Modeling the power generation sectors of east asia in 2050 – The choice of power sources by regulation of nuclear and coal power

Aiko Azuma[i] , Unnada Chewpreecha [ii] , Sung-In Na[iii] , Li-Chun Chen[iv] , Yanmin He[v] , Ken'ichi Matsumoto[vi] and Soocheol Lee[vii] ,

[i] Department of Environmental Planning, Shokei Gakuin University
[ii] Cambridge Econometrics
[iii] Faculty of Human Environmental Studies, Hiroshima Shudo University
[iv] Faculty of Economics, Yanaguchi University
[v] Institute of Economic Research, Kyoto University
[vi] Graduate School of Fisheries and Environmental Sciences, Nagasaki University
[vii] Faculty of Economics, Meijo University

Abstract

This paper investigates the effects of nuclear and coal power regulation on future power generation mix and CO_2 emissions in the four East Asian countries using the E3ME-Asia model complemented by a simulation model of power technology diffusion, FTT:Power. The model results from FTT:Power and E3ME indicates that, a phasing out of nuclear power is likely to result in increases in electricity generation from coal, and does not contribute much to the diffusion of renewable technologies, because in this paper we did not introduce renewable support policies such as feed in tariff or carbon taxes. Therefore, coal power has become the most cost- effective generation technology in the case of nuclear regulation. Similar results occur in the phasing out of coal scenario. Due to lack of supporting policies for renewable technologies, reduction of coal power generation results in increasing nuclear and gas-fired thermal power generation. Meanwhile combined scenario of phasing out coal and nuclear power plants at the same time, generation from renewable energy increase but not considerably. Finally our analysis concludes that additional policies, on top of regulations, to promote renewable and reduce fossil fuels energy sources are necessary if the ambitious renewables and carbon emission reduction targets are to be met.

KEY WORDS : Future power generation mix, East Asia, E3ME-Asia model, FTT:Power, Renewable energy

1. Introduction

This paper investigates the effects of nuclear and coal power regulation on power generation mix and CO_2 emissions from 2017 to 2050 in the four East Asian countries (China, Japan, Korea and Taiwan). The analysis was carried out using the E3ME-Asia model(we call this E3ME model for simplification) complemented by a simulation model of power technology diffusion, FTT:Power (Mercure, 2012). Ogawa,Y,et.al. (2015) analyzed similar effect of nuclear and coal power regulation scenarios from 2015 to 2030 using the same modeling tool. Comparing to Ogawa's paper, policy scenarios in this paper are more sophisticated than before and estimation period are extended from 2030 to 2050.

Having extended period to 2050 means that renewable energy technology will have further evolved. Broadly, research forecasts that the costs of renewable energy generation, and primarily solar power, might become lower than costs for nuclear and coal as the solar reaches grid parity (see, for example, the Center for Low Carbon Society Strategy, Japan (2015), and Cambridge Econometrics (2016)). Besides, most existing coal-fired thermal generation facilities in East Asia will have recouped capital costs (eliminating the capital stock lock-in effect) by 2050, and this timeframe is long enough to ensure an easy transition to renewable energy generation.

We set the reference power generation scenario by using actual data and the assumption of in the Asia/World Energy Outlook (AEO)'s reference scenario produced by the Institute of Energy Economics, Japan (IEEJ) in 2016. Energy statistics projections for East Asian countries through to 2040 (in the reference scenario and advanced technologies scenario) are more detailed in the AEO than in all other reports. We extend AEO projections to 2050 by extrapolating the trend from 2030 to 2040.

In the first scenario, we analyze nuclear regulations. The second scenario we analyze coal-fired power plants regulations. The third and final scenario analyses the restriction on both nuclear and coal-fired power. The focus of this paper is on how coal and nuclear regulations affect the power mix and the power sector emissions. The economic impacts of these same scenarios are explored in Lee,S, et. al. (2018).

In this paper, Section 2 provides an overview of the current power sector situations and related policies in each of the four regions; Section 3 describes the E3ME-FTT modeling methodology that was applied. Sections 4 and 5 describe the scenarios that were assessed, and show the corresponding energy mixes in each case. Section 6 concludes by outlining policy implications from our analysis.

2. Overview of the power sector in East Asia

(1) China

Since initiating market reforms from 1978, China's rapid economic development has brought about a growing demand for electricity. In 2014, it had the largest installed electricity generation capacity in the world with 1505 GW and generated 5679 TWh (IEA, 2016). Characteristically, most of the electricity comes from fossil fuel, supported by massive domestic production. In 2014, 74.7% of electricity was provided by thermal power generation (excluding Hong Kong) (IEA, 2016).Coal is the main source of electricity generation, providing 72.3% of electricity and coal used in power generation alone accounts for 47% of energy-related CO_2 emissions in the country (IEA, 2016). On the other hand, hydropower was the largest among non-fossil fuel energy sources, accounting for 18% of electricity supply (IEA, 2016).

Public concerns over local air pollution and increasing greenhouse gas (GHG) emissions from coal combustion were triggered because of the extremely high levels of PM2.5 in key regions. In order to tackle these crisis, air quality policies, including coal consumption caps in some Chinese provinces was implemented from 2013. Energy strategies for developing other energy sources and moving away from coal dependency have become important. In recent history, China's renewable energy industry is characterized by fast growth and an enormous installed base. As a result of this, it has the largest capacity of renewable energy capacities in the world (199 GW, not including hydropower) (1) , however, challenges included lack of transmission infrastructure and curtailment of wind and solar PV generation (REN21, 2016).

Energy Development Strategy Action Plan (2014-2020), published by the state council in 2014, aims to reduce China's high energy consumption per unit of GDP through a set of measures and mandatory targets, promoting a more efficient, self-sufficient, green and innovative energy production and consumption. The targets include a cap on annual primary energy consumption, set at 4.8 billion tce (ton of standard coal equivalent) until 2020. The annual coal consumption should be held below 4.2 billion ton until 2020. The share of non-fossil fuels in the total primary energy mix is to rise to from 9.8% in 2013 to 15% by 2020.

In addition, national policy on nuclear power has moved from 'moderate development' of nuclear power to 'positive development' in 2004, and after the Fukushima Accident in 2011-12, to 'steady development with safety'. The national nuclear capacity target for 2020 became 58 GW in operation and 30 GW under construction, then up to 150 GW by 2030, and much more by 2050 (2) . China's 13th Five-Year Plan (FYP) on National Economy and Social Development (2016-2020) (National 13th FYP) unveiled in March 2016 outlines an energy consumption cap and a target goal for the share of non-fossil-based energy in the total primary energy consumption by 15%. Furthermore, China's 13th Five-Year Plan for Energy Development (Energy 13FYP) (2016-2020) and the 13th Five-Year Plan for Electricity Development (Electricity 13FYP) (2016-2020) issued by the Chinese National Development and Reform Commission (NDRC) in the same year announced more specific goals of power installed capacity (as shown in Table 1). Electricity 13FYP also outlined the main development direction for China's electricity sector and includes technology-specific targets, goals for grid expansion, as well as projections for electricity demand growth.

China 2050 High Renewable Energy Penetration Scenario and Roadmap Study (2050 Road map) written by the Energy Research Institute (ERI) of the NDRC analyzes how China can gradually phase out fossil energy, especially coal under the high renewable energy penetration scenario. The study results show that it is both technically and economically feasible for renewable energy to satisfy over 60 percent of China's primary energy consumption and 85 percent of electricity consumption by 2050.

(2) Japan

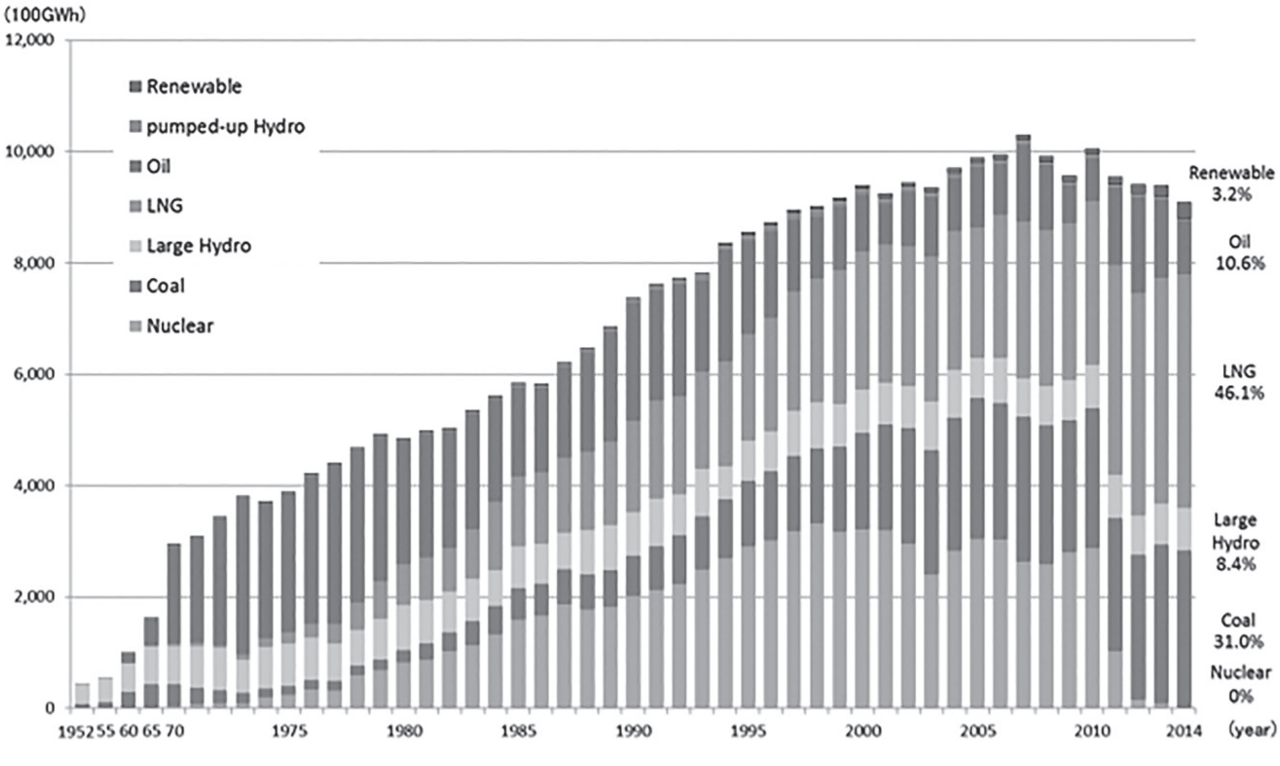
The Fukushima nuclear power plants accident on 11 March 2011, caused by the Great East Japan Earthquake has completely changed the basis on which Japanese energy and climate policy was built. Nuclear

Table 1 Power generation mix plan by NDRC (GW)

	2015 achievements	Targets by 2020		Targets by 2050
		Energy Development Strategy Action Plan	Electricity 13FYP	2050 Road Map
Hydropower	320 GW	350 GW	380 GW (including 40 GW of PSP(3))	554GW
Nuclear	27GW	58GW	58GW	100GW
Wind	131 GW	230 GW	210 GW	2396GW
Solar PV	43 GW	100 GW	110 GW1)	2696GW2)
Bioenergy	10.3 GW	30 GW	15 GW	133GW3)
Geothermal	0.03 GW	0.1 GW	N-A	11GW
Coal	900GW	N-A	<1100GW	886GW
Gas	66GW	N-A	110GW	220GW

Source: State council(2014), ERI(2015), IEA(2016), NDRC(2016)
Note:1) including distributed solar energy systems, 2) including distributed solar energy systems,
3) including biomass pellets, straw and stalks and biogas.

Figure 1 Generation mix in Japan



Source: Agency for Natural Resources and Energy, Japan (2016)

power was regarded as the main source of electricity generation. There were 54 commercial nuclear power plants in Japan and electricity output from nuclear power accounted for about 25-30% of total electricity supply before the accident (see Figure1 , Source: Agency for Natural Resources and Energy, Japan (2016))

Before the accident, energy and climate policy in Japan relied heavily on the expansion of nuclear power capacity, and the Japanese government had planned to build 14 new nuclear plants by 2030. However, immediately after the crisis, most nuclear power plants stations have temporarily shut down to examine the official safety analysis and it does not seem likely that new nuclear power plants will be built in the future because of the strong public opinion against nuclear power.

The Ministry of the Environment Japan established a new regulatory agency for nuclear power plants after the Fukushima accident Which is named the Secretariat of the Nuclear Regulation Authority (NRA). The NRA brought in a new regulation for nuclear power plants, and all nuclear power plants have to pass all the safety criteria under the new law when they restart their plants. The NRA also introduced a lifetime regulation such that nuclear power plants in Japan cannot operate over 40 years. Fukushima No.1 nuclear power plant, which have 6 reactors, has already been determined to decommission. The rest of 48 nuclear power plants were temporary shutdown from September 15th 2013 (4) to August 14th 2015 (5) .

12 nuclear power plants (Kashiwazaki unit No.6 and No.7, Mihama unit No.3, Takahama unit No.1 to No.4, Ikata unit No.3, Genkai unit No.3 and No.4, and Sendai unit No.1 and No.2) passed the official safety test. 5 plants (Takahama unit No.3 and No.4, Ikata unit No.3, and Sendai unit No.1 and No.2) have already restarted as of December 2017 and 7 plants are under investigation to restart. In total 14 nuclear power plants, including Fukushima No.1 power plants, have been decommissioned as of December 2017 because these plants have already operated for almost 40 years and it is not cost effective to introduce additional improvement works to pass the official safety test under the new law. Table 2 summarizes actual condition of Japanese nuclear power plants.

Because of the reduction in nuclear generation, thermal power generation has substituted the entire nuclear power generation. This results in an increase in the electricity generation cost and CO_2 emissions. In 2014, fossil fuels provided 87.6% of electricity supply in Japan (see Source: Agency for Natural Resources and Energy, Japan (2016)). The import bill for fossil fuel went up by 2.4 trillion JPY from 2010 to 2013 (Japan Renewable Energy Foundation, 2014). At the same time, CO_2 emissions from the power generation sector have increased by 110 $MtCO_2$ in 2013 compared to 2010 (Agency for Natural Resource and Energy 2014).

Japanese utilities called for bids for 10 GW of new thermal power plants in 2014 and all the new capacities will switch to coal power plants by 2020 because the variable generation cost of a coal power plant is lower than that of a gas power plant. In addition, the Japanese government accelerated electric retail market deregulation in 2016. This has caused independent power producers to construct 5GW of new coal plants because they intended to enter the electricity market by making use of cheap coal electricity to their advantage. As a result, new investment in coal plants amounting to about 15 GW are under planning in Japan currently.

Before the accident at the Fukushima nuclear power plant, Japan's GHG emission reduction target was 25% lower than the 1990 level. In order to achieve this goal, it is necessary to drastically increase the low-carbon source of power supply, and in the Third Energy Plan issued in 2010 in Japan, the share of nuclear power generation in the power mix in 2030 is 53%. After the Fukushima Nuclear Power Plant accident, it became difficult to restart nuclear power generation and to construct a new nuclear power plant, so the power supply composition in 2030 was greatly revised in 2015. As shown in Figure 2, the target share of nuclear power

Table 2 Actual condition of Japanese nuclear power plants as of December 2017

(unit)

<table>
<tr><td colspan="3">Application for reactor installation is submitted (as of 2016)</td><td>Application for reactor installation is not submitted yet</td><td>decided decommissioning after 2011</td><td>total</td></tr>
<tr><td colspan="3">25</td><td rowspan="5">15</td><td rowspan="5">14</td><td rowspan="5">54</td></tr>
<tr><td colspan="2">Amendment of reactor installation license was permitted by NRA</td><td>Application for reactor installation is under review by NRA</td></tr>
<tr><td colspan="2">12</td><td rowspan="3">13</td></tr>
<tr><td>already operating</td><td>not yet operation</td></tr>
<tr><td>5</td><td>7</td></tr>
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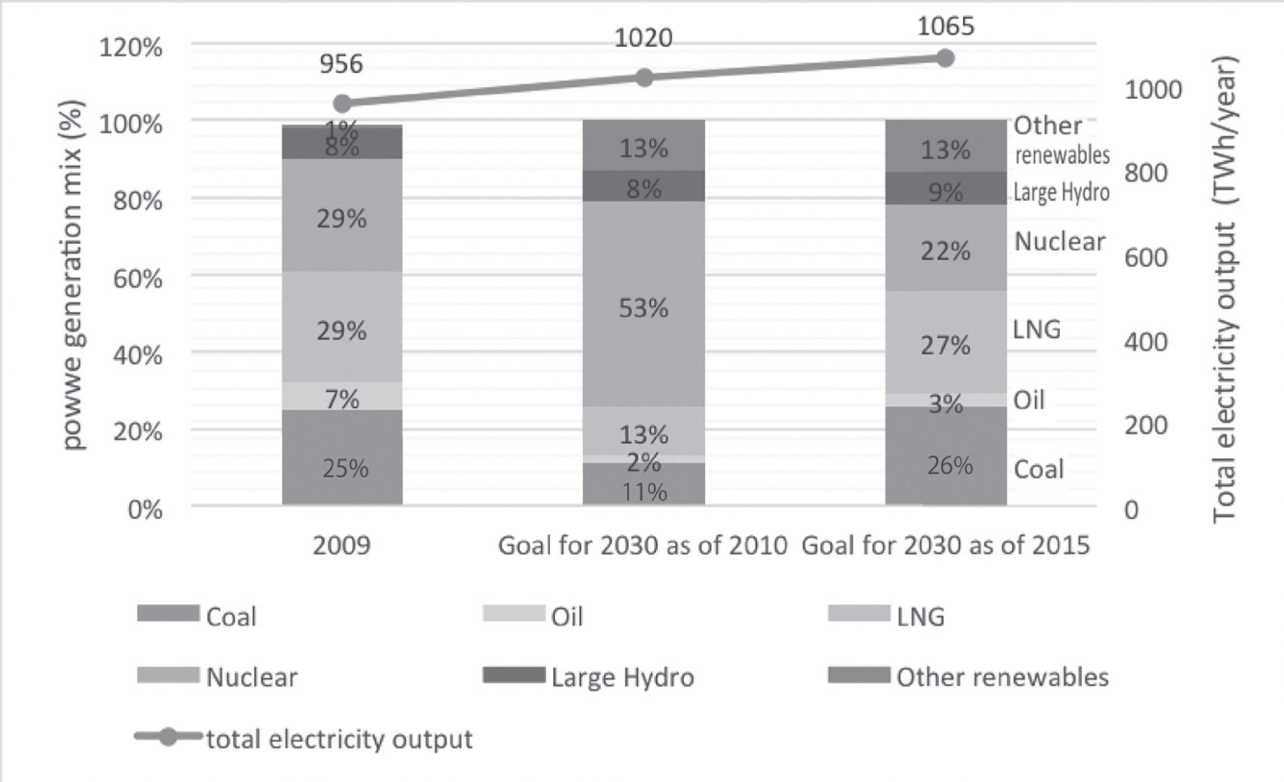
Source: prepared by the author

Figure 2 Future power generation configuration plan in Japan



Source: Agency for Natural Resources and Energy, Japan (2015)

generation in the power generation composition in 2030 has decreased to 22%. Observing the change in the current target from the target in 2010, it turns out that the share of renewable energy has not changed. On the other hand, coal thermal power generation and gas-fired thermal power generation have taken over the amount of power generation of nuclear power generation. In the Paris Agreement, Japan has the goal of reducing GHG by 26% compared to 2013. In order to achieve this climate change target, it is necessary to suppress the carbon intensive power generation and extend renewable energy larger than currently planned.

(3) Korea

Total Korea power generation in 2015 was more than 528 TWh, according to Korea Electric Power Corporation (KEPCO). Korea's power generation has increased by an average of 4% annually since 2005. Although in the past two years, electricity consumption growth rates have slowed down to around 1%. This recent deceleration of electricity consumption is attributed to weaker economic demand and export growth, more temperate weather, and demand side management.

The 7th Basic Plan for Long-term Electricity Supply and Demand published in 2015 showed, the Korean government lowered its anticipated electricity demand growth to 2.2% annually to 2029. The government intends to cut its greenhouse gas emissions through energy conservation measures and through the use of cleaner energy from nuclear and renewable energy sources.

Fossil fuel sources of Korea's electricity generation in 2015 account for 64%, while the share of nuclear power was 31%, and 5% came from renewable sources, including hydro-electricity . Coal-fired power, which was a baseload source, was the dominant fossil fuel used to generate electricity, and natural gas the second largest. Oil contributes to a very small amounts of power generation. Although fossil fuel-fired capacity is dominant in Korea in 2015, nuclear power is also a baseload power source. In 2015, about 55% of electricity consumption was from industries, 25% from commercial and service enterprises, 13% from the residential sector, and 6% from other sectors such as transportation and agriculture.

Korea government has the goal of reducing its greenhouse gas emission levels by 37% from business-as-usual projected levels in 2030. However, the new government of Moon Jae-in started in early 2017

Table 3 Power generation capacity by sources in Korea (2014-2029) (unit:%)

	2014 Achievements	Targets by 2029
Nuclear	22.2	23.7
Coal	28.2	26.7
LNG	28.7	20.5
New and Renewable Energy	6.7	20.0
Others	14.2	9.1

Source: The Ministry of Trade, Industry and Energy(2016)

aims to abolish nuclear power generation in the long term. The government already shut down its oldest Gori-1 nuclear power plant on June 19, 2017. This policy will increase CO_2 emission because nuclear will be substituted by coal and gas.

The government also declared to reduce domestic fine dust emissions by 30 % by 2022. This will be achieved by shutting down old coal-fired power plants and reducing the number of diesel car on the street. This policy will decrease CO_2 emission because coal-fired power is a baseload source in Korea.

Renewable sources (primarily solar, wind, biomass, and waste) account for 5% of electricity generation in 2015. Korea had a feed-in tariff (FIT) system but it was replaced by the Renewable Portfolio Standard (RPS) in 2012 to promote renewable energies. The forth basic plan for new and renewable energies (2014-2035) in Korea includes a new and renewables (NRE) target of 5.0% in the primary energy supply by 2020 and 11% by 2035. The generation target is to achieve 13.4% of total power generation with NRE sources by 2035, with a focus on solar and wind energy, while scaling down waste energy.

The new government announced that it will expand 20% of total power generation with NRE sources by 2020. However, the government does not propose concrete policies to achieve this target. The 8th Basic Plan for Long-term Electricity Supply and Demand will be published in 2018. It has to include policies and measures to achieve targets on nuclear, coal and renewables power generations (see Table 3).

The Korean government announced the 4th Basic Plan New and Renewable Energies in 2014. In this plan, 11.0% of the total primary energy supply should come from new and renewable energies by 2035. As shown in Table 4, it also suggests reduction in the relative importance of waste while developing solar and wind power as main energy sources, so that 13.4% of total electric energy is supplied by new and renewable energies by 2035.

(4) Taiwan

Total power generation amount of Taiwan in 2016 is 264 TWh, which was an increase of 2.3% over 258 TWh in 2015. Of this total, pumped-storage hydropower contributed 1.3%, thermal power 82%, nuclear power 12%, and conventional hydropower, geothermal, solar

Table 4 New and renewable energies supply composition ratio (2014-2035)
(unit:%)

	2014	2025	2035	Mean annual growth rate
Solar-thermal	0.5	3.7	7.9	21.2
Solar-PV	4.9	12.9	14.1	11.7
Wind	2.6	15.6	18.2	16.5
Biomass	13.3	19.0	18.0	7.7
Hydroaulic	9.7	4.1	2.9	0.3
Geothermal	0.9	4.4	8.5	18.0
Marine	1.1	1.6	1.3	6.7
Waste	67.0	38.8	29.2	2.0
Ratio of total primary energy supply	**3.6**	**7.7**	**9.7**	**11.0**

Source: Hwang In-Ha(2014)

and wind power, biogas, biomass and waste constitute 4.8%. The total fuel consumption of thermal power stations of Taiwan power company in 2016 was 30 million KLOE, which was 2.4% more than 29.3 million KLOE in 2015. Of this consumption, coal comprised 50.4%, diesel oil 0.4%, fuel oil 8.4%, and LNG 40.9%. In 2016, the amount of electricity consumed by consumption was 7.4% by the energy sector own use; 53.1% by industry; 0.5% by transportation; 1.1% by agriculture, forestry and fishery; 19.3% by service; and 18.5% by residences. When compared with 2015, energy sector own use decreased by 0.5%; industry increased by 1.6%; transportation increased by 1%; agriculture, forestry and fishery increased by 0.2%; service increased by 1.7% and residences increased by 5.5%. In 2016, the per capita electricity consumption was 10,928 kWh, which was an increase of 1.9% compared with 10,720.7 kWh in 2015 (BOE, 2017).

In Taiwan, the Bureau of Energy (BOE), Ministry of Economic Affairs (MOEA) is the authority responsible for drafting and carrying out the national energy policies, laws and regulations. To cope with the internationalized and liberalized trend of economic development, the energy policies have changed greatly in recent years. On the one hand, it actively encourages energy enterprises to become liberalized and private, opens private power plants and petroleum refining industry, so as to make the domestic oil and electricity price regulated and transparent, and strengthens the management of energy demands. On the other hand, it emphasizes the energy and environmental issues and countermeasures, with the expectation of achieving economic growth, environmental protection and balance of energy demands (Chen, 2014).

All these indicate that Taiwan's energy industry is stepping into liberalization through the relevant laws and regulations. However, since there are still many social factors needed to be taken into consideration with these liberalization policies, the legislations seem not take effect as expected.

Taiwan is now on the path towards its own energy transformation. The Democratic Progressive Party (DPP) administration started from May, 2016 has vowed to eliminate nuclear power in Taiwan, while simultaneously slashing greenhouse gas emissions by 20% from 2005 levels in line with both domestic law and international commitments. At the same time, it pledges to maintain an adequate, reliable, and affordable electricity supply to power Taiwan's industrialized economy. More than replacing the 16% of electricity currently generated by nuclear power, the government aims to see 20% power generation from renewables, based on a planned 20GW of installed solar power capacity and 3GW of offshore wind power. The administration also expects energy conservation efforts to save the equivalent of generation from two nuclear power plants, and envisions investments in renewable energy as sparking new global business opportunities for Taiwan's industrial sector. And all of this is to be achieved in less than a decade by 2025 (see Table 5).

3. Modelling method

In this section, we describes the tools used to model power technology mix in East Asia. The tool used is the E3ME model (Cambridge Econometrics, 2014), complemented by a simulation model of power technology diffusion, FTT:Power (Mercure and Salas, 2012) [6]. E3ME provides the demand for electricity-given industrial activity, household income and electricity prices in 59 world regions including China, Japan, Korea and Taiwan. FTT:Power takes this electricity demand as an input, determines the technology mix with given electricity sector policies such as carbon taxes or technology support mechanisms, and calculates electricity price, power sector investment, power sector fuel demand and its GHG emissions. These FTT outputs are fed back to E3ME to obtain feedbacks on electricity demand and other economic impacts. The coupled E3ME-FTT model has been used for to analyze the impacts of climate policy instruments for emission reductions worldwide in the past (Mercure et al., 2014).

(1) The dynamical equation

FTT:Power is composed of two parts: the choice of investors and the diffusion of technology. The choice of investors is represented by using a method related to discrete choice theory, a binary logit (see the appendix in Mercure et al., 2014), involving sets of distributed diverse agents making cost comparisons between available options. These choices are used to drive the diffusion of technology options according to the rate of replacement (using life expectancies) and the rate of construction. Technical constraints, such as those related to the predictability and/or flexibility of power sources, may not allow particular compositions to arise, due to grid stability problems (e.g. 100% wind power); it

Table 5 The target goal of renewable energy in Taiwan
(unit: MW)

	2015	2020	2025	2030
Hydro	2,089	2,100	2,150	2,200
Wind	737	1,720	3,200	5,200
Solar	842	3,615	6,200	8,700
Biomass	741	768	813	950
Geothermal		100	150	200
Total	4,409	8,303	12,513	17,250

Source: Bureau of Energy MOEA, Taiwan (2017)

is assumed that investors, seeking to avoid stranded assets, have the foresight to avoid making such investment errors. Representing technology choice and using a matrix of preferences between every possible pair of options F_{ij}, a matrix of timescales of technological change A_{ij} and technical constraints G_{ij}, the central equation driving FTT:Power is a set of non-linear finite differences equations:

$$\Delta S_i = \sum_j S_i S_j \left(A_{ij} F_{ij} G_{ij} - A_{ji} F_{ji} G_{ji}\right) \frac{1}{\tau} \Delta t. \qquad \text{Eq.(1)}$$

where S_i is the generation capacity, t is time, and τ_j is life expectancy

This equation generates, for two competing technologies, slow diffusion at low penetration, and then fast diffusion at intermediate stages before saturating at high penetration. It represents, however, the competition between 24 possible technology options (see Mercure and Salas (2012) for a full list of technology options) that can produce more complex patterns – including, for instance, the technology ladder where series of intermediate technologies may diffuse in and out of the system.

(2) Timescales of diffusion

The diffusion of technologies in FTT:Power, expressed by Eq. (1), follows simple population dynamics. Eq. (1) can either be called a 'Replicator Dynamics' (as in evolutionary theory) or 'Lotka-Volterra' (as in population biology). As is commonly done in survival analysis (and demography), one may define survival functions for technologies, corresponding to the probability of survival over years. By also determining a differential rate of upscaling for these technologies, one may derive dynamics of technological change that respect Eq.(1) the statistical lifetime of technologies and Eq.(2) the rate at which they can be replaced, beyond what is related to investor choices. This theory is explained in detail elsewhere (Mercure and Salas, 2013), and leads to Eq. (1).

(3) Natural resource use

The diffusion of renewable power technologies in FTT:Power is limited by the availability of natural resources using cost-supply curves. In this framework, costs increasing with increasing levels of development are fed into costs that influence investor choices, limiting adoption when costs become prohibitive. For this purpose an extensive assessment of renewable energy resources was carried out on the basis of both literature – with some of the results taken from land-use models – and calculations by the authors (Mercure and Salas, 2012). This is included in the terms for investor choices F_{ij} .

In the case of non-renewable resources (fossil and nuclear fuels), a more complex depletion algorithm is used that generates path-dependent scenarios of depletion when given the price history (Mercure and Salas, 2013). In this calculation, the cost distribution of non-renewable resources consumed, and the cost distribution left for future consumption, depends on the price history of the commodity; thus, the price is determined as that generating the required supply. This methodology can reproduce depletion dynamics that are consistent with classic peak oil theory depletion profiles, however, including both conventional and unconventional resources as well as some of the dynamics of the global market. Fuel costs are included in the calculation of levelized costs carried out by investors.

(4) Peak demand, energy storage and grid stability

Grid flexibility issues, peak demand and energy storage are understood in FTT:Power as simple limits to the shares of every technology, beyond which the system becomes unstable. Broadly speaking, three types of electricity generation exist: (1) baseload systems, which we define as having an output that cannot be changed rapidly (in several hours or days, e.g. nuclear and coal), (2) flexible systems, which can change their output rapidly enough to compensate for rapid changes in demand or variable supply (in minutes, e.g. gas turbines, oil generators or hydro), and (3) variable systems, renewables systems that have an uncontrollable variable output (e.g. wind, solar and wave). To maintain stability and supply demand, a grid cannot be uniquely composed of variable or baseload systems, the difference between the supply of baseload together with variable systems and the demand must be buffered by flexible systems, which can switch on and off at the right times. An additional constraint arises related to the profile of the daily demand, which requires further flexibility. However, flexibility can also be provided by storage of electricity, which can displace the time profile of the (demand – variable supply) profile and loosens the constraint.

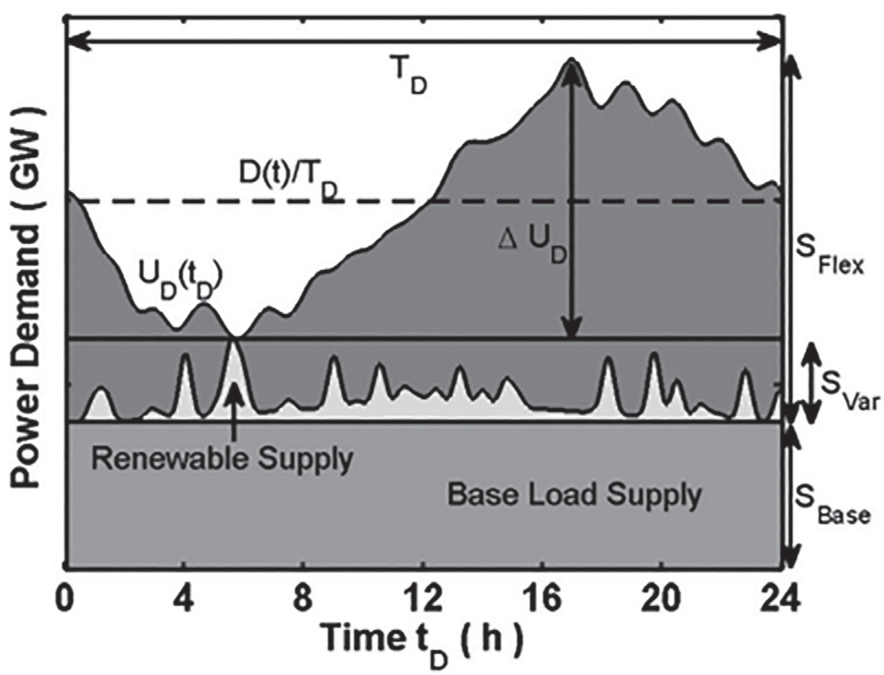
These limits are compactly expressed as inequalities for different types of share, also shown schematically in Figure 3: where S_{flex}, S_{base} and S_{var} stand for the total shares of flexible, baseload and variable systems, respectively. $\frac{\Delta U_D}{U_{tot}}$ stands for the peak load to total capacity ratio, and $\frac{U_s}{U_{tot}}$ stands for the ratio of electricity storage production capacity to total capacity. $\overline{CF}$ is the weighted average capacity factor and $\frac{\Delta D}{D}$ is the peak to average electricity demand ratio. $\frac{U_{var}T_D}{D}$ is the total generation that would be produced by variables were they to have 100% capacity factors, and $\frac{E_s}{D}$ is the total energy storage to total demand ratio. $\overline{CF}_{rated}$ is the weighted average factory rated capacity factors.

Because operating flexible generators in order to backup variable renewables leads to lower capacity factors – as they run only a fraction of the time every day – these inequalities also determine the maximum capacity factors that can be used for flexible technologies.

Thus, because of the share limits, as long as flexibility exists in ample supply no restrictions constrain the development of any technologies. However, when a system ventures near one or the other of its share limits, some types of share exchange become prohibited in Eq. (1).

This can lead to several possibilities. For instance, the variable renewables market may separate from the baseload market, where variable technologies compete for the amount of shares allowed by the amount of flexi-

Figure 3 Simple representation of the share limits for grid stability, associated to Eq. (2-5)



Source:Mercure and Salas (2012)

$$S_{flex}CF_{flex} + S_{var}CF_{var} + S_{base}CF_{base} = \overline{CF} \leq \overline{CF}_{rated}, \quad \text{Eq. (2)}$$

$$S_{flex}CF_{flex} + S_{var}CF_{var} \geq \overline{CF}\left(\frac{\Delta D}{D} + \frac{U_{var}T_D}{D} + \frac{E_s}{D}\right), \quad \text{Eq. (3)}$$

$$S_{flex} - S_{var} \geq \left(\frac{\Delta U_D}{U_{tot}} - \frac{U_s}{U_{tot}}\right), \quad \text{Eq. (4)}$$

$$S_{base} + S_{var} \leq \left(\overline{CF} - \frac{1}{2}\frac{\Delta U_D}{U_{tot}} + \frac{U_s}{U_{tot}}\right), \quad \text{Eq. (5)}$$

bility available; and this can take place at a different price level compared to baseload technologies. Similarly, the market for flexible generation can also form a sub-market at a different price level in order to accommodate the amount of renewables or peak demand. It is often the case that increases in renewable energy are limited by the degree of flexibility and storage. A focus on renewable energy needs to be combined with increases in its storage capacity, demanding management to enable further growth. (7)

(6)Linkage between FTT:Power and E3ME

The two models, FTT:Power and E3ME, are fully integrated within a single framework. While E3ME iterates within a year, it estimates the electricity demand for each region and FTT:Power estimates how the demand will be met. Prices of different fuels are also passed from E3ME to FTT:Power to calculate the cost of electricity generated through technologies that use fuels. Given these information, FTT:Power determines how the electricity demands can be met by 24 technology options. The electricity price, investment cost for new plants and the fuel use are then passed from FTT:Power to E3ME. The electricity price affects the demand, and the demand is fed back into the iteration process. Investment costs outline the intermediate demand from the power sector to other industries through an input-output relationship. Owing to data limitation, investment in the power sector is treated the same for all types of energy-generating technology. Fuel use is used to calculate the emissions.

4. The scenarios

We investigate the effects of nuclear power and coal power regulation on power generation mix and CO_2 emissions from 2017 to 2050 in the four East Asian countries. The scenarios are set based on different nuclear and coal power plants capacity assumptions.

(1) Baseline scenario

To investigate the effect of energy policy on power generation mix between 2017 and 2050, installed capacity of nuclear and coal power plants in 2017 were set at the actual level (8) and projected forward to 2040 using data from AEO2016, estimated by the Institute of Energy Economics, Japan (IEEJ). AEO2016 gives the assumption of power generation mix in 2030, and 2040 in each of the four countries. Based on historical data, the annual operational rate of coal power plant in Japan, Korea and Taiwan is set at 0.70, China's operational rate of coal power plant is set at 0.60, and the annual operational rate of nuclear power plant is set at 0.85 for all four countries. These operation rates were used when we calculate annual electricity output from each power generation technology (9) . The original assumptions of E3ME were used for the other inputs, including historical economic statistics (10) .

Installed capacity of nuclear and coal power plants were interpolated between AEO2016 reference years (e.g. between 2017 and 2030 and between 2030 and 2040). Taking account of the current nuclear power situation of Japan, we assumed 16 GW of nuclear power capacity to restart in 2020 (based on the official safety analysis by NRA(11)) . Therefore, in Japan, installed capacity of nuclear power plant was also interpolated between

Table 6 Baseline assumption of the installed capacity of nuclear and coal power plants
(unit:GW)

Year		2017	2020	2030	2040	2050
China	Nuclear	35.8	-	94.2	131.3	168.4
	Coal	906.4	-	979.3	1091.9	1204.5
Japan	Nuclear	4.4	16.0	22.3	18.8	15.4
	Coal	45.8	-	53.0	50.2	47.5
Korea	Nuclear	23.1	-	41.5	41.5	41.5
	Coal	25.7	-	43.5	46.5	49.4
Taiwan	Nuclear	5.1	-	4.4	4.4	4.4
	Coal	14.5	-	19.2	18.4	17.6

Source: The Institute of Energy Economics, Japan (2016)

2017 and 2020, and between 2020 and 2030. In addition, we extrapolate trends to 2050 using growth rates between 2030 and 2040as the baseline (see Table 6).

(2)Policy scenarios

a. Scenario 1 – limiting the capacity of Nuclear power (S1)

Scenario 1 investigates the effects of nuclear power regulation on generation mix and CO_2 emissions from 2017 to 2050 in the four East Asian countries. In this scenario, nuclear power plants capacity is either greatly reduced or phased out entirely.

■ China, Japan, and Korea

The NRA in Japan introduced a lifetime regulation after Fukushima accident and nuclear power plants in Japan cannot operate more than 40 years in principal. In this analysis, we assumed that all reactors stop operating when they reach the end of their lifetime of 40 years in each countries [(12)] . In addition, new nuclear power plants are not allowed to construct after 2020. Therefore, in Scenario 1, the number of nuclear capacity from 2017 to 2020 is consistent with that of reference scenario, and decrease gradually along with the life time of each nuclear power plants from 2020 to 2050 (see Figure 4).

■ Taiwan

Taiwan government decided to phase out of nuclear power plant by 2025. Therefore, current three nuclear power plants are assumed to shut down along with the 40 years life time from 2018 to 2025 (see Figure 4).

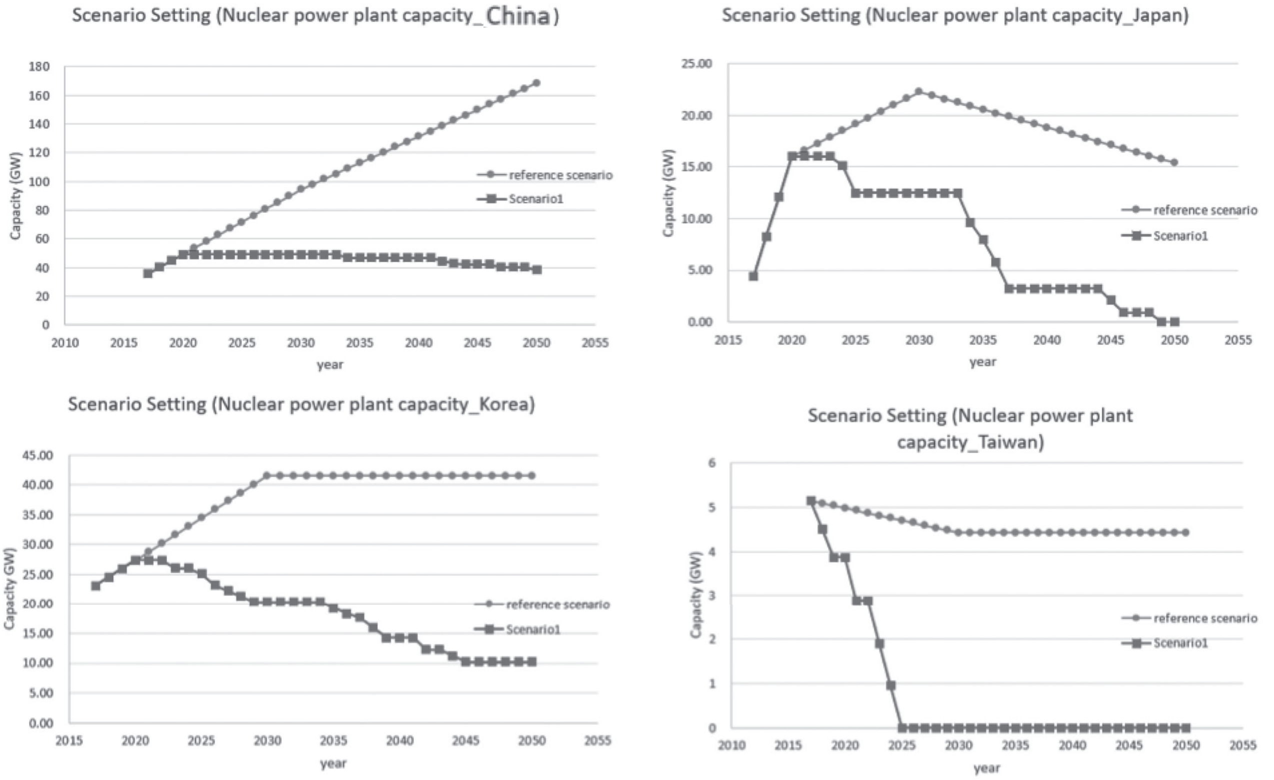
b. Scenario 2 – limiting the capacity of coal-fired power (S2)

In Scenario 2 (restrictions on coal), it is assumed that the installed capacity of coal-fired thermal power is greatly reduced in East Asia. Scenario 2 aims to reduce CO_2 emissions in order to address the climate change issue. In all countries, we assume no construction of coal-fired power plants from 2020 to 2030, and the installed capacity of coal power plant linearly decrease to zero from 2030 to 2050 (see Figure 5). In China, National Development and Reform Committee (NRDC) planned to reduce the share of coal power generation from 67.5% in 2015 to 6.8% in 2050 in their Power Generation mix under High Penetration Scenario in 2015. In Korea, there is a plan to shut down four coal power plants from 2018 to 2025 [(13)] . Therefore, in Scenario 2, the installed capacity of coal power plant is gradually reduced from 2018 to 2025 in Korea. It should be noted that our coal power regulation assumptions in this scenario are not unrealistic considering the current trend of coal power reduction policies in East Asia.

c. Scenario 3 – limiting both nuclear and coal-fired power (S3)

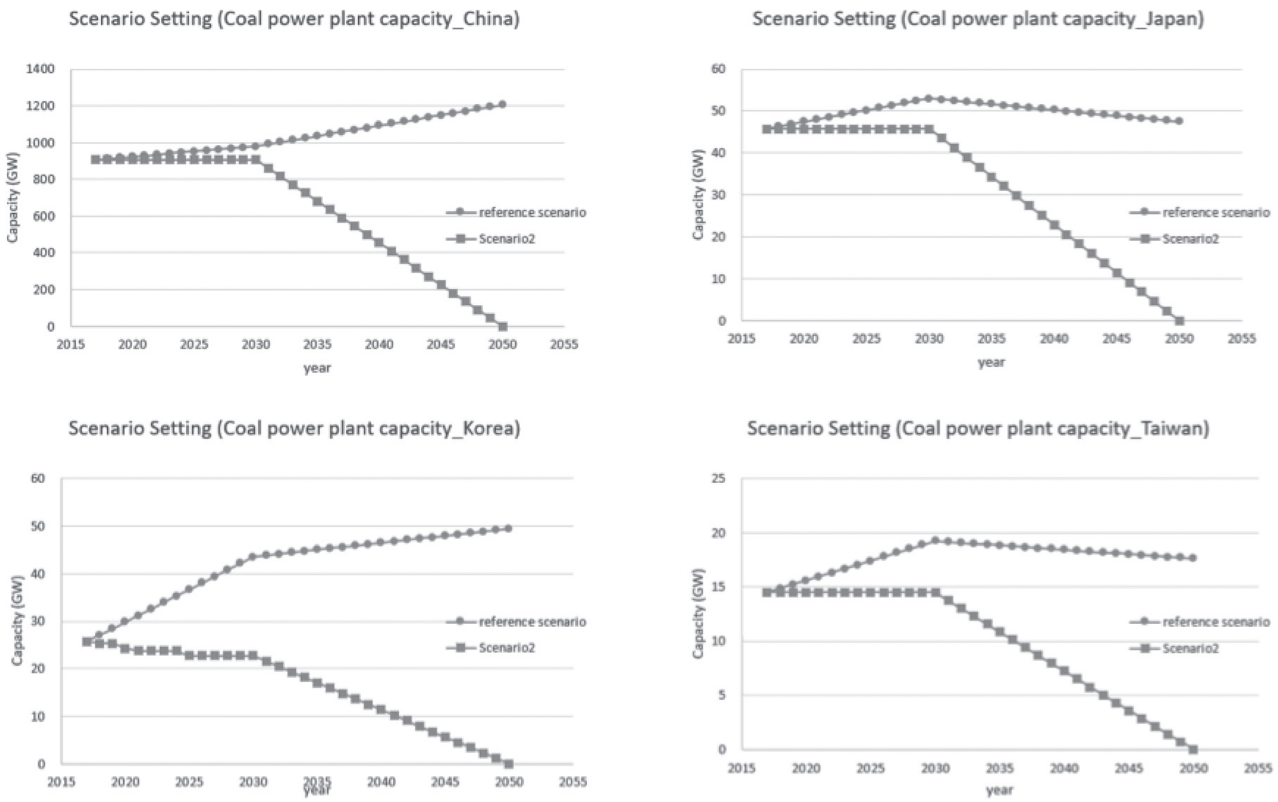
Scenario 3 (simultaneous restrictions on both nuclear and coal-fired thermal) assumes simultaneous application of Scenario 1 and Scenario 2. That is, restrictions on nuclear under Scenario 1 and restrictions on coal-fired thermal power in Scenario 2 are implemented at the same time.

Figure 4 comparison of nuclear power capacity between reference scenario and scenario 1



Source: prepared by the author

Figure 5 comparison of coal power capacity between reference scenario and scenario 2



Source: prepared by the author

5. Modeling results

(1) China

Figure 6 shows model results of the changes in the power generation mix by technology in China. In the baseline scenario, the share of renewable energy does not increase significantly from 2017 to 2050. The reason behind this, is although renewable energy increases in absolute term, coal – which is the baseload technology dominating the China's power sector –grows even faster to supply the rapidly increasing electricity demand. This condition makes further diffusion of renewable energy comparatively difficult. The result of S1 shows that limiting nuclear without other policy means generation shifts back to coal. In addition, we also see only 1.2% increase in renewable technologies compared to the baseline as coal become the main source of power generation. The reason given for this slight increase include (1) an avalanche effect due to economy of scale from coal generation, (2) no coal restrictions in S1, and (3) no incentive to invest in other technologies as coal is the cheapest. On the other hand, our estimation shows that electricity price falls almost 1.6% in 2050 from baseline as cheap coal dominate the power supply, electricity demand increases by almost 0.3%. Meanwhile, limiting coal to zero is a major policy in China because power generation from coal accounts for more than half of total generation in the baseline.

In S2, the model results show big increases in all other technologies to compensate reduction in coal generation. Particularly, nuclear, IGCC, onshore wind power and solar are technologies that see the biggest increase in share of total generation. In addition, not only wind and solar increase, other less mainstream renewable technologies, e.g. geothermal and tidal as well as CCS technologies also take off in this scenario. However, electricity price increases by 32.6% from the baseline in 2050 because the option to use cheap coal to produce electricity is no longer available. As a result of higher electricity price, total electricity demand reduces by 5%.CO_2 emissions reduce by 88.5% compare to the baseline in 2050, which making this policy very effective in decarbonizing the power sector.

In S3, the results are dominated by coal restrictions. This is because nuclear share in the power generation mix in the baseline is much lower than coal in China (74% coal compared to 10% nuclear in 2040). Power generation mix is similar to the results in S2 but without nuclear in the mix. Electricity price in S3 increase by almost 30% since both nuclear (relatively cheap) and coal are no longer part of the generation mix, and electricity demand decreases by 4.5% as a result.

Shares of renewables in China power generation in 2050 is shown in Table 7. The share of nuclear decreases in S1 and S3 from baseline. While the renewable technologies were pushed up in S2 and S3, especially in S3. Share of renewable technology in S3 (78.7%) approach the 2050 high renewable penetration target of National Development and Reform Commission (NDRC) of China (2015). However, the percentage of fossil fuels technologies including gas and oil increase in S3 compared to S2.

In order to reduce the carbon emission from the power sector, the Chinese government should aim to work out a comprehensive policy package including promoting renewable energy by expanding electric power feed-in tariffs, building up a national level carbon emission trading marked, introducing carbon tax and other measures.

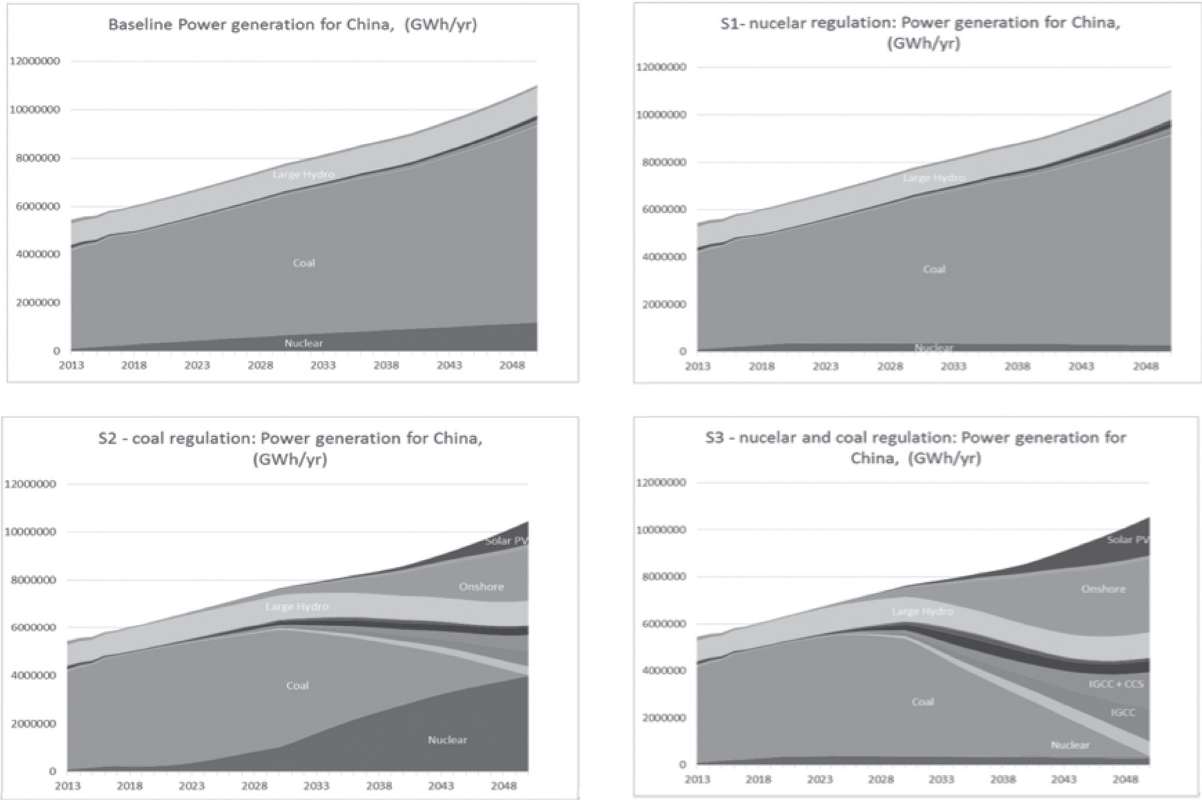
Figure 7 shows CO_2 emissions in the power sector for each scenario in China. In S1 with nuclear regulation, overall CO_2 emissions from the power generation sector is 8,352 $MtCO_2$, increases by almost 38.6% compared to the baseline of 6,028 $MtCO_2$ in 2050 because the limitation of nuclear without additional policy means power generation shifts back to coal. In S2, with coal regulation, CO_2 emissions from the power generation were reduced by 70% compared to the baseline in 2050 to 1,826 $MtCO_2$, making this policy very effective in decarbonization the power sector because of big increases in all other technologies to compensate reduction in coal generation. In S3, with nuclear and coal regulation, the net CO_2 reduction is -60%, slightly less than S2 because nuclear is no longer a low-carbon option available and generation from gas and oil increase to compensate.

Table 7 Share of renewables in China power generation in 2050 in China (unit:%)

	Baseline	S1	S2	S3
Nuclear	10.8	2.5	38.0	2.6
Fossil fuels	76.2	83.4	9.6	18.7
Renewables (incl. CCS)	13.0	14.2	52.3	78.7
Total	100.0	100.0	100.0	100.0

Source: E3ME-FTT Power simulation results

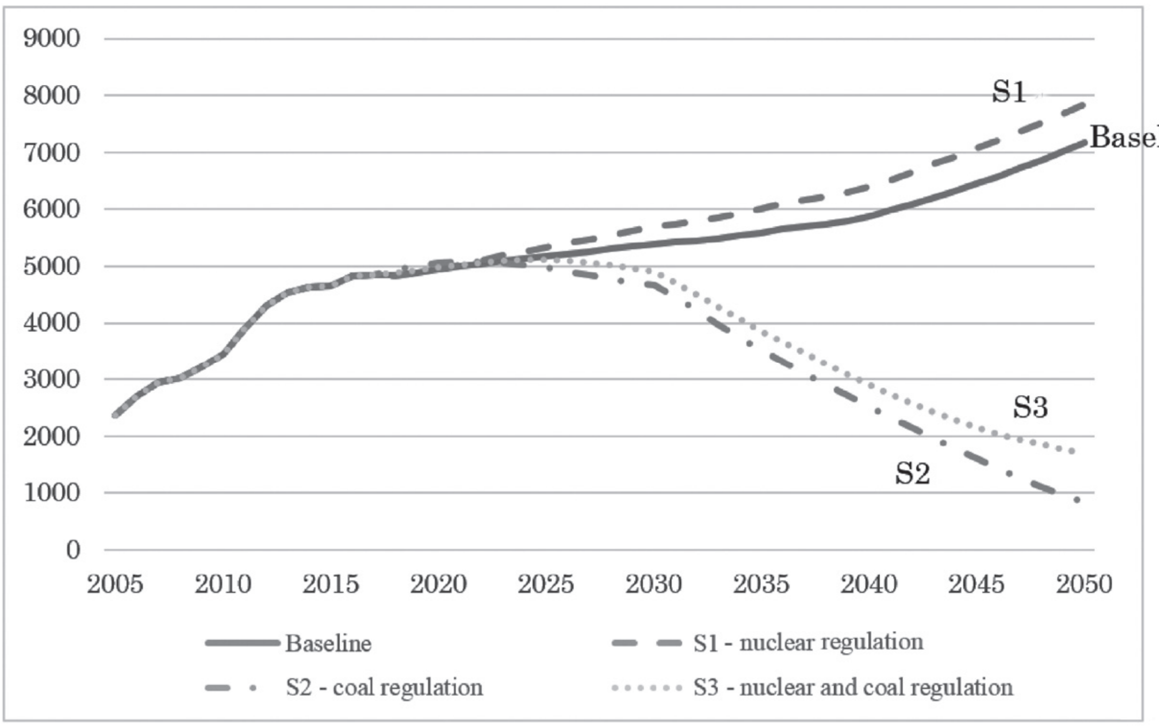
Figure 6 Power generation supply by technology in China



Source: E3ME-FTT Power simulation results

Figure 7 CO_2 in the power sector in China

(unit: $MtCO_2$)



Source: E3ME-FTT Power simulation results

(2) Japan

Figure 8 and Table 8 show power generation mix by technology in Japan. In baseline scenario where the amount of electricity generation from nuclear and coal power is set according to the assumption of AEO 2016, nuclear power generation increases from 3% of total power generation to 9%, coal-fired power generation drastically changes from 28% to 54% from 2017 to 2050. On the other hand, since the generation cost of gas-fired power is assumed to be expensive, the electricity generation from gas-fired power decreases from 42% to 14% from 2017 to 2050. The output from large hydro-power is nearly flat. Renewable energy rises from 5% to 11% due to increased solar and onshore wind power generation. This means that renewable energy gradually increases due to the reduction of generation costs from 2017 to 2050 by the technology innovation even if there is no support policy for renewable energy.

The model results in S1 show that limiting nuclear without additional climate policy or feed in tariff for renewable energy leads to increase coal power generation without CCS, because the generation cost for coal is the cheapest among all the generation technologies. The share of coal increases from 28% in 2017 to 59% in 2050. The electricity generation from renewable technologies and gas-fired power slightly increased compared to the baseline scenario. Because the share of coal-fired power generation is large, electricity price fall by 3.8% and electricity demand increases by 1% in 2050 from the baseline.

In S2, limiting coal without CCS to zero, coal power generation is substituted by not nuclear power but gas-fired power (37%) and renewable energy (36%, mainly solar PV and onshore wind) in 2050. The electricity generation from coal with CCS and from IGCC technology increase by 10% compared to the results of baseline and S1. It means, coal power restriction stimulates investments in other thermal power technologies and renewable energy drastically. In addition, nuclear power generation does not increase even if coal power generation is restricted, because the cost of solar PV, onshore wind and other thermal power generation technologies become lower than that of nuclear power generation especially in Japan. The share of nuclear power generation decrease to 1% in 2050. Electricity price in 2050 increase by 24% from baseline because the generation cost for CCS and IGCC are assumed more expensive than that of coal. The total electricity demand in S2 decrease by 5% as a result of higher electricity price compared to S1.

In S3, nuclear and coal regulation, the shares of other fossil fuel power technology, CCGT and IGCC, and renewable energy are almost same as those of S2 because power generation from nuclear power decrease to almost zero in 2050 in S2 without nuclear regulation.

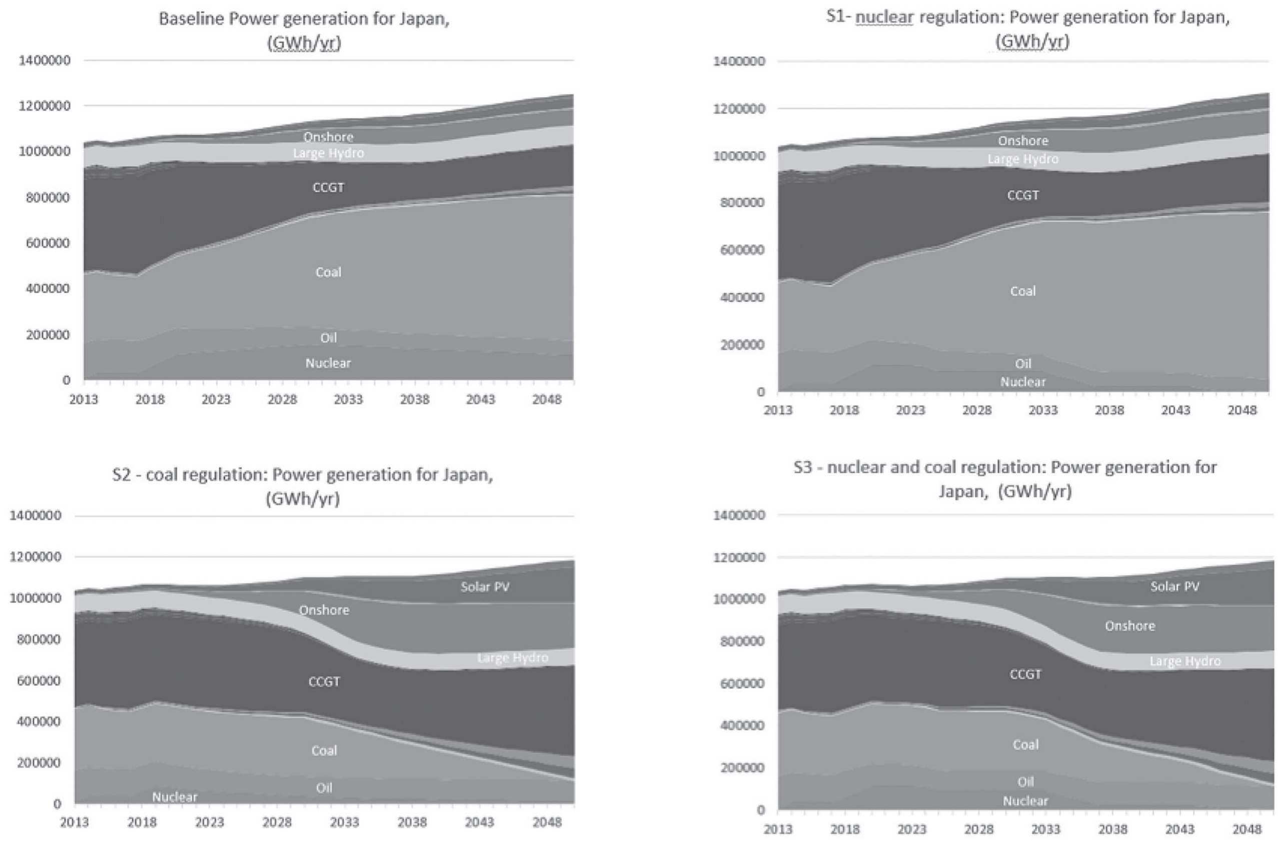
Figure 9 shows CO_2 emissions in the power sector by scenarios in Japan. Because of increase of coal power generation in S1 with nuclear regulation, CO_2 emissions increases from 503 $MTCO_2$ in 2017 to 739 $MTCO_2$, increases by 10% compared to the baseline of 671 $MTCO_2$ in 2050. On the other hand, in S2 with coal regulation, CO_2 emissions in the power sector reduces by 56% compared to the baseline in 2050. The expansion of CCGT and renewable energy in 2050 contributes to the big reduction of CO_2 emissions. In S3, same as S2, most of the power supply comes from CCGT and renewable energy. Therefore, CO_2 emissions in the power sector is reduced by 56% in 2050 compared to baseline.

Table 8 Share of power generation by technology in 2050 in Japan (unit:%)

	Baseline		S1	S2	S3
	2017	2050	2050	2050	2050
Nuclear	3%	9%	0%	1%	0%
Oil	13%	5%	4%	8%	9%
Coal thermal +IGCC (incl. CCS)	28%	54%	59%	10%	10%
Gas thermal (CCGT) (incl. CCS)	42%	14%	16%	37%	37%
Large Hydro	9%	7%	7%	7%	7%
Renewable	5%	11%	14%	36%	36%

Source: E3ME-FTT Power simulation results

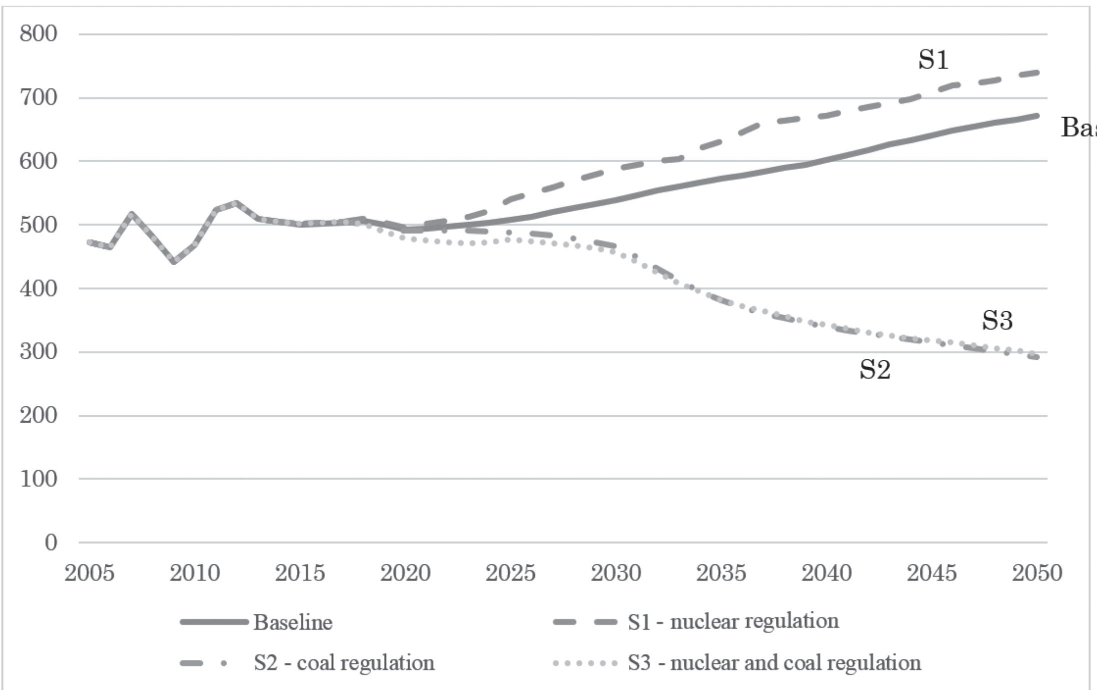
Figure 8 power generation supply by technology in Japan



Source: E3ME-FTT Power simulation results

Figure 9 CO_2 in the power sector in Japan

(unit: $MtCO_2$)



Source: E3ME-FTT Power simulation results

(3) Korea

Figure 10 shows power generation mix by technology in Korea. The model results for S1 show that limiting nuclear without other policy means generation shift back to coal. It also shows big reduction in gas and smaller reductions in renewable technologies compared to the baseline as coal become the main source of power generation. Electricity price falls as we no longer have as many expensive renewables in the power mix, electricity demand increases by almost 4% in S1 which is met by power generation from coal.

In S2, limiting coal to zero has similar implication in Korea to limiting nuclear because both power generations from coal and nuclear account for around a third of total generation in the baseline in Korea (remaining mostly from gas). The model results show increase in all other technologies to compensate reduction in coal generation. Gas and IGCC are technologies that see the biggest increase in share of total generation, interestingly the substitution from coal went mostly to gas and not much to nuclear in Korea. Solar technology increases a lot in this scenario but other renewables, with some exceptions, declines because of gas technology is taking off in this scenario. Electricity price increases (11% from baseline in 2050) because using cheap coal to produce electricity is no longer an option in S2. Total electricity demand reduces by 1.6% as a result of higher electricity price. The introduction of this policy is not effective in Korea because a lot of electricity are still being generated from gas.

In S3, power generation mix is similar to the results in S2 but without nuclear in the mix. This means other technologies must increase to compensate. This pushes up the renewable technologies further but gas and oil technologies also increase in this scenario. Electricity price increase by 14% since both nuclear (relatively cheap) and coal are no longer part of the generation mix. Electricity demand decreases by 3% compared to baseline as a result.

Table 9 summarizes the share of renewables in 2050. The share of nuclear decreases in S1 and S3 but fossil fuels share dramatically increase in S1. Renewable share increases by the most in S3 but overall the mix is still dominated by fossil fuel (gas) despite coal regulation.

Therefore, to meet the same CO_2 reduction target in the power sector as the 2-degree scenario (approximately -80% from 1990), the Korea government need to introduce an effective carbon price mechanism such as a national level carbon emission trading market or carbon taxes. This will help to promote renewable energy in place of nuclear and coal power generation.

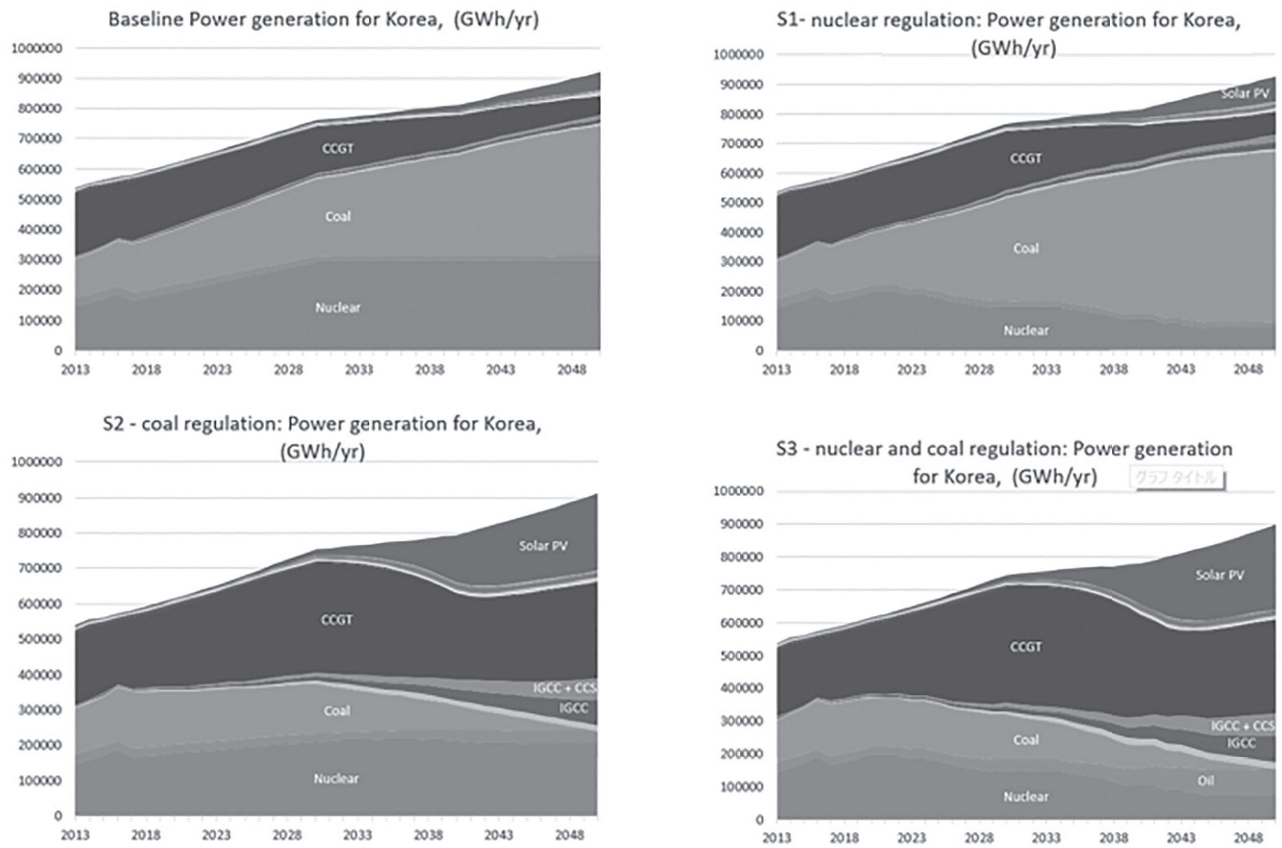
Figure 11 shows CO_2 emissions in the power sector for each scenarios in Korea. In S1 with nuclear regulation, overall power sector CO_2 emissions increase by almost 75% compared to the baseline in 2050 because nuclear is no longer a low carbon option. The additional power generation comes from coal which generate CO_2 emissions. In S2 with coal regulation, power sector CO_2 emissions reduce by 26% comparing to the baseline in 2050 because all other technologies that substituted coal produce lower CO_2 emissions. In S3 with nuclear and coal regulations, the net CO_2 reduction is very small (-2%) because nuclear is no longer a low carbon option and despite coal is limited to zero, all the additional power generation comes from gas which generates CO_2 emissions.

Table 9 Share of renewables in power generation in 2050 in Korea (unit:%)

	Baseline	S1	S2	S3
Nuclear	31.9	7.8	22.2	8.0
Fossil fuels	57.5	75.9	41.7	49.4
Renewables (incl. CCS)	10.6	16.3	36.1	42.6
Total	100.0	100.0	100.0	100.0

Source: E3ME-FTT Power simulation results

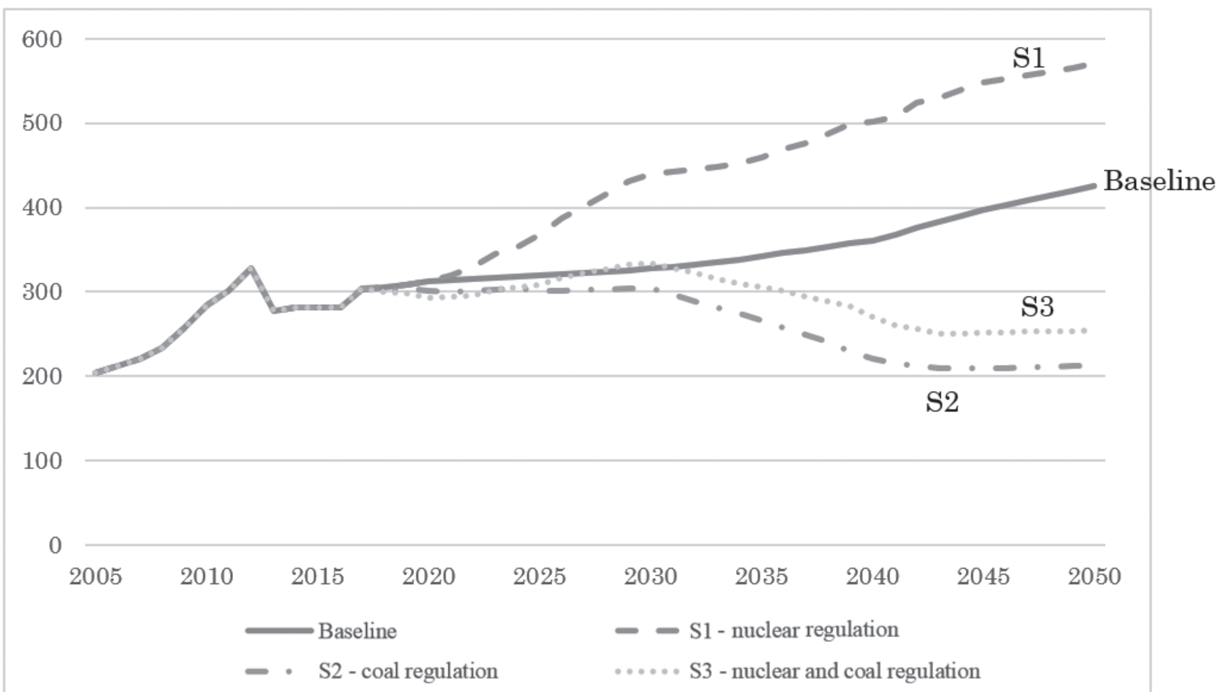
Figure 10 Power generation supply by technology, Korea



Source: E3ME-FTT Power simulation results

Figure 11 CO_2 in the power sector in Korea

(unit: $MtCO_2$)



Source: E3ME-FTT Power simulation results

(4) Taiwan

As showing in Figure 12, power generation mix in Taiwan follows a similar path to Japan and Korea. The share of renewables in Taiwan becomes the largest in S2. Because Taiwan has decided not to increase nuclear capacity other than the two plants that are under construction, reduction in coal-fired power is substituted by gas and renewables. Regarding the national targets, in 2025 the capacity of renewable energy is 7,239MW in total, not meeting the target of 9,952MW. However, in 2030 it increases to 23,678MW, i.e. twice the target 12,502MW for that year. This is because, after going through the slow diffusion at low penetrations, fast diffusion at intermediate stages is realized. In S2, this intermediate stage starts even earlier and the total capacity of renewable energies reaches 35,977MW in 2025, much higher than the national target. The high share of renewable energy is supported by the diffusion of flexible gas-fired power, substituting coal-fired power as well.

Table 10 summarizes the share of renewables in 2050 in Taiwan. The share of nuclear is zero in S1 and S3 but fossil fuels share increase in S1 and S3. Power generation mix is like the results in S2 but with nuclear in the mix. This means other technologies must increase to compensate. This pushes up the renewable technologies further but gas and IGCC technologies also increase in this scenario.

In S1, limiting nuclear without other policy means generation shift back to coal, not only result shows coal substitute nuclear, we also see big reduction in gas and smaller reductions in renewable technologies compared to the baseline as coal become the main source of power generation. In S2, limiting coal to zero has bigger implication in Taiwan than limiting nuclear because power generation from coal account for around a third of total generation in the baseline in Taiwan. The model results show increases in all other technologies to compensate reduction in coal generation. Gas, IGCC and nuclear are technologies that see the biggest increase in share of total generation, and solar increase by the most among renewables, but CCS technologies will also take off in this scenario.

Renewable share increases by the most in S3 but overall the mix is still dominated by fossil fuel (gas) despite the coal regulation. Therefore, it is difficult to meet the CO_2 reduction target in the power sector, even coal regulation is effective at reducing CO_2 emission but some substitutions go to gas generation which also emit CO_2. Nuclear regulation without other policies to promote renewables or limiting fossil fuels results in higher CO_2 emissions as the substitute from nuclear are dirtier fuels like coal or gas.

Figure 13 shows CO_2 emissions in the power sector by scenarios in Taiwan. In S1, nuclear regulation, overall power sector CO_2 emissions increase by almost 36% compared to the baseline in 2050. This is because nuclear is no longer a low carbon option, all the additional power generation comes from coal. In S2, coal regulation, power sector CO_2 emissions reduce by 16% compare to the baseline in 2050 because coal is substituted by all other technologies which have lower carbon intensity. In S3, with nuclear and coal regulations, the net CO_2 reduction is zero (0%) because nuclear is no longer a low carbon option and despite coal is limited to zero, all the additional power generation is substituted by gas.

6. Conclusions

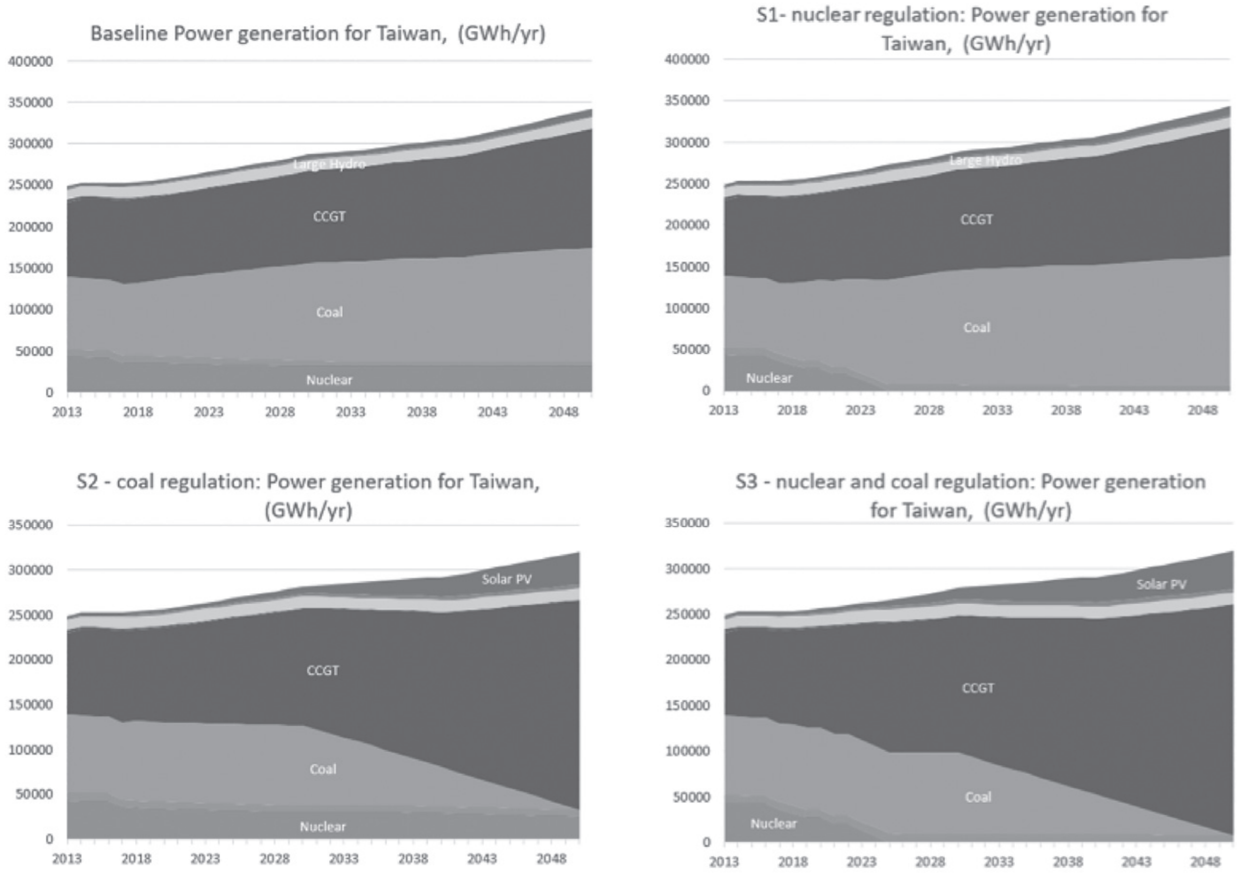
The analysis using FTT:Power and E3ME indicates that, in the power sector, a phasing out of nuclear power is likely to result in increases in electricity generation output from coal drastically because coal power is assumed the cheapest technology. Renewable energy gradually increases due to the reduction of generation costs from 2017 to 2050. In this paper, however, there are no additional renewable energy support policies such as feed in tariff, carbon tax or renewable subsidies. Therefore,

Table 10: Share of renewables in power generation in 2050 in Taiwan (unit:%)

	Baseline	S1	S2	S3
Nuclear	9.1	0.0	7.8	0.0
Fossil fuels	84.1	92.5	75.7	81.6
Renewables (incl. CCS)	6.8	7.5	16.7	18.4
Total	100.0	100.0	100.0	100.0

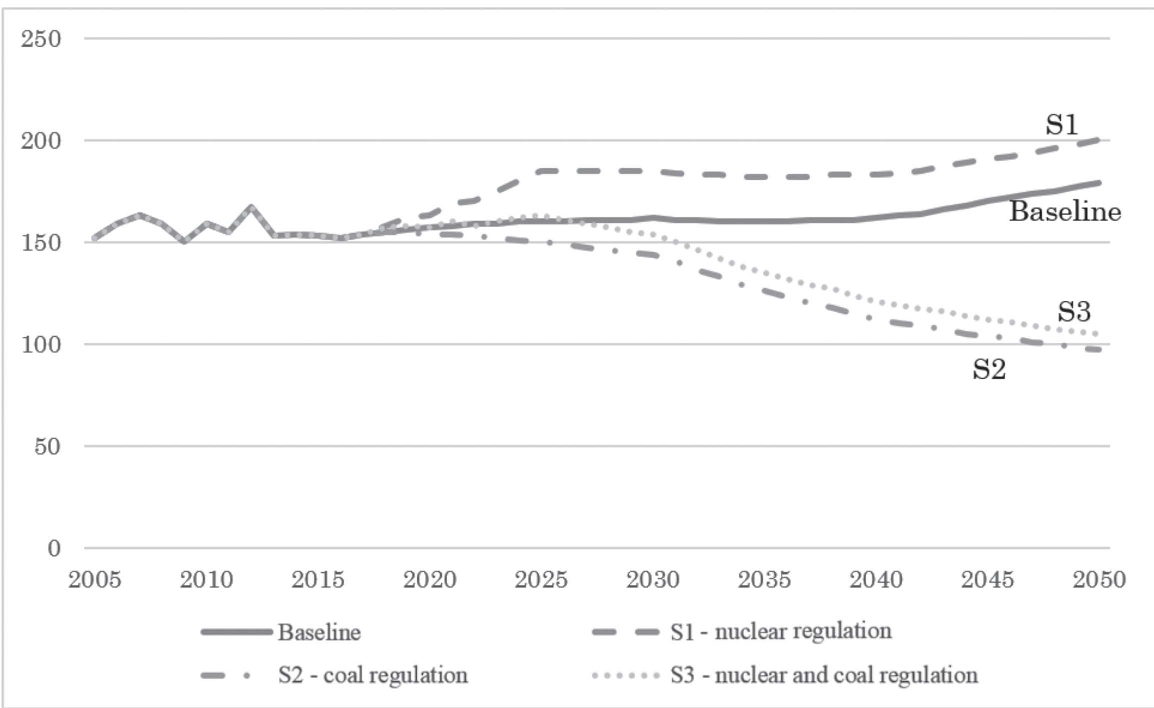
Source: E3ME-FTT Power simulation results

Figure 12 Power generation supply by technology in Taiwan



Source: E3ME-FTT Power simulation results

Figure 13 : CO_2 in the power sector in Taiwan
(unit:$MtCO_2$)



Source: E3ME-FTT Power simulation results

limiting nuclear alone does not contribute much to diffusion of renewable energy because carbon intensive coal power has become the most cost-effective power generation technology.

On the other hands, renewable energy drastically increase in coal regulation scenario. In scenario 2, coal power generation is substituted by not nuclear power but gas-fired power and renewable energy (mainly solar PV and onshore wind) in 2050. This means that nuclear power generation will no longer be the cost-effective technology in 2050. This is because new technological innovations such as renewable energy will proceed quickly and push down their power generation costs rapidly. Therefore, it is important to regulate the share of coal-fired power generation in the power sector to promote renewable energy sources.

This research has two challenges. One is the economic impacts of power mixes in our policy scenarios. To evaluate what power mix is desirable from a social perspective, it is necessary to assess the effects of various power mixes on the economy such as GDP, competitiveness, employment and household income. We will discuss this detail in Lee,S, et.al. (2018). The other challenge is how to promote renewables. Renewables are essential power sources toward sustainable low carbon society in East Asia. In this paper, we showed power mixes will be diversified under nuclear and coal power regulation scenarios. But this promotes mainly gas power and not much renewables technologies especially in Japan and Korea. We discussed how to support renewables introducing Feed-in-Tariff as and carbon taxes in Lee, T-Y, et.al. (2017).

Notes

(1) For more details, see “Collaboration key on green energy, climate: experts” (China Daily, http://usa.chinadaily.com.cn/epaper/2016-07/18/content_26129095.htm, Access day: 2017.04.15).

(2) For more details, see “Nuclear Power in China” (World Nuclear Association, http://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx,Access day: 2017.04.15).

(3) Pumped storage hydropower plants.

(4) Ohi nuclear power plants temporary stopped operation to take inspection and maintenance.

(5) Sendai nuclear power plants restart operation under the new law.

(6) See https://www.camecon.com/how/e3me-model/ for details on E3ME model.

(7) Note that the parameters for storage also implicitly represent the flexibility that is obtained through international trade of flexible generation capacity (e.g. importing Scandinavian hydro in Germany). In this assumption, the amount of electricity traded sums to zero through the day. Since international trade of electricity is not covered in this version of the model, it is taken as an exogenous assumption.

(8) Installed capacity of nuclear power plants in Japan reflects the actual number of capacity restarted as of June 2017.

(9) Annual electricity output (kWh) = installed capacity (kW) ×8760 hours ×annual operational rate.

(10) See Cambridge Econometrics (2014) for more detail.

(11) This number include 10 nuclear power plants (totally 9.25 GW) permitted reactor installation license by NRA as of June 2017, and 6 newest plants (totally 6.77 GW) which will be able to operate after 2035 but did not submit application for reactor installation yet.

(12) Three nuclear power plants in Japan (Mihama unit No.3, Takahama unit No.1 and No.2) allowed 60 years operation by NRA in Japan in 2016. Therefore, in this analysis, these three plants operate for 60 years exceptionally.

(13) Seocheon unit No.1 and No.2 (400 MW) planned to shut down in 2018, Samchonpo unit No.1 and No.2 (1120 MW) in 2020, Honam unit No.1 and No.2 (500 MW) in 2021, Boryeong unit No.1 and No.2 (1000 MW) in 2025.

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