0	0	0	18
Scrap-based EAF, middle efficiency	0	0	0	0	0	0	0	0	0	0	0
Scrap-based EAF, high efficiency	3	12	12	12	20	20	19	19	19	19	3
China											
BF-BOF, low efficiency	0	0	0	0	0	0	0	0	0	0	0
BF-BOF, middle efficiency	217	0	0	0	0	0	0	0	0	0	0
BF-BOF, high efficiency	538	367	0	0	0	0	0	0	0	0	0
BF-BOF, next-gene. coke oven	0	57	0	0	0	0	0	0	0	0	0
Internal hydrogen use + CCS	0	265	687	687	687	332	437	383	364	192	57
Hydrogen use from other sectors + CCS	0	0	0	0	0	355	0	0	0	0	355
Natural gas-based DRI	0	1	3	3	3	3	2	4	6	4	4

Hydrogen-based DRI	0	0	0	0	0	0	176	228	244	419	198
Scrap-based EAF, low efficiency	0	31	22	10	0	0	9	5	0	0	0
Scrap-based EAF, middle efficiency	4	8	8	8	8	8	0	0	0	0	0
Scrap-based EAF, high efficiency	45	83	92	104	114	114	116	119	124	124	124
India											
BF-BOF, low efficiency	8	0	0	0	0	0	0	0	0	0	0
BF-BOF, middle efficiency	5	2	2	0	0	0	0	0	0	0	0
BF-BOF, high efficiency	32	15	0	0	0	0	0	0	0	0	0
BF-BOF, next-gene. coke oven	0	82	0	0	0	0	0	0	0	0	0
Internal hydrogen use + CCS	0	105	106	141	81	65	192	82	105	0	0
Hydrogen use from other sectors + CCS	0	0	39	0	15	31	0	39	0	15	31
Natural gas-based DRI	10	9	66	71	117	117	10	77	88	145	145
Hydrogen-based DRI	0	0	0	0	0	0	86	89	95	128	112
Scrap-based EAF, low efficiency	9	2	0	0	0	0	1	0	0	0	0
Scrap-based EAF, middle efficiency	1	0	0	0	0	0	0	0	0	0	0
Scrap-based EAF, high efficiency	25	97	99	99	99	99	155	156	156	156	156
Malaysia and Singapore, Thailand											
Scrap-based EAF, low efficiency	5	3	0	0	0	0	0	0	0	0	0
Scrap-based EAF, middle efficiency	1	0	0	0	0	0	0	0	0	0	0
Scrap-based EAF, high efficiency	3	8	11	11	11	11	11	11	11	11	11

Unit: Mt-crude steel/yr

Table VII. Technological Measures in cement sector (clinker production).

	2015	2040					2050				
		DO 2.0C	O2.0C	DO1.5C	O1.5C	1.5C-CN	DO 2.0C	O2.0C	DO1.5C	O1.5C	1.5C-CN
Japan											
Small size, low-mid. Efficiency	1	0	1	0	0	0	0	0	0	0	0
Small size, high efficiency	6	0	0	0	0	0	0	0	0	0	0
Small size, best available efficiency	0	5	4	5	5	5	5	4	5	5	5
Large size, low-mid. Efficiency	0	0	0	0	0	0	0	0	0	0	0
Large size, high efficiency w/o CCUS	5	0	19	0	0	18	1	25	0	0	11
Large size, high efficiency w/ CCUS	0	0	0	0	0	6	0	0	0	0	16
Large size, best available efficiency	39	33	14	33	33	9	29	5	30	30	4
Korea											
Small size, low-mid. Efficiency	0	0	0	0	0	0	0	0	0	0	0
Small size, high efficiency	1	0	0	0	0	0	0	0	0	0	0
Small size, best available efficiency	0	0	0	0	0	0	0	0	0	0	0
Large size, low-mid. Efficiency	3	0	0	0	0	0	0	0	0	0	0
Large size, high efficiency w/o CCUS	29	19	18	11	10	1	18	18	2	2	1
Large size, high efficiency w/ CCUS	0	0	0	0	1	22	0	0	0	0	19

Large size, best available efficiency	5	5	5	12	12	0	2	2	18	18	0
China											
Small size, low-mid. Efficiency	948	601	601	601	601	530	500	348	348	348	309
Small size, high efficiency	114	113	113	113	113	113	95	95	95	95	95
Small size, best available efficiency	0	0	0	0	0	71	0	152	152	152	190
Large size, low-mid. Efficiency	49	0	1	1	1	0	0	0	0	0	0
Large size, high efficiency w/o CCUS	652	561	561	561	561	0	502	502	502	502	0
Large size, high efficiency w/ CCUS	0	0	0	0	0	580	0	0	0	0	518
Large size, best available efficiency	19	19	19	19	19	0	16	16	16	16	0
India											
Small size, low-mid. Efficiency	60	143	86	86	36	6	171	72	72	27	11
Small size, high efficiency	2	2	2	2	2	2	1	1	1	1	1
Small size, best available efficiency	0	0	57	57	107	137	0	99	99	144	160
Large size, low-mid. Efficiency	52	33	33	33	25	0	9	9	8	8	0
Large size, high efficiency w/o CCUS	81	323	323	323	96	9	438	438	438	96	23
Large size, high efficiency w/ CCUS	0	0	0	0	6	352	0	0	0	0	425
Large size, best available efficiency	5	5	5	5	234	0	2	2	2	345	0
Malaysia and Singapore, Thailand											
Small size, low-mid. Efficiency	5	4	4	4	4	4	3	3	3	3	3
Small size, high efficiency	0	0	0	0	0	0	0	0	0	0	0
Small size, best available efficiency	0	0	0	0	0	0	0	0	1	1	0
Large size, low-mid. Efficiency	10	7	7	7	7	1	2	1	1	1	0
Large size, high efficiency w/o CCUS	29	28	28	28	28	2	31	31	31	24	2
Large size, high efficiency w/ CCUS	0	0	0	0	0	32	0	0	0	0	31
Large size, best available efficiency	0	0	0	0	0	0	0	0	0	8	0

Unit: Mt-clinker/yr

4.5 Discussions

Different emission pathways and energy transitions toward the net-zero emissions among countries exist even within Asian regions and even for the least cost measures in the world. As discussed in Section A, the consistency in the existing global scenarios were compared, and the MACs and sectoral emissions estimated in this study are consistent with the existing scenarios reported in the IPCC [4], and the ranges of sectoral emissions of the IPCC are covered among the assumed five scenarios of this study.

The emissions reduction pathways in Asian countries vary across countries due to the development stages even for the global net-zero emissions. In addition, the sectoral emission pathways and the specific measures are also different. Muti-pathways are needed, particularly considering the manufacturing industries as well as different energy supply systems among Asian countries.

In the orderly scenarios which assume to coordinate emissions reduction efforts, in other words, to coordinate carbon prices, much lower costs are estimated. Hydrogen-based energy sources, such as hydrogen, ammonia, and e-methane, will be important in industry sectors, and e-fuels will be important in the transport sector after 2040 in the Asian region. Large parts of the supply of hydrogen-based energies are imported in Japan, while those in China and India are produced domestically due to large potentials of renewables and CCS. Therefore, the development of the supply and demand systems among Asian countries will be important for achieving net-zero emissions. Coordination in climate and energy policies among Asian countries will be important, including the cooperative development of several types of technologies contributing to net-zero emissions.

The role of transition finance has been increased, as well as the green finance. It is important how to transit toward net-zero emissions particularly in Asian countries having high shares of manufacturing industries.

In the transition finance, the roadmaps for meeting the Paris long-term goals are important tools. The roadmaps for Asian countries developed in this study are expected to support also the financial schemes for better transitions**.**

5. CONCLUSION AND FUTURE WORKS

This study presents energy transition scenarios in Asian countries, where the manufacturing industries have a relatively large share in the world, for meeting the Paris long-term goals of 2 °C or 1.5 °C by using a global energy systems model having high resolutions in country, sector, and technology. The study shows that the different deployments in energy systems including the response measures in manufacturing industries among countries meet the globally cost-efficient measures even for the 2 °C or 1.5 °C goals.

Only five scenarios are developed in this study; however, there is a large range in reality. Given the uncertainties not fully accounted for in these five scenarios, careful interpretation is necessary. Sensitivity analyses will be required.

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