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東アジアにおける電力部門のモデル分析：エネルギー選択による経済・環境への影響

Modelling the power sector in East Asia:
Economic and Environmental impacts by choices of Power Sources

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本論文は，電源選択が及ぼすマクロ経済および環境への影響を定量的に評価したものである。道具立ては，ケンブリッジ・エコノメトリックスが開発した「E3ME-FTT:Power モデル（①マクロ経済は計量経済型，②電源選択は離散選択型，③産業活動水準は I-O 表）」を原型とし，新たにアジア 4 カ国（中国，日本，韓国，台湾）を推計可能とした拡張モデルである。シミュレーションでは脱原子力や脱石炭といったシナリオを設定し，各国および域内の再生可能エネルギー導入量・マクロ経済指標・CO2 排出量等を推計しシナリオ間で比較検討する。

データ整備やモデル拡張に研究者の実力を知ることができ，確率的な離散選択モデルを電源選択に適用した点も新しい。また，得られた結論も示唆に富んでいる。

東アジアにおける電力部門のモデル分析：
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要約

本稿は日本・中国・韓国・台湾の東アジア 4 カ国についてエネルギー選択が経済や環境にどのような影響を与えるかについてモデル分析したものである。分析には技術普及モデルである FTT: Power モデルおよびマクロ計量モデル E3ME-Asia を用い、原子力発電や石炭火力発電またその両方を規制した場合の経済指標や二酸化炭素排出量の変化を定量的に評価した。

Abstract

This paper models the power sector in 4 regions, China, Japan, Korea and Taiwan, in East Asia to look into the economic and environmental impacts by choices of power sources. Analysis is done by combination of technology diffusion model, FTT: Power, and macro-econometric model, E3ME-Asia. Scenarios that restricts share of nuclear power, coal-fired power or both in electricity generation are assessed.

キーワード：エネルギー、電力、原子力発電、モデル分析
Key Words: Energy, Electricity, Nuclear, Model Analysis

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1. Introduction

East Asia currently faces choices concerning the use of power sources for the future. Choices made during the next few years are likely to affect and determine the directions of energy sector developments for the next few decades. This is made particularly relevant after the Fukushima-Dai-ichi Nuclear Power Plant Accident (the Fukushima Accident). However such choices will also affect the regional economy and the environment.

In this work we explore possible scenarios of power sector development for four East Asian regions (China, Japan, Korea, and Taiwan), which have specific targets for changing the composition of their power generation technology mix. The method used is one of technology diffusion basis where pathways of technology result from energy policy choices. We explore the feasibility of current aspirations and targets, through an evaluation of the effectiveness of possible electricity policy instruments in chosen scenarios.

After the Fukushima Accident, public concern about the safety of nuclear power plants has become widespread in East Asia. Each government in the region has tried to emphasise its low cost and low CO2 characteristics and stated that existing nuclear plants are safe enough to continue operating. The risk of economic loss that might occur from reducing nuclear has clearly factored in this position. On the environmental side, nuclear power does not emit carbon when generating electricity but, as revealed by the Fukushima Accident, it can carry serious risks to human and environmental welfare. In this chapter our first scenario analyses the extent to which reducing nuclear power affects economic growth rates, if at all, and what the impact on carbon emissions would be from reducing the nuclear share.

Reduction of carbon emissions has also become an important issue in East Asia in recent years and our second scenario focuses on this policy goal. Japan, Korea and Taiwan are heavily dependent on imported fossil fuel and China relies on domestic coal production as an energy source. As coal is the cheapest fuel for power generation, the three fuel importing regions are highly dependent on coal as well. Coal-fired power plants are the largest GHG emission source in the power sector and we assess the environmental impact of phasing out conventional coal-fired power plants. The economic impacts of these same scenarios are explored in chapter 4.

The paper is structured as follows: Section 2 provides an outline of the power sectors and related policies in each of the four regions; Section 3 describes the modeling methodology that was applied. Sections 4 and 5 describe the scenarios that were assessed and show the corresponding environmental impacts in each case. Section 6 concludes by suggesting what the policy implications of the analysis might be.

2. Overview of the power sector in East Asia

2.1 China

Energy demand continues to grow rapidly in China. Coal has been the main source of energy supply in China, supported by massive domestic production. Concern over the local air pollution and increasing GHG emissions coming from coal combustion has become a great concern. While making efforts to build more efficient coal-fired power plants, developing other energy sources has drawn great interest as well. Nuclear power is regarded as an important energy source, even after the Fukushima Accident. Renewable energy, including large scale hydro, is also strongly supported to meet the growing demand and reduce GHG emissions.

In 2012, 78.0% of electricity was provided by fossil fuel in China (IEA [2014b]). Coal remains the main source, providing 75.9% of electricity, and accounting for 49.5% of energy related CO_2 emissions in the country, only including generation of electricity (IEA [2013]). Hydro was the largest among non-fossil fuel energy sources, accounting for 17.2% of electricity supply. China has the largest capacity of wind power in the world (75GW) and the fourth largest capacity of PV (7GW, REN21 [2013]), but the share of these technologies in domestic energy supply is still low given the very large level of total energy demand.

China has made a target of total consumption of renewable energy to be account 9.5% of the total primary energy consumption in the 12^{th} Five Year plan, which is for 2010-2015. This target contains different targets for different types of renewable energy as summarized in Table 2.1.

Table 2.1: Targets of different renewable technology in 12th FYP

Technology	Installed capacity target for 2015 (GW)
Large scale hydro	260
Pumped storage hydro	30
Wind, onshore	100
Wind, offshore	5
PV	21
Ocean energy	0.05

(Source: IEA [2014c])

Total capacity of nuclear power plants is planned to reach 40GW by 2015 in the 12th FYP and 58GW by 2020; 150GW of nuclear capacity is expected by 2030.

2.2 Japan

Before the Fukushima Dai-ichi Nuclear Power Plant Accident (the Fukushima Accident) occurred on March 11th, caused by the Great East Japan Earthquake, nuclear power was regarded as the main energy source that can contribute to reducing both greenhouse gas (GHG) emissions and fossil fuel imports. However, the Fukushima Accident has led to acute concern over the safety of nuclear power. Currently, as of July 2014, no nuclear power plant is operating to supply electricity (Japan Nuclear Technology Institute [2014]).

In 2013, fossil fuels provided 88.3% of electricity supply in Japan (IEA [2014a]). Renewable energy, excluding conventional hydro (8.5%), accounted for only 2.2% of the electricity supply. According to the IEA [2014b], 99.5% of fossil fuel consumed in Japan is imported in terms of thermal unit and the import bill for fossil fuel went up by 2.4 trillion JPY from 2010 to 2013 (Japan Renewable Energy Foundation [2014]). The bill has increased recently because electricity supplied by nuclear power is now substituted by fossil fuels and also because of the low exchange rate of the yen and price increases of fossil fuels. This situation reveals the economic risk of relying too heavily on imported fuel as an energy source. At the same time, CO_2 emissions from the power sector have increased by 12.0% in 2013 compared to 2010.

Renewable energy will be one of the most important energy sources to tackle both security of the national energy supply and mitigating climate change by substituting and reducing fossil fuel consumption. In 2012, the Feed-in Tariff Scheme (FIT) was introduced to replace the Renewable Portfolio Standard Scheme (RPS) and Net-metering Scheme for Photovoltaic Power to push forward the deployment of renewable energy. Different tariffs are applied for different kind of renewable energy to support various kinds of technologies (Table 2.2). In two years from when FIT started in July 2012 to July 2014, 11.8 GW capacity of renewable energy was installed and connected to the grid.

Table 2.2: FIT tariff price and installed capacity of renewable energy in Japan

Technology	Tariff price (JPY)			Installed capacity (July 2012~ July 2014) (MW)
	2012	2013	2014	
PV (smaller than 10kW)	42	38	37	2482.5
PV (larger than 10kW)	40	36	32	9145.1
Wind (smaller than 20kW)	55	55	55	0.003
Wind (larger than 20kW)	22	22	22	111.7
Small hydro (smaller than 200kW)	34	34	34	2.9
Small hydro (200-1000kW)	29	29	29	4.2
Geothermal (smaller than 15000kW)	40	40	40	0.2
Biogas	39	39	39	6.3
Solid biomass (unutilized wood)	32	32	32	13.7
Solid biomass (wood and processed residue from agriculture)	24	24	24	15.1
Waste	17	17	17	53.7

Source: Agency for Natural Resources and Energy, Japan [2014]

2.3 Korea

Korea is highly dependent on imported fossil fuels as energy sources. In 2013, 71.7% of electricity supply originated from fossil fuel combustion (IEA [2014a]) and 99.0% of the fossil fuels consumed in the country were imported (IEA [2014b]). Nuclear power has relatively large share, 25.7%, compared to other East Asian regions. Though renewable energy has been supported by policy instruments, its share in the overall fuel mix is still low, only 0.7% (excluding conventional hydro) in total.

Renewable energy technologies were supported by a FIT until 2012, but the FIT was replaced by a RPS in that year. This was because tariff spending on the FIT in Korea was not shared by the consumers but supported by a special government budget that ran into financing issues.

Korea adopted its latest National Energy plan for 2030 in January 2014. Nuclear power remains an important part of the electricity supply, but its share will be reduced from the original plan before the Fukushima Accident since concerns over the safety issues of nuclear power are now wide-spread. In the latest National Energy plan, the share of nuclear power is set to be 29% of total electricity generation in 2035[5]. Renewable energy is assumed to provide 10% of total electricity generation in 2022 and 11% of primary energy consumption in 2035.

2.4 Taiwan

Similarly to Japan and Korea, Taiwan is highly dependent on imported fossil fuels. The high share of fossil fuels both contributes to Taiwan's carbon emissions and presents security of supply issues. Nuclear power has been regarded as an important energy source to deal with these problems, but now faces public opposition after the Fukushima Accident. Renewable energy is also an important energy source in this context and it has been supported by a FIT since 2009.

In 2011, 78.6% of electricity was generated from fossil fuel combustion (Bureau of Energy, Taiwan, 2014). 98.7% of fossil fuel (coal, oil and gas) consumed in Taiwan is imported (IEA, [2014b]). Nuclear power accounted for 16.7% and renewable energy including conventional hydro accounted for 3.6% of the electricity supply.

The Taiwanese government published a New Energy Policy of Taiwan in June 2014 (Bureau of Energy, Taiwan [2014]). In the plan, a steady reduction of nuclear energy and full scale promotion of renewable energy are anticipated. There would be no extension to the life spans of existing nuclear plants and no more new nuclear plants. The capacity of renewable energy, which is

[5] Nuclear's share of the 1st National Energy Plan in 2008 was set to be 41% of total electricity generation in 2030.

3615MW in 2012, is planned to reach 9,952MW by 2025 and 12,502MW by 2030.

3 Modeling method

In this work we model the choice and diffusion of power technology in East-Asia using a global macro econometric model with high regional resolution including Japan, China, Taiwan and Korea, E3ME-Asia (Cambridge Econometrics [2014]), complemented by a simulation of power technology diffusion, FTT:Power (Mercure [2012]). E3ME-Asia provides the demand for electricity given industrial activity, household income and electricity prices in 53 countries. FTT:Power uses this demand, and with given electricity sector policies such as carbon taxes or technology support mechanisms, determines the technology mix and calculates greenhouse gas emissions. The model was recently used for studying the impacts of climate policy instruments for emissions reductions worldwide within the E3MG-FTT:Power framework that operates under 21 regions (Mercure et al. [2014]). It is now integrated to E3ME-Asia in 53 regions. See Appendix for more detailed description of E3ME-Asia.

3.1 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 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. Finally, 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 is assumed that investors, seeking to avoid stranded assets, have the foresight to avoid making such investment errors. Representing technology choice 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 non-linear set of finite differences equations:

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

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

3.2 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 evolutionaly theory) or 'Lotka-Volterra' (as in population biology). As is commonly done in survival analysis (and demography), one may defines survival functions for technologies, corresponding to the probability of survival along years. By also determining a differential rate of upscaling for these technologies, one may derive dynamics of technological change that respect (1) the statistical lifetime of technologies and (2) the rate at which they can be replaced, beyond what is related to investor choices. This theory is explained in detail in (Mercure [2013]), and leads to eq. (1).

3.3 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 influencing investor choices, limiting adoption when costs become prohibitive. For this purpose an extensive assessment natural renewable energy resources was carried out based both on literature, with some of the results taken from land use models, and calculations by the authors (Mercure & 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 which generates path-dependent scenarios of depletion given the price history (Mercure & Salas [2013]). In this calculation, the cost distribution of the amount of non-renewable resources consumed and the distribution left for consumption depends on the price history of the commodity, and the price is thus determined as that which generates the required supply. This methodology can reproduce depletion dynamics consistent with classical 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 levelised costs carried out by investors.

3.4 Peak demand, energy storage and grid stability

Grid flexibility issues, peak demand and energy storage are understood in FTT in terms of simple limits to the shares of every technology beyond which the system becomes unstable. Broadly speaking, three types of electricity generators exist: (1) *baseload* systems, which we define as having an output that cannot be changed rapidly (timescale of 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, renewable energy systems that have an uncontrollable variable output (e.g. wind, solar and wave). In order 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 the storage of electricity, which can displace the time profile of the (demand – variable supply) profile and loosens the constraint.

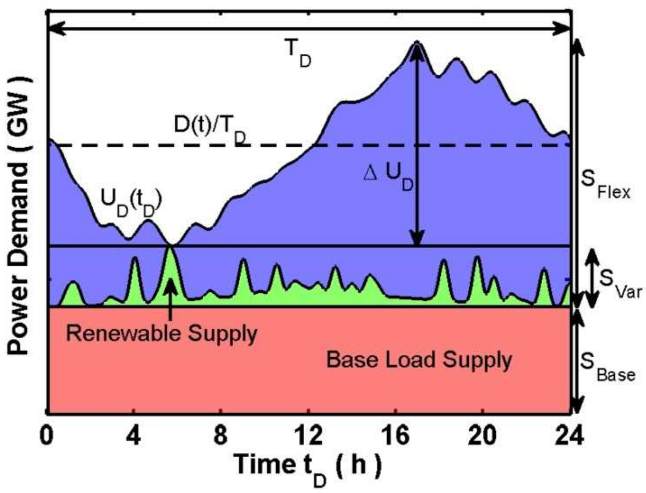

Figure 3.1: Simple representation of the share limits for grid stability, associated to equations (2-5).

These limits are compactly expressed as inequalities for different types of shares, also shown schematically in Figure 3.1:

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

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

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

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

where S_{flex}, S_{base} and S_{var} stand for the total shares of flexible, baseload and variable systems. $\frac{\Delta U_D}{U_{tot}}$ 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, and $\overline{CF}$ is the weighted average capacity factor. Finally $\frac{\Delta D}{D}$ 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.

Since the operation of flexible generators for backup to variable renewable energy leads to lower capacity factors, as they run only a fraction of the time every day, these inequalities also determine what maximum capacity factors can be used for flexible technologies.

Thus the result of the share limits is that as long as flexibility exists in ample supply, no restrictions constrain the development of any technologies. However when a system ventures near to 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 renewable energy market may separate from the baseload market, where variable technologies compete for the amount of shares allowed by the amount of flexibility 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 that is required in order to accommodate the amount of renewable energy or peak demand. It is often the case that the growth of renewable energy will be limited by the amount of flexibility and storage, where support for renewable energy need to be combined with increases in storage capacity or demand management in order to enable further renewable energy growth.[6]

[6] Note that the parameters for storage implicitely represent also the flexibility that is

3.5 Linkage between FTT:Power and E3ME-Asia

Two models, FTT:Power and E3ME-Asia, are fully integrated within a single framework. While E3ME-Asia iterates within a year, it provides 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-Asia to FTT:Power to calculate the cost of electricity by technologies using fuels. Given these information, FTT:Power determines how the electricity demands are matched by 24 possible technology options. Electricity price, investment cost for new plants and the amount of fuel use are passed from FTT:Power to E3ME-Asia afterwards. Electricity price affects the demand and the demand comes back in the iteration process. Investment cost gives the amount of intermediate demand from power sector to other industry through I-O relationship. Due to data limitation, investment in the power sector is treated the same for all kind of generation technologies. Fuel use is used to calculate the emissions.

4 The scenarios

4.1 Baseline assumptions

The decision of building nuclear power plants in analysed regions are assumed to be made politically rather than in the market. Therefore, electricity supply from nuclear power plants in the analysed regions is set exogenously and not solved endogenously by FTT:Power. Analysed period is from 2015 to 2030.

In Japan, electricity supply from nuclear until 2013 follows the historical data from IEA [2014a] and IAEA [2014]. Supply in 2014 is set to zero as no nuclear power plant is online at the moment. There are 48 operational nuclear reactors in Japan and 18 of them are now under safety evaluation. Two reactors, Sendai No.1 and No.2 have gone through all the safety evaluation process and assumed to restart from 2015 in this analysis. Other 16 reactors are assumed to restart from 2016 in our baseline. Other 30 are assumed to restart from 2017, excluding the ones which have serious safety problems. All the reactors will stop operating when they come to their lifetime, 40 years. China, Korea, and Taiwan follow the historical data until 2013 and then assumed to follow their national plan.

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obtained through international trade of flexible generation capacity (e.g. importing Scandinavian hydro in Germany). In this assumption, this amount of electricity trade 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.

Being members of IEA, Japan and Korea are not going to increase the capacity of oil-fired power plants. Taiwan is following this principle as well. Therefore in this analysis, these three regions keep the latest capacity of oil-fired power plant exogenously from 2014 onwards. The capacity of hydro power plants is set exogenously as well in analysed region according to each region's national plan since construction of new dams is subject to not only available natural resource but also social context.

The policies supporting renewable energy are also considered in the baseline. According to IEA [2014c], Japan, China and Taiwan have FIT schemes and Korea has an RPS scheme. They differ in terms of technologies covered and tariff rate or target. These are taken into account to build the baseline.

Other inputs including historical economic statistics follows general assumptions for E3ME[7].

4.2 No more nuclear power scenario (S1)

In this scenario, electricity supply from nuclear power plants is solved endogenously by FTT:power from 2015 onwards with restriction of not increasing the share of nuclear power in electricity supply for China and Korea. As Japan has zero share of nuclear power in 2014, the share remains zero in the whole period afterwards. Taiwan planning to stop further increases in nuclear power in the baseline and this scenario is not applied. The scenario is analysed for each single region and then integrated to see if there are any spill-over effect between four regions.

4.3 No more coal-fired power scenario (S2)

In this scenario, electricity supply from conventional coal-fired power plants is restricted not to increase their share in electricity supply, and plants are left to operate until the end of their lifetime. Other assumptions, exogenous capacity of nuclear and oil-fired power plants and support for renewable energy, are held as in the baseline.

4.4 No more nuclear and coal-fired power scenario (S3)

In this scenario, holding all other baseline assumptions, both nuclear power and coal-fired power are restricted not to increase their share in electricity supply. Scenarios above are summarized Table 4.1.

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7 See Cambridge Econometrics [2014] for more detail.

Table 4.1: Summary of scenarios

Scenario						Description
	Cn	Jp	Kr	Tw	Ea*	
Baseline	Base					Reference case with current policies
S1	S1Cn	S1Jp	S1Kr	(same as Base)	S1Ea	No more nuclear power scenario
S2	S2Cn	S2Jp	S2Kr	S2Tw	S2Ea	No more coal-fired power scenario
S3	S3Cn	S3Jp	S3Kr	(same as S2TW)	S3Ea	No more nuclear and coal-fired power scenario

note* : Ea corresponds to putting the same restriction simultaneously in all four regions.

5 Modelling results

5.1 China

Though the baseline for China includes support schemes for renewables, the share of renewables does not increase significantly. The reason behind this is that, while renewables grow in capacity, coal, which is the baseload technology dominating the power sector, grows even faster to supply the rapidly increasing electricity demand. This condition makes further diffusion of renewables comparatively difficult. In S1, this situation does not change significantly, since nuclear, not having a large share of electricity supply, is substituted by coal which is the least expensive energy source. Meanwhile, in S2, the share of coal fired power sufficiently decreases over time and opens space for renewables, while nuclear power, not planned through market-based decisions, cannot replace all the decommissions of coal-fired power. Given the constraints to maintain the grid stability, baseload technologies and variable renewable energy are competing against each other. The sum of the capacity of both kind of technologies can't exceed the minimum demand amount in a day. When both coal fired power plant and nuclear is restricted which is the case of S3, renewable energy gets more share than S2 as the baseload capacity decreases further. Not the entire decreased baseload share is covered by renewable energy and some part is substituted by gas power plants, which is flexible power source.

The dominating technology in renewable energies (excluding hydro) is solid biomass, given the support from the government and huge resource availability. The second is onshore wind and the third is solar PV.

Cross-border interactions, such as the trade of electricity between the power sectors in the four regions, are not modelled here. The results for the Chinese power sector from S1CN and S1Ea are therefore almost the same and are not presented in the figure. This applies for other three regions, Japan, Korea and Taiwan, as well and Ea scenarios are not presented in the figures in latter section.

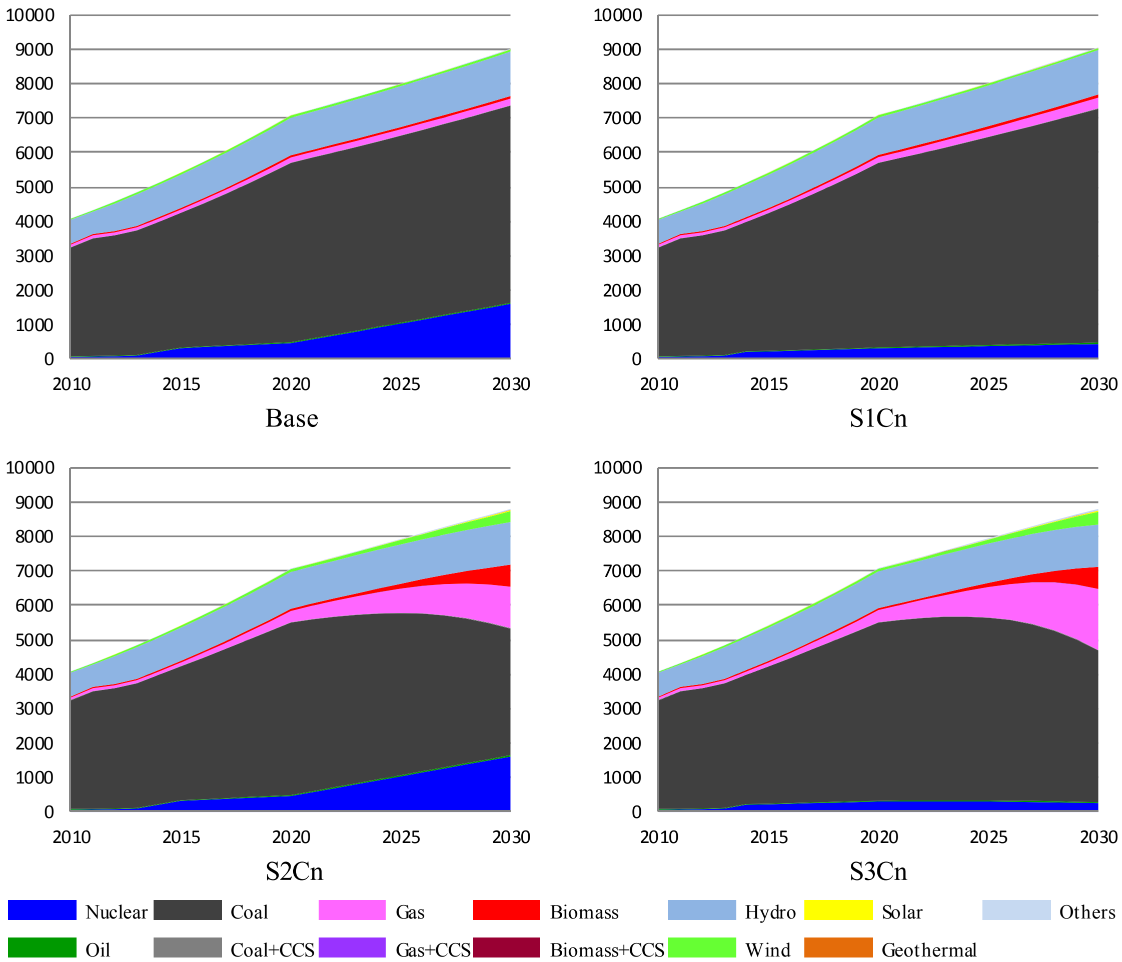

Figure 5.1: Electricity generation from each technology by scenario, 2010 - 2030, TWh, China

E3ME being a macro-econometric model, increased investment is not regarded as costs but as effective demand having spill-over effects to the whole economy through input-output relationships between the power sector and other industries.

In S2 and S3, though the price of electricity is increased by nearly 60% from the baseline, GDP and all other economic indicators are increased (Figure 5.2). This is because of the investment increase in electricity sector, substituting coal-fired power plants by other technologies. S2 makes the largest investment in the power sector among all the scenarios and therefore the largest GDP. In S2, coal-fired power, the least expensive technology, is substituted by other technologies the most among the scenarios. S3 makes the second largest investment in the power sector and GDP. They are slightly less than the baseline in S1 since nuclear power is substituted by less expensive coal-fired power.

On the environmental side, S1 increases the CO2 emissions by 9.4% from the baseline in 2030 as nuclear power would be mostly replaced by coal-fired power which is the most emission intensive. CO2 emissions are reduced by 13.6% from the baseline in 2030 in S2 thanks to the coal-fired power share decreasing. Emission reduction in S3 is limited, 1.8% from the baseline in 2030, as the share of coal-fired power is not much decreased. The smaller share decrease of coal-fired power here compared to S2 is caused by restriction on nuclear making it difficult for the power sector to match the demand without certain amount of coal-fired power.

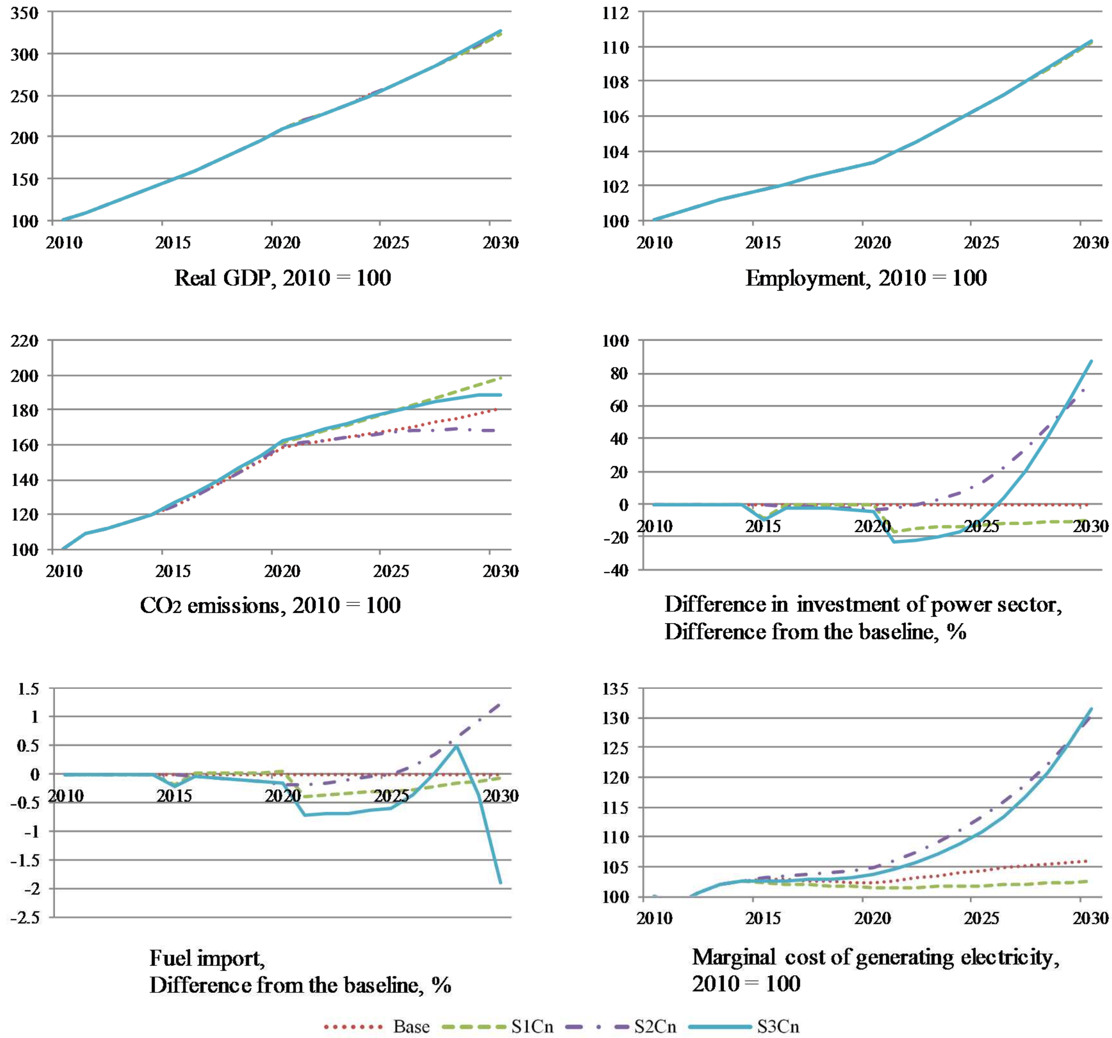

Figure 5.2: Economic and environmental indicators, %, China

5.2 Japan

The largest increase in the share of renewables in Japan is in S3. In this scenario, the share of coal and nuclear, which is considered a baseload technology, decreases. When electricity supply is dominated by baseload technologies, there is restricted market space for variable renewables according to the amount of available flexibility, which thus compete in a sub-market determined by grid stability. Nuclear power is also a baseload technology, but in both S1JA and S1all the share increase of renewables remains comparatively small, not able to reach the share 21% which was the referred target of renewable energies' (including conventional hydro) share in the latest national plan. This is due to coal power not being restricted in S1 and since coal is the least cost technology, coal fired power substitute the share of nuclear, making the total share of baseload technologies higher than in S2. Meanwhile in S2, the capacity of nuclear power is held exogenously and coal is predominantly replaced by flexible gas power, making the total baseload share decrease considerably. The total share of renewable energy including conventional hydro is above the referred target in S2 and S3. The dominating technology is solid biomass.

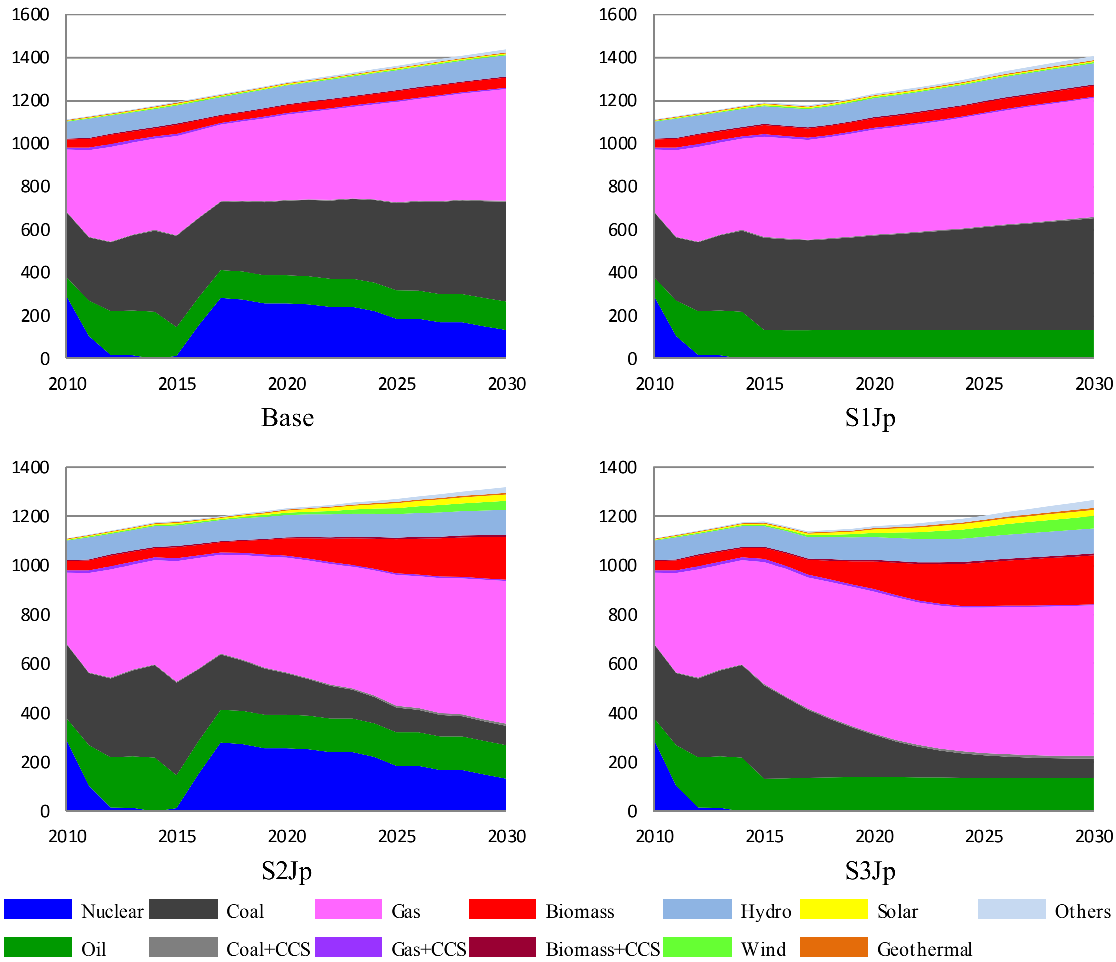

Figure 5.3: Electricity generation from each technology by scenario, 2010 - 2030, TWh, Japan

S1 has a moderate negative effect to the economy during the whole period. This is due to the higher electricity price, less investment in the power sector and increased import of fossil fuels. CO_2 emissions are increased over the period, electricity from nuclear power mainly substituted by coal-fired power generations. Restrictions on coal power makes the import of fossil fuels significantly lower, which has a positive impact, while on the other hand increases the price of electricity, which has a negative impact. The price hike thus generates a burden on the economy. CO_2 emissions are decreased dramatically in S2, making the emission less than 75% of baseline emissions this single technology regulation policy. In S3, the investment in the power sector initially drops down similarly to the trend in S1 as the capacity of nuclear power is set to be zero from 2015. Afterwards the share of renewable energy gets high as in S2 and the investment is boosted. Fuel import is also reduced at the same time. These factors push up the GDP. CO2 emissions are higher than that in S2 since the share decrease of coal-fired power is smaller and some of the reduced share of two technologies is covered by gas-fired power.

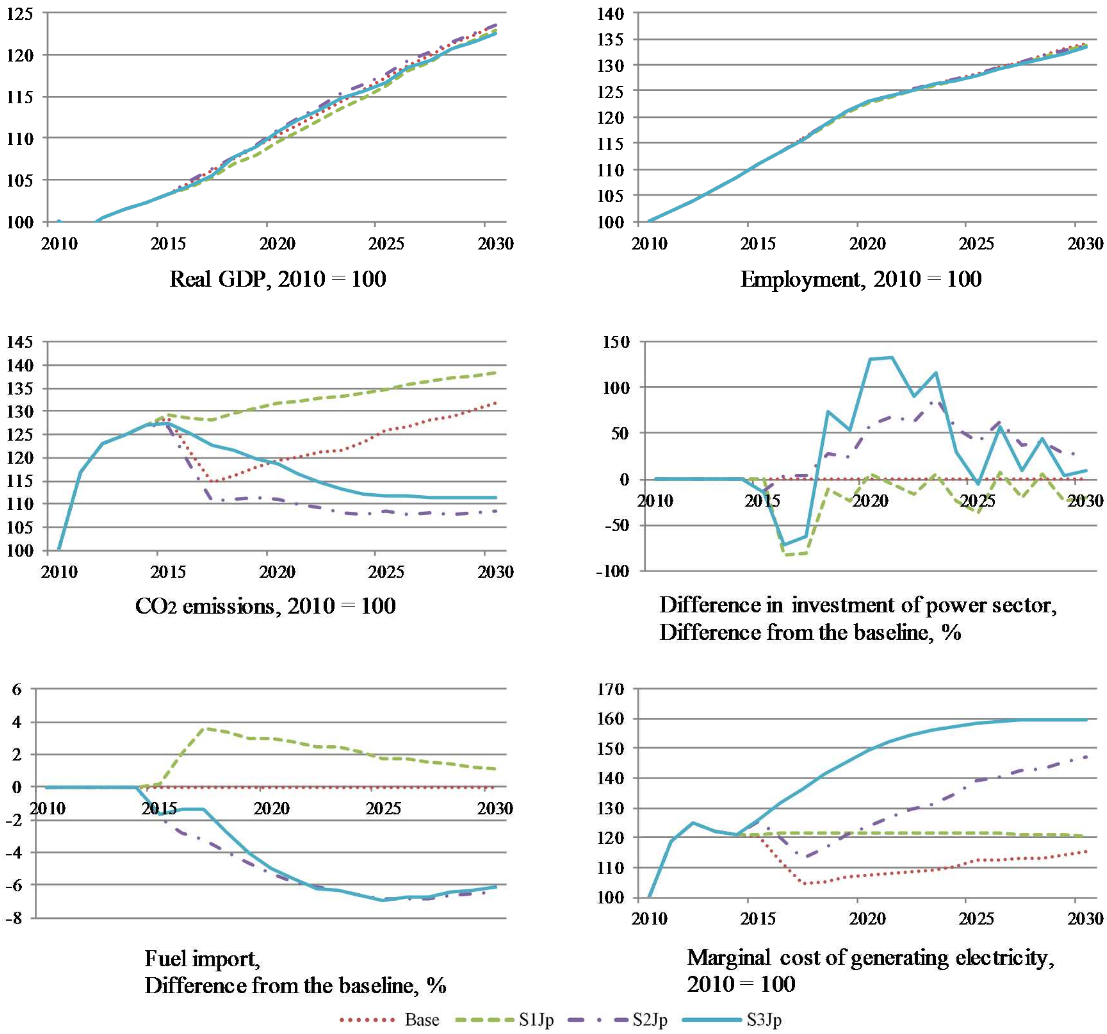

Figure 5.4: Economic and environmental indicators, %, Japan

5.3 Korea

The trend in Korea is similar to that of Japan, with S3 having largest share increase of renewables. Korea has larger share of nuclear than Japan, but the total share of baseload technologies is similar to that of Japan and the basic structure of the power mix is essentially the same. The share of renewables, however, becomes significantly higher than in the other three regions with all the scenarios. This is due to biogas being included with renewables, mainly using methane gas from landfills, becoming competitive and increasing its share. The other reason of the high share of renewable energy in S2 and S3 is the gas-fired power, which is a flexible technology capable to deal with variability of renewable energy, becoming to dominate the power sector. The national target for renewable energy, 10% of total electricity generation in 2022, is not met in the baseline, S1 and S2, and met only in S3.

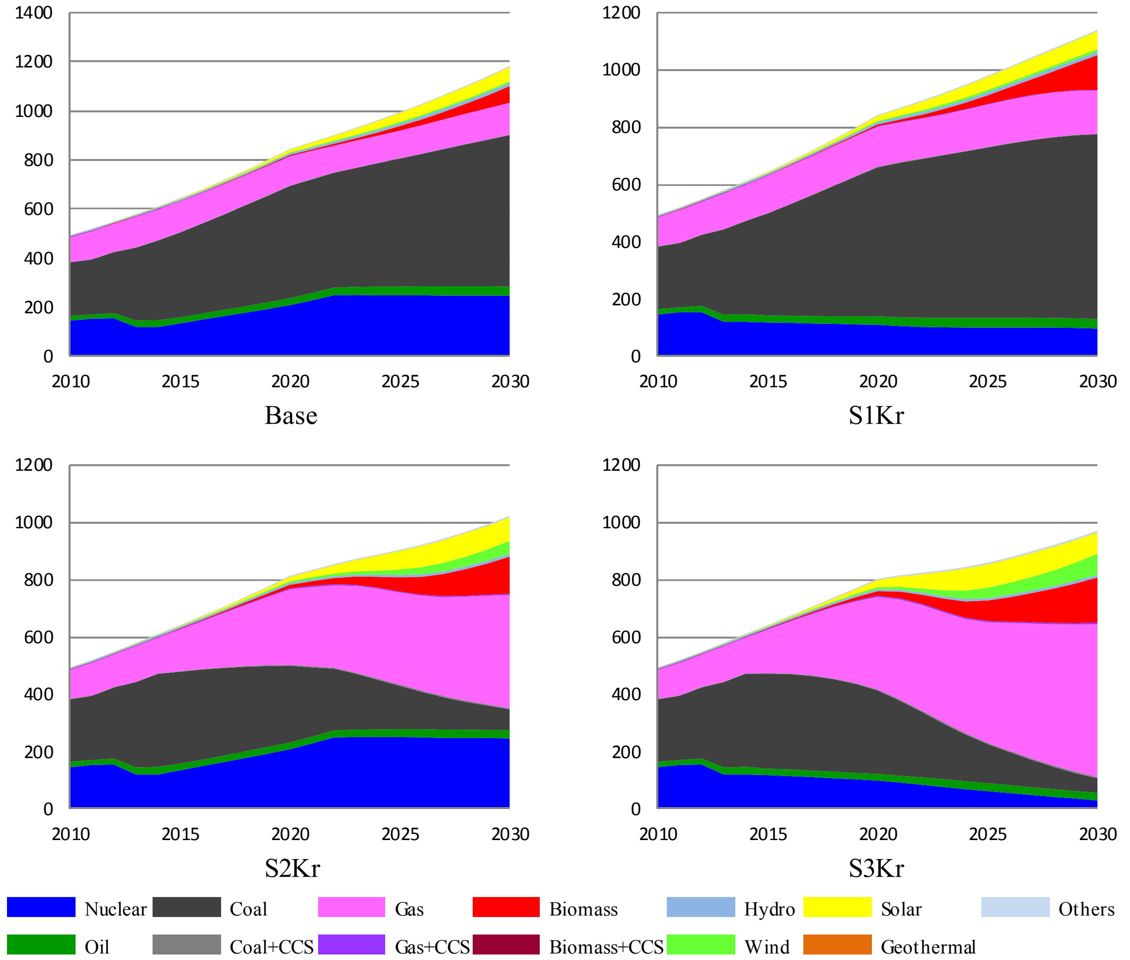

Figure 5.5: Electricity generation from each technology by scenario, 2010 - 2030, TWh, Korea

On economic impact, unlike Japan, the Korean economy gains from all the scenarios, S1, S2 and S3 (Figure 5.6). Reducing the share of nuclear, coal or both of them leads to switching towards other technologies in the power sector. Switching requires investment to new power plants, which has a spill-over effect to the national economy. In S2, the decrease in coal imports has a positive effect to the economy as well. These positive impacts compensate the negative impact of the higher electricity price.

CO2 emissions follows similar trend as in Japan. They are increased in S1 and reduced in S2 and S3. The reduction amount in S2 is larger than in S3.

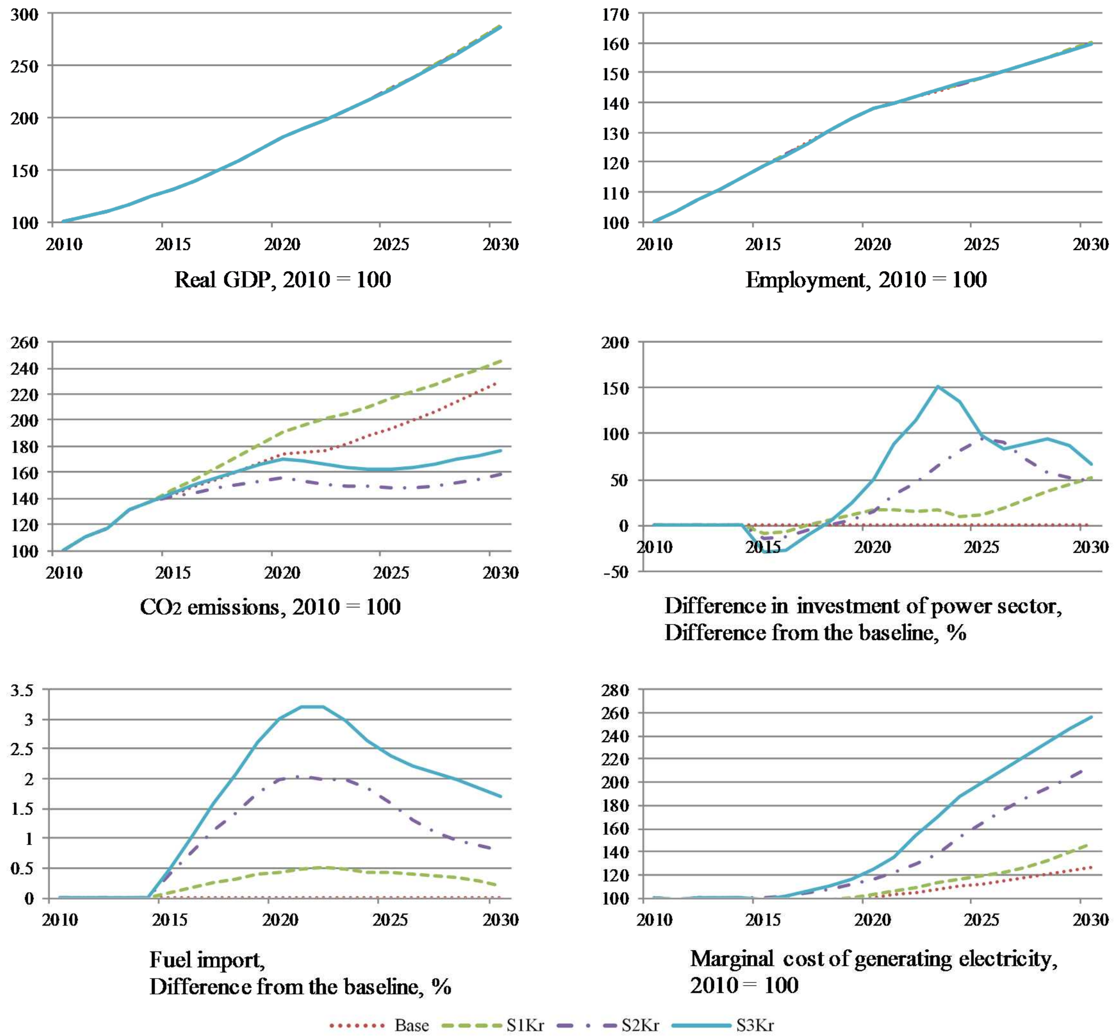

Figure 5.6: Economic and environmental indicators, %, Korea

5.4 Taiwan

Following the same path as Japan and Korea, the share of renewables in Taiwan becomes the largest in S2. Since Taiwan has decided not to add nuclear capacity other than two plants under construction, reduction in coal fired power is substituted by gas and renewables. The capacity of renewable energies in total is 7,239MW in 2025, not meeting the target of 9,952MW, it increases to be 23,678MW in 2030 to be twice of the target, 12,502MW. This is because after going through the slow diffusion at low penetrations, fast diffusion at intermediate stages is realised. In S2, this intermediate stage starts even earlier and the total capacity of renewable energies reaches 35,977MW in 2025, high above 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.

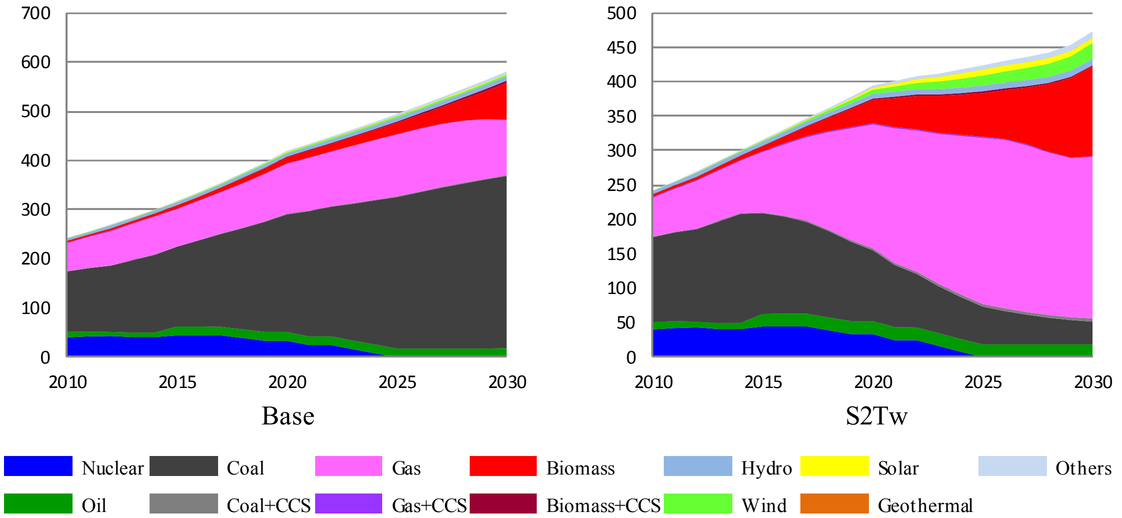

Figure 5.7: Electricity generation from each technology by scenario, 2010 - 2030, TWh, Taiwan

Reduction of coal turns out to benefit the economy with reduced coal imports and increased investment (Figure 5.8). Taiwan makes the largest relative CO_2 emissions reduction of the four regions analysed, by more than 40% compared to the baseline in 2030.

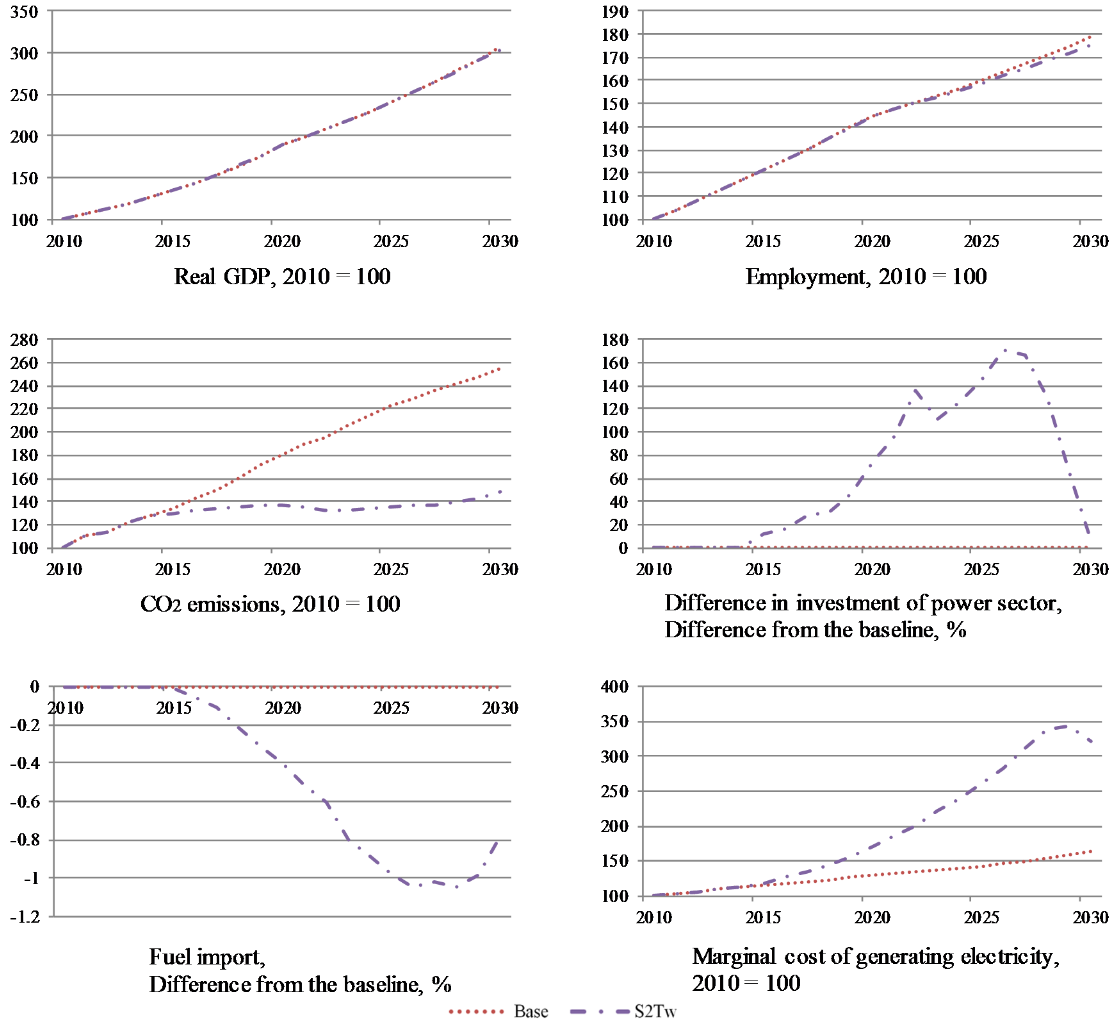

Figure 5.8: Economic and environmental indicators, %, Taiwan

5.5 Simultaneous restriction case in four regions

There are two different kind of effect spilling when the restrictions are implemented simultaneously in all four regions. One is the effect from electricity price. When each restriction is implemented in single region, only that region has to face higher electricity price. Higher electricity would make the products from the region less competitive. If the restriction is put at the same time in all four regions, not only one region but four regions would face higher price at the same time and be more competitive than restriction on a single region.

The other effect is from technology learning. It is assumed that the cost of each technology will decline as its cumulative capacity grows in whole world. When a restriction is implemented at the same time for four regions, restricted technology will have less cumulative capacity leading to higher cost. On the other hand, alternative technologies will get more cumulative capacity but as there are various options for alternative while restricted is a single technology, total cost of producing electricity becomes higher than the scenario with restriction in a single region. This would have negative effect to the economy. Having these two effects, in all regions and all cases, except Japan in S1 and China in S3, simultaneous restriction gives better effect on GDP compared to individual restriction as seen in Table 5.1. This result implies if cooperating with each other, East Asian regions can reduce both the dependence on nuclear power and the dependence on coal-fired power with smaller economic loss or economic benefit from that energy choice.

Table 5.1: Real GDP in 2030 by scenario in each region, difference from baseline, %

	S1, individual	S1, Ea	S2, individual	S2, Ea	S3, individual	S3, Ea
Cn	-0.06	-0.07	0.82	0.80	0.99	0.96
Jp	-0.46	-0.47	0.00	0.00	-0.80	-0.82
Kr	0.10	0.09	-0.26	-0.19	-0.43	-0.38
Tw	-	-0.02	-0.97	-0.83	-	-0.87

note: individual represents each policy is implemented only in the subject region and Ea represents each policy is implemented simultaneously in all four regions

6 Conclusions

The model analysis using FTT:Power and E3ME indicates that in the power sector, phasing out nuclear power plants is likely to result in increases of conventional energy sources and does not contribute much to the diffusion of renewable energy. In contrast, phasing out coal-fired power plants results in significant increases of renewable energy. This is because coal-fired power is a very low cost baseload technology dominating the power sector in each region, leaving little market space for renewable energy technologies. It may thus be not only important to support renewable energy technologies but also to regulate the share of coal-fired power in the power sector to enable renewable energy sources to become the main energy sources.

Decreasing the share of nuclear power does not contribute to increasing the share of renewable energy without additional support and policy such as carbon pricing since most of it is substituted by coal fired power plants, also a baseload technology. Support for further diffusion of low carbon flexible technologies (e.g. gas turbines, coal and or biomass gasification), electricity storage or demand management, may be necessary to enable the further diffusion of renewable energy systems while maintaining grid stability (including by regulating traditional coal).

On the economic side, our model analysis suggests that de-nuclearising power generation in East Asia may not have a large impact to the economy, with GDP decreases less than 0.2% compared to the base line. On the environmental side, it has a negative impact on CO_2 emissions reductions compared to the baseline. The Fukushima Accident revealed risks of severe accidents with nuclear power. Our analysis suggests that this risk can be mitigated with modest economic loss. Decreasing the share of nuclear power however does not lead to increases in shares of renewable energy, even with FIT, without additional support (such as regulations) since most nuclear decommissions become substituted by baseload coal fired plants, the lack of grid flexibility restricting the growth of renewable energy for grid stability reasons.

The regulation of coal fired power can be an effective measure to reduce CO_2 emissions from the power sector, but it can result in a burden to the economy through increased operation costs and prices of electricity, coal being the least cost energy source. Reduced imports of coal, however, have positive effects to the economy for fuel importing regions. If the restriction on coal-fired power plants is implemented in all four regions simultaneously, the negative effect on GDP becomes lower in all four regions, which face in severe international trade competition in which the price of electricity becomes a determinant of comparative competitiveness. Even if the restriction on both nuclear and coal-fired power is implemented, three out of four regions, namely Japan, Korea and Taiwan would get higher GDP than individual implementation of the restriction. The negative impact on competitiveness from reducing nuclear or coal, or both, can be reduced by policy harmonization in East Asia.

In the power sector, reducing coal fired power as a baseload technology creates market space for the diffusion of renewable energy while maintaining grid stability. Renewable energy are significantly more investment and labour intensive compared to coal fired power. Investments and up-scaling costs of renewable energy can spill over across sectors of the economy, which, unlike fossil fuel costs, can significantly benefit the economy.

Appendix: The E3ME-Asia Model

E3ME is a global E3 model, covering the world's economic and energy systems and the environment. The acronym stands for 'Energy-Environment-Economy Model that is Econometric in design'. It was originally developed through the European Commission's research framework programmes and is now widely used for policy assessment, forecasting and other research purposes. A brief description is provided here; for further details the reader should refer to the model website[8], which includes an electronic version of the full manual (Cambridge Econometrics [2014]).

The current version of E3ME, E3ME-Asia was finalized in early 2014 by the collaboration work with Cambridge Econometrics in UK and East Asia Environmental Policy Study Group (REEPS) in Japan includes explicit coverage of the following East Asian countries to carry out in-depth analysis of these countries:

- China
- Japan
- Korea
- Taiwan

The ASEAN countries are included as a single region in the model, with the exception of Indonesia, which is modelled separately. Other major economies are covered explicitly and the remaining countries are grouped into regions to give complete global coverage.

The model includes a complete historical database with annual data going back to 1970 and can project forward annually to 2050, although a shorter time horizon is usually more relevant for policy makers. A key feature of E3ME is its relatively high level of disaggregation. Aside from the geographical classification, the main dimensions of E3ME are:

- 43 industry sectors, based on standard international classifications
- 28 categories of household expenditure
- 22 different users of 12 different fuel types
- 14 types of air-borne emission (where data are available)

These dimensions represent the different characteristics (e.g. cost patterns, energy usage, trade ratios) of different parts of the economy.

The main data sources for European countries are Eurostat and the IEA, supplemented by the OECD's STAN database and other sources where appropriate. For regions outside Europe, additional sources for data include the UN, OECD, World Bank, IMF, ILO and national statistics.

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8 www.e3me.com

Gaps in the data are estimated using customised software algorithms. The main data sources for the East Asian countries are:

- Asian Development Bank (main economic variables)
- OECD Statistics (economic data, sectoral breakdowns)
- WIOD (economic data, sectoral breakdowns, IO tables)
- National Statistics Offices (economic data, sectoral breakdowns)
- International Labour Organisation (labour force)
- World Bank (population, macroeconomic data)
- UN (exchange rates, macroeconomic data)
- IEA (energy balances and prices)
- EDGAR (emissions data)

Figure A.1 shows the basic structure of the model and the linkages between the three E's. The economic structure of E3ME is based on the system of national accounts (see Figure A.2), as defined by European Communities et al [2009], with further linkages to labor markets. There are econometric equations for the components of GDP (consumption, investment, and international trade), prices, and labor demand and supply. Each equation set is disaggregated by country/region and by sector. Formal definitions of the equations are provided in the model manual (Cambridge Econometrics [2014]). The sectors are linked by using input-output tables and the countries are linked through the model's trade equations.

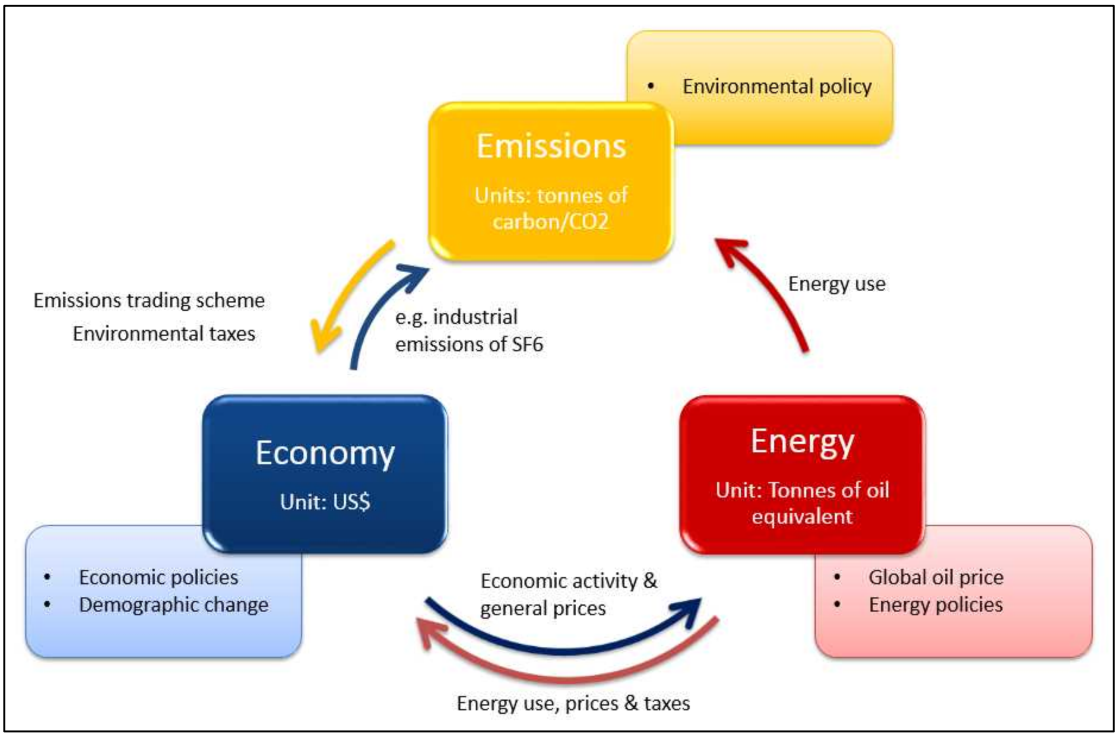

Figure A.1: Basic structure of the model and the linkages between the three E's

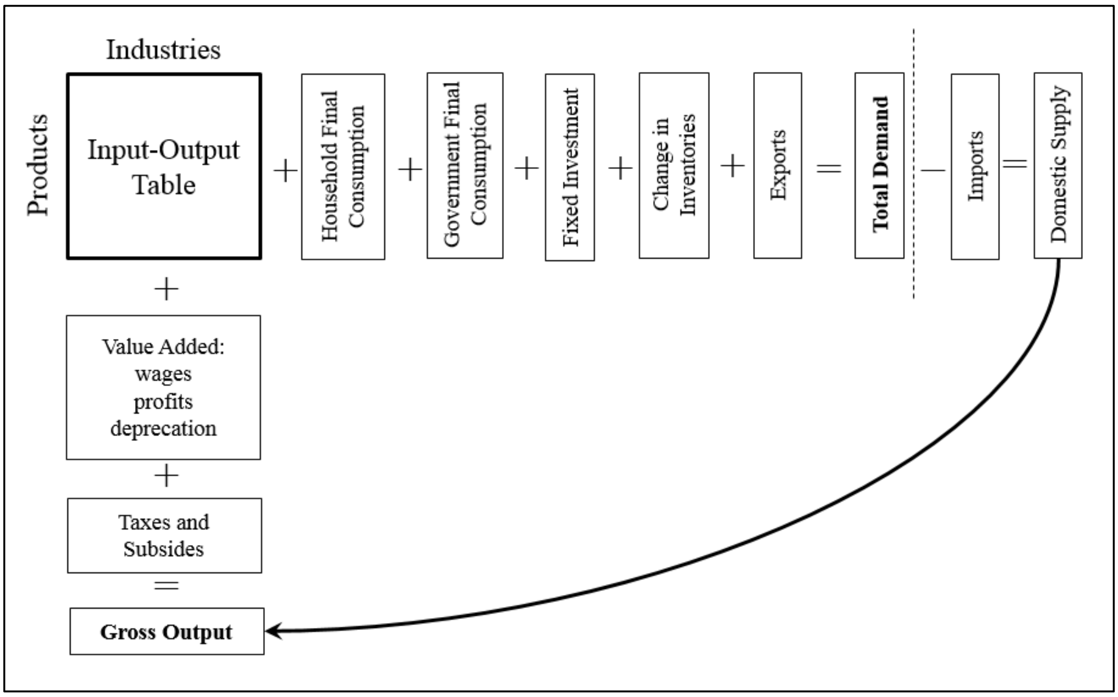

Figure A.2: System of national accounts in E3ME

Energy demand is determined in the model as a function of economic activity, prices and the state of technology. The model solves first for aggregate energy demand and then for individual fuels.

This sequence makes it possible to incorporate in the model changes of fuel type within a sector. Fuel demands feed back to the economy via the energy supplying and extraction sectors.

The model's representation of the power sector includes a representation of specific conventional and renewable technologies. As the power sector is an important source of emissions in East Asia (and most other parts of the world), this is a very important part of the model. It is described in much more detail and applied in Chapters 3-4 of this book.

CO_2 emissions from fuel consumption are determined by using fixed coefficients. The model outputs also include CO_2 emissions from industrial processes and calculations of other CO_2 emissions resulting from fuel consumption. However, other GHG emissions from agriculture, waste or changes in land use lie beyond the scope of E3ME and so are not covered by the model.

E3ME includes measures of technological progress that are defined at the sectoral and national/regional level. There are various different ways of measuring technology in macroeconomic models (see Bosetti and Galeotti [2009] for a discussion); in E3ME the formulation is based on accumulated capital, with an adjustment for R&D expenditure. Advances in technology may lead to improvements in efficiency (price competitiveness) or a higher quality of output (non-price competitiveness). Other modelling approaches also measure technological progress, because the consequences of new technologies can have a considerable influence on the overall costs and benefits of climate policy (Barker and Jenkins [2007]).

Behavioral relationships in E3ME (e.g. price elasticities) are estimated by econometric equations. The techniques used to specify the functional form of the equations are the concepts of cointegration and error-correction methodology, particularly as promoted by Engle and Granger [1987] and Hendry et al [1984]. Essentially this method allows the model to assess both the initial response to a shock and the gradual transition to a long-term outcome. Estimated variables are 29, most of them having two dimensions (e.g. there are 43 industry sectors and 53 regions). Overall this version of E3ME includes up to 47,000 individual estimated equations, excluding bilateral trade.

Demand for industrial goods consists of 5 components, intermediate demand, household consumption, government consumption, investment and international trade. Government consumption is given by assumption and other components are estimated by econometric equations. Intermediate demand, which is the sum of demand from other production sectors, is determined by the input-output relationships in the model. Further information about the model equations is provided in Chapter 8 of the model manual (Cambridge Econometrics [2014]).

E3ME is used to assess policy through a scenario-based approach, which can either be forward looking (*ex ante*) or a representation of a past that might have been, but was not (*ex post*). The analysis in this book is mostly *ex ante* and the starting point is a baseline case (often called "business as usual") that is based on current policy. Additional policy inputs are then entered for each scenario and the model outputs from the scenario are compared to those from the baseline. In this way the effects of the policy are identified. Typical model outputs include:

- GDP and the aggregate components of GDP (household expenditure, investment, government expenditure and international trade)
- sectoral output and Gross Value Added, prices, trade and competitiveness effects
- international trade by sector, origin and destination
- consumer prices and expenditures
- sectoral employment, unemployment, sectoral wage rates and labour supply
- real incomes by socio-economic group (where data are available)
- energy demand, by sector and by fuel, energy prices
- CO_2 emissions by sector and by fuel
- other GHG and air-borne emissions

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