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Feasibility Study of the Post-2020 Commitment to the Power Generation Sector in South Korea

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Abstract: We analyze the economic effects of greenhouse gases (GHG) reduction measures of the generation sector of South Korea to accomplish the 2030 GHG reduction target using a scenario-based approach. We estimate the GHG emission of the South Korean power industry in 2030 based on both the 7th Electricity Supply and Demand Plan and the GHG emission coefficients issued by the International Atomic Energy Agency (IAEA). We establish four scenarios for reduction measures by replacing the coal-fired power plants with nuclear power, renewable energy and carbon capture and storage, and liquefied natural gas (LNG) combined cycle generation. Finally, the nuclear power scenario demonstrates the most positive measure in terms of GHG reduction and economic effects.

Keywords: post-2020; climate change; GHG reduction; the 7th electricity supply and demand plan; GHG emission coefficients; economic effects

1. Introduction

According to the IPCC (Intergovernmental Panel on Climate Change) Report Volume 5, greenhouse gases (GHG) from human activities had increased the average global temperature by 0.85 °C from 1880 to 2012. Furthermore, GHG emissions will raise the global temperature by 3.7 °C at the end of the century without abatement measures. Assuming Business As Usual (BAU) is kept as the projection, the official target from the 16th Conference of the Parties, which is to restrain the increase of the average global temperature by 2 °C until 2050, seems highly impossible in reality, recommending international involvement with aggressive GHG reduction policies.

The previous international attempts of GHG reduction had a serious limitation in terms of its effectiveness because China and the United States, the first and second largest GHG emitters, did not participate in GHG reduction activities from the promises of the Kyoto Protocol [1]. However, the Post-2020 Climate Change Mitigation Commitments require submissions of Intended National Determined Contributions (INDC), including China and the United States, unlike Kyoto Protocol. On 30 July 2015, South Korea announced its INDC as 37% of the reduction from the BAU in 2030. Recently, the Act on Allocation and Trading of Greenhouse Gas Emissions Allowances was passed in Korea's National Assembly and, by 2015, the Greenhouse Gas Emission Trading Scheme will be implemented.

The INDC of South Korea states a 25.7% reduction in domestic emissions and an 11.3% purchase from the international carbon market mechanism from the BAU for the year 2030 in order to accomplish the total of 37% in 2030. This means any industry sector, emitting large amounts of GHG, will anticipate a more intensive reduction quota. In 2011, the GHG emission of the generation sector in South Korea was estimated as 251.5 million tons which accounted for 36.7% of the national emission amount of 685.7 million tons. In addition, the major government-owned thermal power generators emitted 30.2% (206.8 million tons) in the generation sector, suggesting an intensive GHG reduction quota in the generation sector is inevitable to achieve the 2030 national reduction target. The International Energy Agency (IEA) considers de-carbonization in power generation as the most important measure for achieving the GHG reduction target of the year 2050, as followed by reduction in sectors of industry, transport, and construction in the order of significance [2]. In addition, the IEA considers renewable energy, carbon capture and storage (CCS), nuclear power, energy efficiency, and fuel switching as the major technologies for GHG reduction in the generation sector (Figure 1).

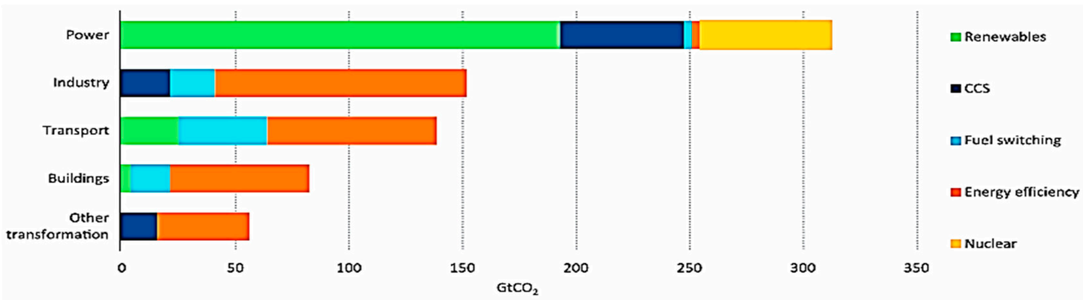

Figure 1. Cumulative CO_2 reduction by technology in two degrees by 2050. Source: International Energy Agency (IEA) [2].

In order to analyze the economic effects of the Post-2020 Climate Change Mitigation Commitments from the generation sector's perspective, we conduct modeling and empirical analysis in our study. As shown in Figure 2, we first aim to calculate the excess GHG emission amount that must be reduced to achieve the national reduction target of year 2030. In order to do that, we analyze the INDC of South Korea and the reference documents and find the required GHG reduction target of the generation sector in 2030. Then, we used the Wien Systematic System Planning (WASP) model (Wien Systematic System Planning (WASP) model: the IAEA's comprehensive planning tool that permits finding the optimal facility expansion plan for a power generating system over a period of thirty years by evaluating the optimum in terms of minimum discounted total costs) to find the optimal generation for the year 2030, which can also be applied to determine the projected GHG emission volume of the generation sector in 2030.

Consequently, we calculate the excess GHG emission amount by comparing the GHG reduction target of the generation sector in 2030 with our projected GHG emission of the generation sector in 2030 derived from the WASP model. By applying the standard emission coefficient of GHG to the calculated excess GHG emission volume, we are able to determine the generation amount of the coal-fired plant that must be replaced in order to achieve the national GHG emission reduction target of the generation sector in 2030.

Therefore, we set up four scenarios, including nuclear, renewable energy, and CCS, to replace the coal-fired plant, as shown in Figure 2. We used modeling by applying specifications for the reference power plant for each scenario to calculate the equivalence of the generation amount from the coal-fired plant, which satisfies the GHG reduction target of 2030. Then, we calculate the economic effects and impacts on the wholesale electricity price of each scenario to attain comparative analysis results.

We calculate the required GHG reduction quantities based on the 7th Electricity Supply and Demand Plan to achieve the national target of the INDC and provide the quantitative economic effects from the GHG reduction using the scenario analysis approach.

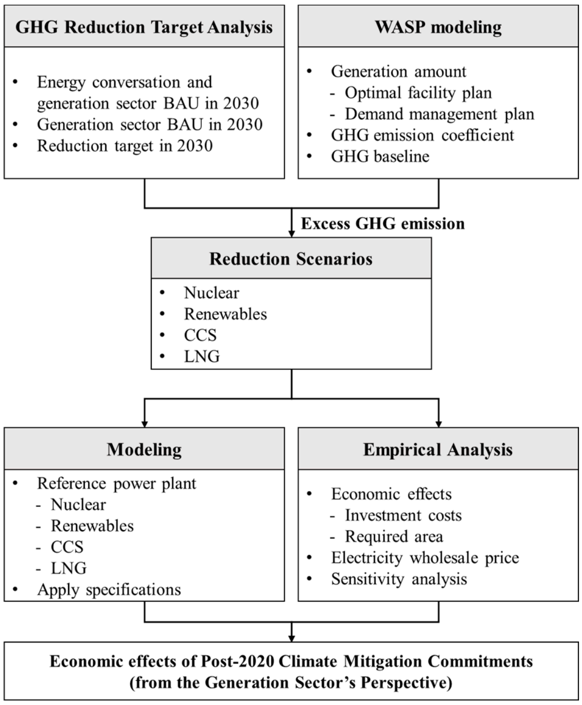

Figure 2. Analysis process for the economic effects of Post-2020 climate change.

2. Previous Research

According to the study on the roadmap policy and alternatives for the South Korean GHG reduction by Lee et al. [3], they demonstrate the reduction measures for the energy conversion and generation sector, which is composed of generation, city gas, and district heating sectors, will cause the most negative impacts on the South Korean macro economy. The impacts are estimated as a 4.96% decrease in the real output, a 5.05% decrease in the real gross domestic product (GDP), and a 4.96% decrease in employment relative to BAU in 2020. They also claim minimizing negative impacts on the macro economy is particularly important as the technologies, such as innovation in renewables, improvement in generation efficiency, and GHG management technology, are expected to be implemented as the reduction measures. Lee et al. [3] also examines the reduction measures in the energy conversion and generation sector and suggests demand management policy enhancement, renewable energy increase, intelligent demand management expansion, and leading technology development for alternatives. Among these solutions, KEI regards renewable energy increases and leading technology development as the major alternatives, along with demand management (Table 1).

Table 1. Alternatives of the energy conversion and generation sector.

Alternative	Description
Demand Management Policy Enhancement	• Rationalize energy price structure • Normalize electricity fare, reflecting environmental and social costs, and expand application of demand managed electricity fare system
Renewable Energy Increase	• Enforce and expand Renewable Portfolio Standards (RPS)
Intelligent Demand Management Expansion	• Apply smart-grid technology • Expand EMS (Energy Management System)
Leading Technology Development	• Develop source and core technology for CCS plant • Develop leading technology via examinations

Source: Lee et al. [3].

In addition, the Dong-Woon Noh [4] also emphasizes GHG reduction in the generation sector in order to achieve national GHG reductions and sustain economic growth. According to Dong-Woon Noh [4], GHG reduction in the generation sector is not only cost-effective, but also coincides with the national policy that is currently being implemented as a response to climate change. In terms of reduction measures, Dong-Woon Noh [4] also suggest enforcing the Renewable Energy Portfolio Standard (RPS) and the rationalization of an energy price structure which would deliver the impact of increased costs from GHG reduction measures to the consumers of electricity. Although a carbon tax may be appealing as a GHG emission restraint, it is not encouraged by Dong-Woon Noh [4] since it would significantly increase the financial burden to the industry. Therefore, technology development for low-carbon generation is fundamentally needed in order to reduce GHG emission by replacing the current coal-fired plants with stronger governmental supports.

On Dae-Gyun Oh [5], which accounts for GHG reduction technology in thermal power plants and development in renewables as suggested in the 6th Electricity Supply and Demand Plan, eight technology categories were selected for analysis as the applicable technologies to the generation sector. For thermal power plants, technology development of CCS, ultra-super critical boiler, high-efficiency gas turbine, and integrated gasification combined cycle are considered for implementation to reduce GHG emissions, while technological improvements in fuel cell, biomass, wind, and photovoltaic power are also reviewed to partially replace the current thermal power plants. While the reduction target of the generation sector was 26.7% in 2020, the projected GHG reduction was estimated as 3.44% to 4.79% in 2020 based on the reduction roadmap plan. Since the projected GHG reduction in 2020 is far lower than the target of 26.7% in the generation sector, this result suggests that the reduction target of the generation sector is highly difficult to achieve solely with technical attempts (Figure 3).

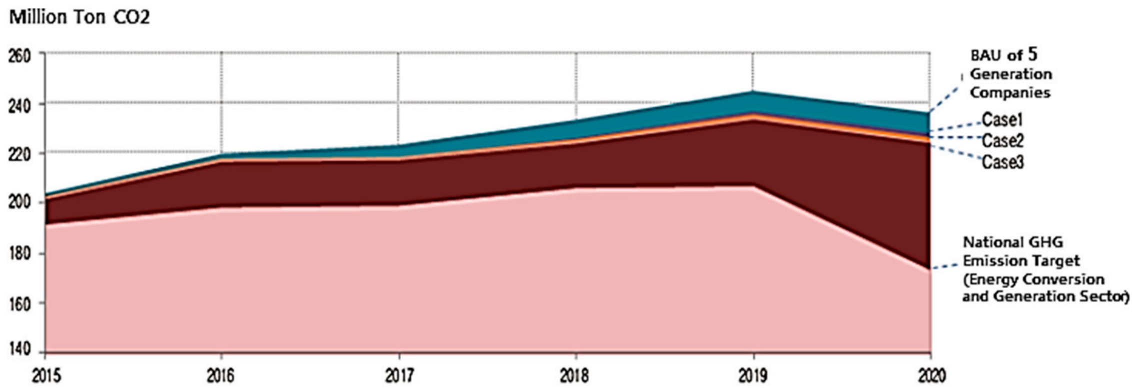

Figure 3. Comparison of reduction quantity by scenario and national target. Source: Dae-Gyun Oh [5].

Various previous studies have been conducted to analyze the potential of the environmental policies or the low-carbon scenarios from the system perspective, but they have not considered the effects of the alternative energy adoption from the system perspective. Alderson et al. [6] analyzed energy saving scenario for the United Kingdom (UK) by 2050, deriving that the GHG emissions reduction could be achieved at 46% by 2030. Ashina et al. [7] studied the future low-carbon society road map in Japan and showed that the CO_2 emissions reduction rate would reach 31%–35% by 2030. Hu et al. [8] analyzed the successful cases of low-carbon economic planning in China for the last 30 years; as a result China would achieve 16.55 billion tons of CO_2 emissions reduction, as well as 4.38 billion tons of oil-equivalent energy savings by 2030. Additionally, some of the quantitative national level GHG reduction studies that have been carried out include Gomi et al. [9], Kainuma et al. [10], Nakata et al. [11], Shrestha et al. [12], Shrestha and Shakya [13], and Winyuchakrit et al. [14]. There have been conceptual and analytical models presented in international journals that have been very useful for country-level implementation of low carbon measures and assessments.

The results of the previous studies validate that the generation sector holds a critical role in GHG reduction. Therefore, we analyze the impacts of the national GHG reduction measures for the Post-2020 Climate Change Mitigation Commitment on the generation sector and South Korean macro economy based on the recent governmental policies, which include National GHG Reduction Roadmap [15], released in 2014, and the 7th Electricity Supply and Demand Plan, released in 2015.

Yang et al. [16] suggested the optimization model to evaluate how appropriately the 2050 target emission quantities established in California were matched with those under the Post-2020 climate change regime formation. The forte of this model encompassed the limit of technology, costs, and even the policy-oriented characteristics. The authors emphasized the effects of introducing renewable energy and CCS. The adoption of CCS was especially instrumental in reducing GHG.

Muis et al. [17] developed a methodology to draw a portfolio of electricity generation sources per nation. In a bid to reduce GHG up to 50%, compared with the current emission, it was essential to introduce new generation technologies rather than the existing fossil fuel generation, such as integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), nuclear power, and biomass from landfill gas, palm oil residues, and the like.

Mustafa Ozcan [18] performed the research to estimate electricity generation, GHG emission, costs incurred from the carbon tax per each generation source from 2013 to 2017. He asserted, in order to reduce GHG, renewables and nuclear power were efficient measures to generate electricity. However, so as to use nuclear power as a generation source, a couple of factors of concern, such as various hazards, and hurdles by Non-Governmental Organizations (NGOs), should be considered.

Lee et al. [19] developed a numerical model of reducing GHG in South Korea for power expansion planning to support various environmental policies. The authors identified 36% of GHG could be reduced far over 30% of the 2020 reduction target. In addition, considering only the domestic economic situation, nuclear power was one of the favorable alternatives. However, they both focused on hazards of the nuclear power and insisted more a supplemented power expansion planning allowing for renewable policies.

To date, the cost incurred from severe accidents of nuclear power plants, like that of the Fukushima event, is not included in the generation cost when the government established the electricity supply and demand plan. Regardless of the scale of accidents, those potential costs should be considered since nobody can deny the possibility of accidents of nuclear power plants.

The Fukushima accident demonstrates the external costs of nuclear power plants would be higher than those of the existing evaluation to date.

In this research, we analyze a number of precedent references and quantify a reasonable nuclear accident cost appropriately customized for the South Korean situation.

Hence, we apply the major alternatives for GHG reduction to the analysis scenarios of our study and comply with the demand management of the generation sector from the 7th Electricity Supply and Demand Plan.

Additionally, the sustainability of the generation technology should be considered over the long-term. In general, sustainability refers to the integration of three issues, i.e., including economic, environmental, and social approaches [20,21]. Sustainable development is also defined as "development that meets the needs of the present benefit without compromising the ability of future generations to meet their own needs" [22,23]. Li, Geng and Li [24] compared and analyzed various studies on aspects of sustainability for a variety of energy conversion systems. Three-quarters of the quantities of CO_2 emission has been from the energy generation system using fossil fuel, which is the main factor producing GHG emissions. However, in order to avoid this environmental hazard, abruptly changing the current energy infrastructure is not an efficient approach to secure economic energy production. Hence, it is essential to perform R and D with regard to the energy system from the long-term perspective [24].

3. Methodology

3.1. Establishing the Baseline of GHG Emission Using WASP Model

In order to maintain consistency with the ongoing energy policy of South Korea, we refer to the 7th Electricity Supply and Demand Plan [15] to estimate the baseline of the GHG emission of the year 2030 for the generation sector, the major features of which focus on the low carbon energy mix; firstly, the four pre-arranged coal-fired power plants are excluded due to their high GHG emissions, the result of which eventually decreases the ratio of the coal-fired power plants. Policy planners reached an agreement that these excluded plants will be replaced with two new 1500 MW nuclear power plants. Secondly, the facility capacities of the renewable energy are expected to be up to 33,890 MW and its portion will be 11% in 2035. Finally, the active demand management plan is fortified in connection with the energy efficiency and information technology.

For the purpose of establishing the baseline of the 2030 GHG emission volume, we make use of the WASP model in which the International Atomic Energy Agency (IAEA) has distributed to estimate the electricity generation quantities. We anticipate the emission volume using the standard emission coefficient issued by the IAEA [25] in Table 2.

Table 2. Emission coefficient. (Unit: g-CO_2/kWh).

Classification	Coal	LNG	Oil	Nuclear	Renewables
Coefficient	991	549	782	10	-

Source: IAEA (2006) [25].

3.2. Scenario Composition

Since a detailed plan to reduce the emission volume for each generation sector is not determined yet, we assume a 95% emission volume of the energy conversion and generation sector as that of the only generation sector. Comparing the GHG reduction target of the Post-2020 Climate Change Mitigation Commitments with that of the generation quantities following the 7th Electricity Supply and Demand Plan, we estimate the additional reduction volume from the simulation using the WASP model. We decided to replace the coal-fired power plants to reduce the estimated additional emission volume as the main scenario in Table 3. As the IEA [1] considers nuclear power, renewables, and CCS as the three main technologies to reduce GHG, we also set those technologies as the alternatives to the coal-fired power plants. In addition, not as a totally carbon-free technology but as an efficient carbon capture technology, IGCC could be in the limelight as an alternative to reduce GHG. IGCC is the technology reducing GHG to the level of GHG emission level of LNG (liquefied natural gas). Since IGCC is still a premature technology which is not worthy of replacing high-capacity coal power plants, we exclude it from this study. In the current stage, LNG combined cycle technology can be considered as one of the practical base load technologies to replace coal power technology. Not only has this technology a significant low carbon emission compared with coal and oil power technology, but it also has a carbon emission coefficient that is almost similar to the IGCC technology. From the economic perspective, the price of LNG will plummet up to 75% in 2025 by the production increase of shale gas [26]. For those reasons, we add the LNG combined cycle technology as an alternative of coal power technology.

- Scenario 1: replacing the coal-fired power plants with nuclear power plants
- Scenario 2: replacing the coal-fired power plants with renewable energy
- Scenario 3: installing CCS to the existing coal-fired power plants
- Scenario 4: replacing the coal-fired power plants with LNG combined cycle power plants

Table 3. Main factors impacting the wholesale price per scenario.

Main Factor	Reasons Chosen as the Main Factor	Effects on the Wholesale Price
Generation Sources	Scenario 1 Replacing the coal power with low-carbon technology Scenario 2 Replacing the coal power with renewable energy: carbon-free technology Scenario 3 Install CCS to the existing coal power plants: good effects of GHG abatement Scenario 4 Replacing the coal power with LNG combined cycle power: carbon reduction technology	Change of wholesale prices per each generation technology
Investment Costs	Different investment costs per scenario	The effect on the wholesale price = investment costs of each scenario/the total generation quantities in 2030
GHG Emission Prices	Decrease of GHG purchasing costs per scenario	Decrease of GHG purchasing costs = The GHG price in 2030 × the decreasing quantities/the total generation quantities in 2030

4. Analysis and Estimation of Input Data

The main objective of this study is to perform comparative analysis regarding investment costs, necessary land size, and wholesale price as the economic effects.

First of all, we estimate investment costs for the replacement of coal-fired power plants with other alternatives using Equation (1):

$$Investment\ costs\ (\$) = Alternative\ capacities\ (\mathrm{MW}) \times Unit\ cost\ of\ alternative\ (\$/\mathrm{MW}) \quad (1)$$

In regards with new nuclear power technologies, the construction cost in South Korea is well below that of other major countries with the exception of China. The reasons embrace multiple factors; firstly, the economies of scale, such as savings from administration costs, site selection costs, and regulatory costs due to multiple units gathered in one site; secondly, construction capability, lessons learned from repeated construction; and finally, refined supply chain. The information on the construction costs of major countries are delineated in Table 4 [27]. According to D'haeseleer [28], constructing new nuclear power plants in the EU is very much capital intensive and generation costs are as good as other countries. On the other hand, he mentioned that recent repetitive construction of nuclear power plants in the EU showed a learning effect, serial effect, fleet effect, and economies of scale which could be a factor to decrease construction and generation costs.

Table 4. Construction cost of nuclear power plants.

Country	Technology	Capacity (MWe)	Overnight Cost (USD/kW)	Total Investment Cost (USD/kW)
Belgium	EPR	1600	5383	6185
China	CPR1000	1000	1763	1946
	CPR1000	1000	1748	1931
	AP1000	1250	2302	2542
South Korea	APR+	1500	1959	2254
France	EPR	1630	3860	4483
Germany	PWR	1600	4102	4599
Hungary	PWR	1120	5198	5632
Japan	ABWR	1330	3009	3430
Netherlands	PWR	1650	5105	5709
Slovak Republic	VVER	954	4261	4874
Switzerland	PWR	1600	5863	6988
	PWR	1530	4043	4758
United States	Adv. Gen3+	1350	3382	3814
Russia	VVER	1070	2933	3238

Source: International Energy Agency (IEA) [27], Ministry of Trade, Industry and Energy (MOTIE) [15].

Where we use the concept of overnight costs for the investment costs in 2030 and the GHG price for the year 2030 is estimated as \$13.48/ton-CO_2 on the basis of the historical GDP rate and price ranges during January to August of 2015 in the Korea Power Exchange in which the GHG rights are traded.

For the calculation of the necessary land size, we follow the NEI report [29] for each generation technology (Table 5).

Table 5. Necessary land size. (Unit: km^2/MW).

Classification	Nuclear	Wind	Solar
Capacity	1000 MW	1000 MW	1000 MW
Capacity Factor	90%	32%–47%	17%–28%
Necessary Land Size	0.0034	0.803	0.155

Source: Nuclear Energy Institute (NEI) [29].

To estimate the effects on the electricity wholesale price, we use the real data from 2001 to 2014 and draw an annual increasing rate of wholesale price to anticipate a selling price of each generation technology to the Korea Power Exchange in 2030.

$$\frac{\Delta P}{P} = LN\left(\frac{P_{t+1}}{P_t}\right) \tag{2}$$

where $\Delta P/P$ is an annual increasing rate, P_{t+1} is the wholesale price of the year $t+1$, and P_t is the wholesale price of the year t. We assume the annual increasing rate follows the function of the natural logarithm to reflect the general economic phenomena which explain the asymptotical increase of the commodity prices (Table 6).

Table 6. Wholesale prices from 2001 to 2014.

Classification	Wholesale Price (\$ [a]/MWh)				Annual Increasing Rate (%)
	2001	2005	2010	2014	
Nuclear	33.46	33.00	33.43	46.31	0.98 [b]
Coal	35.66	37.09	52.96	55.82	3.45
Oil	62.00	78.29	155.78	186.71	8.48
Gas	74.08	73.54	108.08	135.78	4.66
Pump storage	62.38	91.38	170.98	144.84	6.48
Renewables	48.95	58.55	99.00	109.47	6.19

[a] The exchange rate of 1085 KRW/\$ is applied in this study; [b] In the case of the nuclear power plant, we apply one third of the average price index for the past three years since the selling price of nuclear power plant to the Korea Power Exchange is regulated by the government. We found from the price history that the increasing rate of the selling price of the nuclear power is normally under one percent per each year.

With an estimated selling price of each generation technology including the impacts of the increase of investment costs, a price of GHG emission, we calculate the increased average wholesale price per each scenario. We are able to infer the economic insights of the increased wholesale price in the case of each scenario.

By dividing the investment costs per each scenario with the total generation quantities in 2030, we estimate variations of the wholesale price in which the positive effects of the decreased GHG effects are considered as well:

$$P(2030)_i = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} Q_i} \tag{3}$$

where $P(2030)_i$ is the wholesale price in 2030, C_i is investment costs of each scenario, and Q_i is the generation quantity of each generation technology.

Risks of severe nuclear accidents are reflected with reference cases considering the domestic situation. According to the Second Energy Basic Plan [30], accident and policy costs are applied \$0.0015 to \$0.0049/kWh. In addition, the representative research in South Korea [31] demonstrated that accident response and policy costs as additive costs ranged from \$0.0034 to \$0.0538/kWh.

D'fhaeseleer [28] suggested that external costs from the normal operation in Europe were in the range of 1 to 4 €(2012)/MWh (\$0.0013–\$0.0051/kWh). This result was well below that compared with other generation technologies. The external costs of the severe accidents are on average 1 €(2012)/MWh (\$0.0013/kWh), with a minimum of 0.3 €2012/MWh (\$0.0004/kWh) and a maximum of 3 €(2012)/MWh (\$0.0039/kWh).

Preiss et al. [32] estimated the external cost of a nuclear power plant in a normal operation was in the range of 3–3.5 €(2010)/MWh (\$0.40–\$0.46/kWh). Furthermore, external costs of coal power plants influencing the environment and humans were 40 €(2010)/MWh (\$0.0531/kWh), those of gas power plants were 20 €(2010)/MWh (\$0.0265/kWh), those of photovoltaic power plants were 10 €(2010)/MWh (\$0.0133/kWh), and those of wind power plants were 2 €(2010)/MWh (\$0.0027/kWh). Excluding wind power, the external costs of all of the power plants were estimated higher than for nuclear power. Preiss et al. [32] also estimated the external costs of the severe accidents of nuclear power plants. The external costs were drawn by an accident grade from minimum 0.13 €(2010)/MWh (\$0.00017/kWh) to 0.15 €(2010)/MWh (\$0.0002/kWh), the total external costs were 0.23 €(2010)/MWh (\$0.00031/kWh).

Lévêque [33,34] assumed accident costs of nuclear power plants were 430 billion €, yearly generation quantities, 10 TWh, the frequency of accidents, 2×10^{-5}/reactor-year on the basis of core damage accidents only among various past accidents. Under these assumptions, the external costs were estimated 0.86 €/MWh (\$0.0011/kWh).

Rabl and Rabl [35] quantified the external costs of nuclear power including core loss, transmission and distribution losses, cancer, crop damages, refugees following serious accidents, and purification of the surroundings. In addition, accident damage costs were presumed to be 360 billion € (2010) and the accident probabilities one accident per 25 years in a periodic manner with the combination of Chernobyl and Fukushima accidents. As a result, the external costs were drawn at 3.8 €(2010)/MWh (\$0.0050/kWh) at the median, 0.8 €(2010)/MWh (\$0.0011/kWh) at the minimum, and 22.9 €(2010)/MWh (\$0.0304/kWh) at the maximum.

According to Ludivine and Patrick [36], the technology institute supporting the French Nuclear Safety Authority divided the nuclear accident into two categories; severe accidents and major accidents. The costs from severe accidents and major accidents were 120 billion € (2010) and 430 billion € (2010) respectively. The probability of nuclear accidents applied a large early release frequency of radioactive materials suggested by IAEA Safety standard [1]. With the large early release frequency, 10^{-5}/reactor year, of the third generation were applied, the external costs were estimated at 0.12–0.43 €/MWh (\$0.00016–\$0.00057/kWh). In the more conservative frequency, 10^{-4}/reactor year, the external costs were estimated at 1.2–4.3 €/MWh (\$0.0016–\$0.0057/kWh).

In Japan, both the Accident Costs Validation Committee and the Operation Costs Validation Committee drew generation costs and accident response costs based on the Fukushima accident (see Table 7).

Table 7. Comparison of generation cost estimate.

Classification	Accident Costs Validation Committee (2011)	the Operation Costs Validation Committee (2015)
Damage costs	5.8 trillion ¥	9.1 trillion ¥
Probability of Accident	1 time/2000 reactor·year	1 time/4000 reactor·year
Cost estimation	0.5 ¥/kWh (\$0.0063/kWh)	0.3 ¥/kWh (\$0.0038/kWh)

From reviewing many case studies, we reached the conclusion that the external costs applied in South Korea are similar to the $0.0049/kWh being used in Europe, which was estimated by William D'fhaeseleer [28]. Hence, we use $0.0049/kWh as the benchmark cost of severe accidents and analyze the various economic effects in the end.

5. Empirical Analysis

5.1. GHG Emission Baseline of the Generation Sector

We estimated the total electricity generation in the year 2030 to be 724,823 GWh by applying the optimal facility plan derived from the WASP model, which takes account of load, existing facilities, planned facilities, and operation costs of the 7th Electricity Supply and Demand Plan [15]. Accordingly, we calculate the GHG emission baseline of the generation sector by multiplying the GHG emission coefficient of the IAEA to our projected total generation in 2030. Thus, the GHG emission baseline is 266 million tons and the coal-fired power plants are responsible for 95% of the 266 million tons by emitting 253 million tons of GHG (Table 8) [25].

Table 8. Electricity generation and greenhouse gas (GHG) emissions in 2030.

Classification	Generation (GWh)	GHG Emission (Million Tons)
Nuclear	290,397	2.9
Coal	255,505	253
Oil	4,434	3.5
Gas	11,693	6.4
Hydro	37,964	-
Renewable	55,188	-
Others	69,642	-
Total	724,823	266

Despite the submitted INDC with the 37% reduction target, the detailed reduction plan is not yet determined for the generation sector for the year 2030. Therefore, we set the difference between the emission volumes by the BAU and our projected base line in 2030 as a standard to calculate excess GHG emission amounts of the generation sector.

5.2. Scenarios for Reduction Measures of the Generation Sector

The forecasted national GHG emission in the year 2030 is 850.6 million tons based on Post-2020 Climate Change Mitigation Commitment. Out of a total of 850.6 million tons, the energy conversion and generation sector will emit 333.1 million tons in 2030. We assume that the generation sector emits 95% of emissions from the energy conversion and generation sector. The BAU-based emission volume of the generation sector is 316.4 million tons, which is the permitted emission level for the generation sector according to the INDC of South Korea in 2030 (Table 9).

Table 9. GHG emission (BAU) projection of the generation industry.

Year	National (Million Tons)	Energy Conversion and Generation Sector (Million Tons)	Generation Sector (Million Tons)
2013	679.8	233.4	221.7
2020	782.5	295.5	280.7
2025	809.7	303.9	288.7
2030	850.6	333.1	316.4

When we apply a 20% reduction target to the BAU based emission volume in the generation sector in 2030, the targeted emission volume of the generation sector is 253.2 million tons. By comparing with our GHG emission baseline of the generation sector, 266 million tons, the difference is 12.8 million tons of excessive emissions that need to be reduced in order to achieve the reduction target (Table 10).

Table 10. Excess GHG emission of the generation sector in 2030.

Classification	GHG Emission (Million Tons)
Reduced BAU	253.2
Base line emission	266.0
Excess GHG emission	+ 12.8

Since the coal fired power plants emits 95% of the generation sector, we assign the excess of 12.8 million tons to replace the coal-fired power plants. While this excessive 12.8 million tons of GHG is equivalent to 12,957 GWh from the coal-fired power plants, as shown by Equation (4), this excessive emission is equivalent to 2.1 units of 800 MW coal-fired power plants which needs to be replaced (Table 11).

$$C_r = \frac{GHG_{exess}}{C_{cof.}} = \frac{12.8\,\text{Million ton}}{991\,\text{g} - \text{CO}_2/\text{kWh}} = 12,957\,\text{GWh} \tag{4}$$

where C_r is the generation from the coal-fired power plant for replacement, GHG_{excess} is excess GHG emission amount, and $C_{Cof.}$ is a GHG emission coefficient of coal.

Table 11. Coal fired power plant specifications.

Capacity	800 MW
Capacity factor	90%
Generation	6307 GWh
GHG emission coefficient	991 g-CO_2/kWh
GHG emission	6.3 million tons

In order to replace 2.1 units of 800 MW coal fired power plant, we set four scenarios by the reduction measures as nuclear, renewables, CCS, and LNG combined-cycle power, which are also the alternatives suggested by IEA.

5.3. Results of Scenario Analysis by Reduction Measures

5.3.1. Scenario 1: Replacing the Coal Fired Power Plants with Nuclear Power

As described in Equation (5), the generation from 1.2 units of the nuclear power plant is equivalent to 12,957 GWh from the coal fired power plant as shown in Table 12. However, a single nuclear power plant is constructed in a pair according to its fundamental design, meaning two nuclear power units are required instead of 1.2 units. Therefore, two nuclear power units generate 22,338 GWh, which is also capable of replacing an additional 9381 GWh from the coal fired power plant, reducing additional 9.3 million tons of GHG. In total, Scenario 1 is able to reduce 22.1 million tons of GHG. Accordingly, the investment costs of two nuclear power units is $6 billion based on the 7th Electricity Supply and Demand Plan [15] as shown in Table 13.

$$N_r = \frac{C_r}{N_g} = \frac{12,957\,\text{GWh}}{11,169\,\text{GWh}} = 1.2\,\text{Unit} \cong 2\,\text{Units} \tag{5}$$

where N_r is a number of nuclear power units, C_r is the generation from the coal fired power plant replacement, and N_g is the generation from one nuclear power unit.

Table 12. Nuclear power unit specifications.

Capacity	1500 MW
Capacity factor	85%
Generation	11,169 GWh

Table 13. Investment costs of nuclear power plant.

Capacity (MW)	Construction Costs (Million $/MW)	Investment Costs (Billion $)
3000	1.992	6.0

5.3.2. Scenario 2: Replacing the Coal-Fired Power Plants with Renewable Energy

According to the 7th Electricity Supply and Demand Plan [15] and its renewable energy plan, the projected generations from wind and solar power are 16,663 GWh and 21,210 GWh, respectively, for a total of 37,873 GWh in 2030. We decided on wind and solar power for replacement of the coal-fired power plants among the numerous renewables because wind and solar power hold the first and second places among renewables in terms of generation by the 7th Electricity Supply and Demand Plan [15]. By applying the ratio of wind and solar power from the renewable energy plan, 12,957 GWh from the coal fired power plants are replaceable by wind and solar power as of 5701 GWh and 7256 GWh for each. The average capacity factors for wind and solar power are 22.3% and 14.1% based on the capacity and capacity factors from 2015 to 2029 on the 7th Electricity Supply and Demand Plan [15]. As we apply these average capacity factors, the additional capacity of 2913 MW is required for wind power and 5883 MW for that of solar power (Tables 14 and 15).

Table 14. Generation and capacity factor of wind and solar in 2030.

Classification	Generation (GWh)	Generation Share (%)	Average Capacity Factor (%)
Wind	16,663	44	22.3
Solar	21,210	56	14.1
Total	37,873	100	-

Table 15. Renewable energy replacing coal in 2030.

Classification	Generation of Coal Replacement (GWh)	Required Capacity (MW)
Wind	5701	2913
Solar	7256	5883
Total	12,957	8796

We apply the estimated investment costs of the year 2030 from Dae-Gyun Oh [5] to the capacity addition of the solar and wind power plants. The investment costs of wind and solar power are, respectively, $1.51 million/MW and $1.02 million/MW in 2030. For the result of Scenario 2, the total investment costs for replacing the coal-fired power plants with renewables is $10.4 billion, as shown in Table 16.

Table 16. Investment cost of renewables.

Classification	Capacity (MW)	Construction Costs (Million $/MW)	Investment Costs (Billion $)
Wind	2913	1.51	4.4
Solar	5883	1.02	6
Total	8796	100	10.4

5.3.3. Scenario 3: Installing Carbon Capture and Storage

CCS is a direct reduction measure to reduce GHG emissions from coal-fired power plants. According to Energy Information Agency (EIA) [37], the GHG emission coefficient for the coal-fired power plants with CCS installed is 112.1 g-CO_2/kWh which is significantly reduced by 878.9 g-CO_2/kWh from the GHG emission coefficient of the coal fired power plant without CCS. As described by Equation (6), the generation from the coal-fired power plants with CCS is 14,609 GWh in order to reduce 12.8 million tons of excess GHG emissions to zero. This generation amount of 14,609 GWh is equivalent to 2085 MW, which is the required capacity of the coal-fired power plants with CCS installment.

$$CCS_g = \frac{GHG_{exess}}{CCS_{cof.}} = \frac{12.8\,\text{Million ton}}{878.9\,\text{g} - CO_2/\text{kWh}} = 14,609\,\text{GWh} \quad (6)$$

where CCS_g is the generation of the coal-fired power plants with CCS installment, GHG_{excess} is excess GHG emission amount, and $CCS_{cof.}$ is the reduction in the GHG emission coefficient by CCS installation.

$$CCS_r = \frac{CCS_g}{8760\,\text{hours} \times \text{Capacity factor}} = \frac{14,609\,\text{GWh}}{8760\,\text{hours} \times 0.8} = 2085\,\text{MW} \quad (7)$$

where CCS_r is the required capacity of the coal fired power plants with CCS installation, and CCS_g is the generation of the coal-fired power plant with CCS. We use the capacity factor in the analysis of the GHG reduction roadmap of the South Korean power industry (2014) (Table 17).

Table 17. Investment costs of CCS.

Required Capacity for CCS	Construction Costs (Million $/MW)	Investment Costs (Billion $)
2085 MW	4.54	9.5

5.3.4. Scenario 4: Replacing the Coal-Fired Power Plants with Natural Gas Combined-Cycle Plants

We test four scenarios on the 2030 GHG emission quantities as the hard constraint. Scenario 4 differs from the other scenarios in that it does not assume a carbon-free situation, but rather assumes LNG combined cycle with a small amount of GHG. Hence, keeping the 2.1 plants as an alternative to coal power plants could not maintain the target GHG emission. In other words, the carbon emission coefficient, 549 g-CO_2/kWh of LNG combined cycle generation substitutes for the 991 g-CO_2/kWh of coal power plants. Assuming the same capacities, the alternation effect to one coal power plant with one LNG combined cycle is a reduction of approximately 442 g-CO_2/kWh as shown in Table 18.

Table 18. Liquefied natural gas (LNG) combined cycle plants unit specifications.

Capacity	800 MW
Capacity factor	90%
Generation	6307 GWh
GHG emission coefficient	442 g-CO_2/kWh

The assumptions above needs new values to test the effect of Scenario 4 instead of the 2.1 alternative value for coal power plants. For this purpose, we suggest specific values from

Equation (9). In this case, despite a little higher value, 4.1, being needed, it is meaningful for the future theoretical and applicable research to estimate alternative capacities to coal power plants.

$$\begin{aligned} &\textit{Generation quantities of Coal - LNG} \\ &= \textit{excessive } CO_2 \textit{ emission} \div \textit{Coal - LNG } CO_2 \textit{ emission} \\ &= 12.8 \textit{ million tons-}CO_2 \div 442 \textit{ g-}CO_2/kWh \\ &= 29{,}050 \textit{ GWh} \end{aligned} \quad (8)$$

$$\begin{aligned} &\textit{Number of LNG combined cycle plants needed} \\ &= \textit{coal generation need to alternate with} \div \textit{one LNG combined cycle plants} \\ &= 29{,}050 \textit{ GWh} \div 6307 \textit{ GWh} \\ &= 4.6 \textit{ plants} \end{aligned} \quad (9)$$

The cost of 4.6 plants of LNG combined cycle generation is approximately $5.6 billion USD from the basis value of the 7th Electricity Supply and Demand Plan (Table 19).

Table 19. Investment costs of natural gas combined-cycle plant.

Capacity (MW)	Construction Costs (Million $/MW)	Investment Costs (Billion $)
3685	0.806	5.6

Source: The 7th Basic Plan of Long-Term Electricity Supply and Demand (2015).

5.3.5. Land area Requirement by Scenarios

We calculate the required land area of nuclear, wind, and solar power facilities in Scenario 1 and 2. Nuclear power of 3000 MW requires 10.1 km^2, while the wind and solar power need 2338 km^2 and 914 km^2 for their designated capacities of 2913 MW and 5883 MW, respectively, to replace 12,957 GWh from the coal-fired power plant. Accordingly, the required land area for wind power is 229 times more than nuclear power, and solar power also needs 90 times more area than nuclear power (Table 20).

Table 20. Required area.

Classification		Required Capacity (MW)	Required Area (km^2)	Comparison (Times)
Scenario 1	Nuclear power	3000	10.2	1
Scenario 2	Wind	2913	2338	229
	Solar	5883	914	90

5.3.6. Effects of Electricity Price by Scenarios

We estimate the average electricity unit price in 2030 to be $0.1343/kWh. As described in Table 19, the estimated unit price for nuclear power is $0.0541/kWh, while it is $0.6866/kWh for oil in 2030. While the unit price of oil reaches the highest price with an annual increase of 8.48% from 2001 to 2014, the unit price of nuclear power is maintained relatively low compared to the other energy sources (Table 21).

Table 21. Wholesale prices estimation in 2030.

Classification	Unit Price ($/kWh)	Generation (GWh)
Nuclear	0.0541	290,397
Coal	0.096	255,505
Oil	0.6866	4434
Gas	0.2815	11,693
Pump storage	0.3955	37,964
Renewable	0.2863	55,188
Other	0.2863	69,642
Average/Total	0.1343	724,823

We estimate the impacts of the average electricity unit price on the electricity price in 2030 by the scenarios in Table 22. In Scenario 1, the increase of nuclear power generation (22,338 GWh) and decrease of coal power generation (22,338 GWh) derive $0.0013/kWh reduction to the electricity unit price. The nuclear power investment costs of $6 billion increases the electricity unit price by $0.0082/kWh. The reduced purchase of emission credit decreases the electricity unit price by $0.00041/kWh. Considering the risks of a nuclear power plant, a $0.0049/kWh external cost of severe accidents are additionally added. The average electricity unit price for Scenario 1 is $0.1457/kWh, which is 8.1% higher than base average electricity unit price of $0.1343/kWh.

Table 22. Effects of wholesale price by scenario.

Classification	Scenario 1 ($/kWh)	Scenario 2 ($/kWh)	Scenario 3 ($/kWh)	Scenario 4 ($/kWh)
Generation	–0.0013	0.034	-	+0.0074
Investment costs	+0.0082	+0.0144	+0.0131	+0.0077
Emission credit	–0.00041	–0.00024	–0.00024	–0.00024
External cost	+0.0049	-	-	-
Average electricity unit price	0.1457	0.1518	0.1471	0.1492

In Scenario 2, the increase of renewable energy generation (12,957 GWh) and decrease of coal power generation (12,957 GWh) derive $0.0034/kWh addition to the electricity unit price. The renewable energy investment costs of $10.4 billion increase the electricity unit price by $0.0144/kWh. The reduced purchase of emission credit decreases the electricity unit price by $0.00024/kWh. The average electricity unit price for Scenario 2 is $0.1518/kWh and it is 12.3% higher than the base average electricity unit price of $0.1343/kWh.

In Scenario 3, the CCS investment costs of $9.5 billion increase the electricity unit price by $0.0131/kWh. The reduced purchase of emission credit decreases the electricity unit price by $0.00024/kWh. The average electricity unit price for scenario 3 is $0.1471/kWh and it is 9.1% higher than the base average electricity unit price of $0.1343/kWh.

In Scenario 4, the increase and decrease of 29,050 GWh in the LNG combined cycle plants and coal power plants anticipate a $0.0074/kWh increase of the electricity selling price, the construction cost of $5.6 billion of the LNG combined cycle plants contribute to raise $0.0077/kWh increase of the electricity selling price. In addition, carbon credit from the reduction of coal power plants decreases $0.00024/kWh of the electricity selling price. Hence, the average electricity selling price is estimated around $0.1492/kWh which is 10% higher than the BAU selling price ($0.1343/kWh).

5.3.7. Sensitivity Analysis

Figure 4 shows the sensitivity analysis result with different GHG reduction target in 2030. We set the three reduction targets for the analysis: 30%, 25%, and 20%. In Scenario 1, the investment costs vary from $6 billion to $17.9 billion and the GHG reduction amount varies from 22.1 million to 66.4 million ton. In Scenario 2, the investment costs vary from $10.4 billion to $36.1 billion and GHG reduction amount vary from 12.8 million to 44.5 million tons. In Scenario 3, the investment costs vary from $9.5 billion to $32.8 billion and GHG reduction amounts vary from 12.8 million to 44.5 million tons.

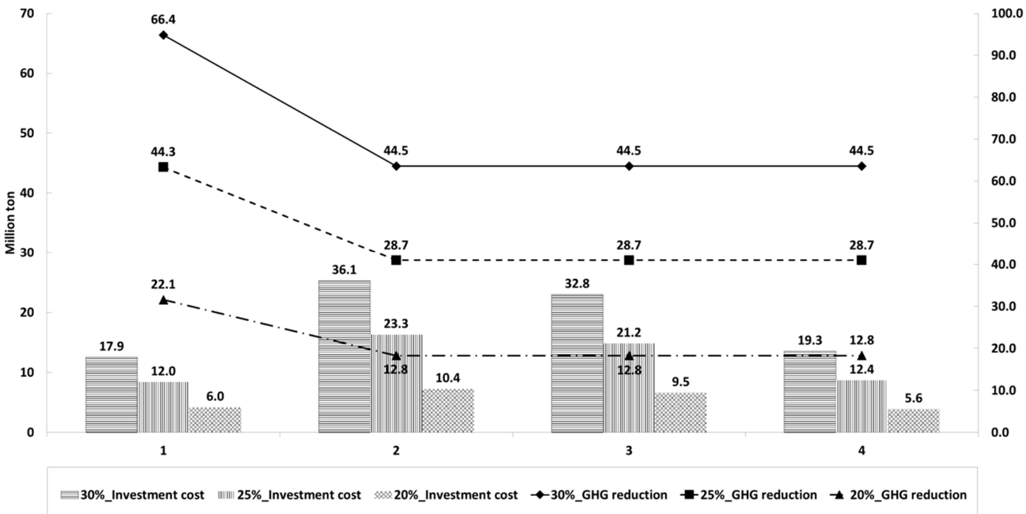

Figure 4. Sensitivity analysis of GHG reduction target in 2030.

By comparison, Scenario 1 shows higher GHG reduction than the other scenarios because of the additional power generation from nuclear power due to its two unit-pairing design characteristic. However, Scenario 2 shows the highest sensitivity variance for the investment costs.

6. Conclusions

Considering its position as the seventh-highest GHG emitter in the world [38], South Korea submitted a substantially high GHG reduction target, as announced in its INDC. In order to achieve the total of the 37% reduction target, which is composed of a 25.7% domestic emission reduction and an 11.3% purchase from the international carbon market from the BAU of 2030, the intensive GHG reduction measures are inevitable, especially for the generation sector, which emits 30% of the national GHG emissions. Thus, the major government-owned thermal power generators will face direct challenges and require aggressive actions to reduce their GHG emission.

According to our calculation, the forecasted excess GHG emission of the generation sector of the year 2030, complying with the 7th Electricity Supply and Demand Plan [15], is 12.8 million tons. We used the WASP model to estimate generation and GHG emission volume in order to maintain congruence in policy with the Korea Power Exchange, which also uses the same WASP model to develop the Electricity Supply and Demand Plan. To replace 2.1 or 4.6 units of coal power plants, which are accountable for the excess GHG emission, we set nuclear power, renewable energy, and CCS installation as the alternatives to the coal-fired power plants for our scenario base analysis. After analyzing GHG reduction quantity, investment costs, and electricity fare increment for each scenario, we conclude that Scenario 1 provides the most positive results (Table 23).

Table 23. Comparison of scenario analysis results.

Scenario	GHG Reduction (Million Tons)	Investment Costs (Billion $)	Change in Electricity Fare (%)
Scenario 1 Replacement with Nuclear Power Plant	22.1	6.0	+8.14
Scenario 2 Replacement with Renewables	12.8	10.4	+12.3
Scenario 3 Installment of CCS	12.8	9.5	+9.10
Scenario 4 Installment of CCS	12.8	5.6	+10.5

While GHG reduction in the generation sector is critical to achieve the national reduction target in 2030, the significant reduction in GHG emissions requires low-carbon energy and technology development. As our study elaborates, nuclear power is a promising alternative to reduce GHG in the generation sector. Therefore, a long-term plan to increase nuclear power plants in South Korea is required, along with genuine attempts to reach social compromise in expanding nuclear power.

Although we sought to maintain congruence in policy as much as possible, a limitation still exists due to the usage of a hypothetical approach for any policy which is not agreed upon, either domestically or the internationally. A detailed discussion of the BAU and reduction measures for the generation sector for the national reduction target by the year 2030 will be held in 2016 after the 21st Conference of the Parties, scheduled in December, 2015. Thus, we expect a change in the research results depending on future policy, since we applied the hypothetical approach to our study.

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Abbreviations

BAU	Business as Usual
CCS	Carbon Capture and Storage
EIA	Energy Information Agency
GHG	Greenhouse Gases
GDP	Gross Domestic Product
INDC	Intended National Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
KEEI	Korea Energy Economics Institute
KEI	Korean Environment Institute
LNG	Liquefied Natural Gas
NGOs	Non-Governmental Organizations
RPS	Renewable energy Portfolio Standard
UK	United Kingdom
WASP	Wien Systematic System Planning

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