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Feasibility Analysis of Alternative Electricity Systems by 2030 in the Post-Fukushima Era

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ABSTRACT

The Fukushima nuclear accident in 2011 had an extensive impact on the national electricity plans. This paper outlines alternative electricity scenarios that meet the goals of nuclear phase-out and greenhouse gas (GHG) emission reduction. This paper also analyzes the results of each scenario in respect to the electricity mix, GHG emissions, costs and employment effects. The Long-range Energy Alternatives Planning system (LEAP) model was used to simulate the annual electricity demand and supply system from 2011 to 2030. The reference year was 2009. Scenarios are reference (where existing plans are continued), A1, A2, B1, B2, and C2 (where the levels of demand management and nuclear phase-out are different). The share of renewable energy in the electricity mix in 2030 for each scenario will be increased from about 1% in 2009 to 8% in the reference scenario and from 11% to 31% in five alternative scenarios. Total cumulative cost increases up to 14% more than the reference scenario by replacing nuclear power plants with renewable energy in alternative scenarios could be affordable. Deploying enough renewable energy to meet such targets requires a roadmap for electricity price realization, expansion of research, development and deployment for renewable energy technologies, establishment of an organization dedicated to renewable energy, and ambitious targets for renewable energy.

Key words: Electricity system analysis, Renewable energy, LEAP model, Greenhouse gas emissions, Cost

1. INTRODUCTION

On March 11, 2011, the Fukushima nuclear accident had a significant impact on the energy policies of not only Japan, the country directly affected by this event, but also countries worldwide that have been operating or have planned nuclear power plants. Before the Fukushima nuclear accident, the International Energy Agency (IEA) and the countries of the world expected that nuclear power could contribute to the reduction of the greenhouse gas (GHG) emissions (IEA, 2010a; IEA, 2010b), and the nuclear power industry was excited by the prospects of a nuclear power renaissance. Japan was pursuing the basic energy plan to enhance the share of power generated by nuclear power plants, which accounts for 26% of present power generation, and to increase this share to 45% by 2030. However, Japan has established a new energy strategy after the Fukushima nuclear accident, which abandoned the construction of additional nuclear power plants (EEC, 2012). Many countries in Europe considerably modified their policies for nuclear power plants. Germany, Belgium, and Switzerland devised plans to phase out nuclear power plants that are in use, and Italy scrapped its plan for building nuclear power plants, while France is trying to reduce dependence on nuclear power plants.

Korea continues to pursue a basic energy plan to expand its nuclear power plants. According to the national basic energy plan published in August 2008, the power generation share of nuclear power plants is expected to increase from 34% (installed capacity of 24%) in 2009 to 59% (installed capacity of 41%) in 2030 (PMO *et al*., 2008). However, the power generation share of renewable energy is only 1.0%, 0.6% of which is attributed to hydroelectric power generation (IEA, 2012). Per capita electricity consumption in Korea in 2009 was 8,980 kWh, which is higher than that of Japan (7,841 kWh) and OECD countries (7,983 kWh) (IEA, 2012). Korea's per capita electricity consumption is expected to increase by 2030, further widening the gap with Japan and OECD countries.

However, as social demand for reducing the use of nuclear power and for establishing alternatives increases due to concerns about existing nuclear power plants after the Fukushima nuclear accident, alternatives to reduce dependence on nuclear power plants are being actively sought in Korea as well. The Korea Energy Economics Institute, which has contributed to the development of the government's basic energy plan, estimated the costs of scenarios that expand renewable energy while reducing the use of nuclear power (Moon *et al.*, 2011). It was predicted that an additional investment of 106.4 trillion won (about 96 billion US dollar) would be required, and that the electricity prices would increase by 17.1%p by 2030 compared to the existing plan if 10 GW of nuclear power plant capacity is replaced by renewable energy installations. Moon *et al.* (2011) interpreted that result to indicate a significant cost burden on the national economy due to replacement of nuclear power by renewable energy. However, from a different point of view, it showed the possibility of replacing nuclear installations with renewable energy if certain social and political conditions are formed.

After experiencing serious social conflict over radioactive waste disposal, the government conducted alternative energy studies that analyzed the possible transition to an energy policy based on demand management rather than a supply-driven energy policy based on nuclear power (KEI, 2004). Non-governmental organizations (NGOs) that were critical of the government's supply-oriented energy policy and its nuclear power expansion policy have actively proposed alternative policy directions in the past as well. Byrne *et al.* (2004) asserted that the gradual abolition of nuclear power plants was possible if energy efficiency was increased through a bottom-up analysis of energy technologies. The Green Power Study Group (2003) insisted that balancing electricity supply and demand is possible without additional construction of nuclear power plants by strengthening electricity demand management via the introduction of high-efficiency motors.

Park *et al.* (2013) received attention by analyzing the scenario of gradually abolishing nuclear power by expanding natural gas combined cycle (NGCC) power and renewable energy in the power generation sector. The significance of this study is that it suggests alternative energy scenarios available for discussion and validation through the energy system model widely used in government and academic societies, compared to the weak methodology of existing studies of energy alternatives in the NGOs. After the Fukushima nuclear accident, several NGOs and political groups have proposed a long-term energy policy vision and alternative scenarios with the goal of nuclear phase-out (Energy Alternatives Forum, 2012; EREC and Greenpeace, 2012; Han *et al.*, 2011). Among them, EREC and Greenpeace (2012), in collaboration with the German Aerospace Center (DLR), which has performed considerable research on renewable energy systems in Germany and Europe, presented scenarios for Korea to increase the power generation share of renewable energy to over 25% while phasing out nuclear power plants by 2030 using energy system analyses and forecasting models. The Energy Alternatives Forum (2012) has not only offered an ideal vision and academic research, but it has also established 2030 Energy Alternative Scenarios as realistic policy alternatives to convince Korea's leading and opposition politicians to propose them to Korea's next government.

This paper has introduced and upgraded the methodology of the Energy Alternatives Forum's 2030 Energy Alternative Scenarios and the overall results of their analyses. The purpose of the 2030 Energy Alternative Scenarios is to investigate the possibilities of alternative policies by establishing alternative scenarios to phase out nuclear power plants and reduce GHG emissions in Korea using energy system analysis models and by comparing them with the government's existing plans.

2. METHODOLOGY

2.1 LEAP Model

The Long-range Energy Alternatives Planning system (LEAP) model was developed by the Stockholm Environment Institute in 1980 to analyze long-term energy plans. Unlike the optimization model deriving a combination of energy technologies to reduce GHG emissions or meet energy demand prospects at minimum cost, the LEAP model is an accounting model that analyzes energy supply and demand, costs, and environmental impact based on energy technology distribution scenarios. Studies on long-term energy and GHG reduction using the LEAP model are generally conducted for medium- and long-term periods, such as until 2030 or 2050, and are mainly used at the national or city level. The LEAP model is designed to integrate and analyze the energy supply and demand system, or to analyze the energy demand sectors such as transportation, buildings, etc., or the energy supply sector such as power generation (Park *et al.*, 2013; Takase and Suzuki, 2011; Heaps *et al.*, 2009; Cai *et al.*, 2007; Zhang *et al.*, 2007). Approximately 16,000 people across 191 countries were using the LEAP model as of December 2012.

The LEAP model consists of a key assumption module to enter social and economic premises including population, households, gross domestic product (GDP), and industrial structure; a demand module including residential, commercial and public sector, industry, and non-energy use sectors; a transformation module including power generation, oil refining, and gas production; a resources module that lists domestic production and the import and export of energy sources such as coal, oil, and renewable energy; and a non-energy sector module that lists non-energy sector GHG emissions from industrial process, agriculture, land-use change and forestry, and waste sectors. In the supply and demand sector, the 1996 Intergovernmental Panel on Climate Change (IPCC) Tier 1 default emission factors embedded in the LEAP model were used for calculating the GHG emissions.

In this study, the LEAP 2011 model was used for analysis. The electricity demand forecasts by scenario were input by separating them into industrial, residential, commercial and public sectors. The electricity generation to meet the demand was determined by considering transmission and distribution losses and self-use, system peak load shape and planning reserve margin in the transformation sector. The current distribution status, future installations remaining after lifetime, and the government's plans for installations using nuclear power, coal-fired power, natural gas-fired power, NGCC power, oil internal-combustion power, hydropower, pumping, solar power, wind power, geothermal power, biomass, fuel cells, integrated gasification combined cycle (IGCC) power, by-product gas power, and tidal power were input as the power generation technologies. The characteristic values of efficiency, availability factor, cost etc. by power generation technology were also input (Park *et al.*, 2013). Environmental impacts such as GHG and air pollutants were calculated by applying the 1996 IPCC Tier 1 default emission factors, and the global warming potential (GWP) of the 1995 IPCC Second Assessment Report was applied. Power plants are dispatched using merit order except in the reference scenario where nuclear power plants are dispatched in proportion to a process share to meet 59% by 2030.

2.2 Input Assumptions and Scenarios

This study used the data of the main outlook such as population, economic growth, industrial structure, etc., that were used during the establishment of the national basic energy plan when predicting power generation by 2030 (PMO *et al.*, 2008). Population increases from 48.75 million people in 2009 to 52.16 million in 2030 and then decreases (Statistics Korea, 2011). The annual average GDP growth rate between 2009 and 2030 is expected to be 3.5% (KDI, 2010; MKE and KPX, 2010). The value-added share of the three biggest energy-consuming industries decreases from approximately 30% in 2008 to approximately 20% in 2030 (PMO *et al.*, 2008). The oil price is assumed to go from \$60/barrel in 2009 to \$130 (2009 US\$)/barrel in 2030 in accordance with the crude oil import price of the IEA's current policy scenario (IEA, 2010b). The electricity demand forecasting for each sector was entered. The electric power installations, GHG emissions, costs and jobs based on the electricity supply mix were analyzed annually. The reference year for the analysis was set as 2009, and the simulation was run until 2030.

Scenarios included combinations of four demand scenarios and three supply scenarios, and a total of six scenarios (Reference, A1, A2, B1, B2, C2) were established (see Fig. 1).

First, the four demand scenarios were as follows.

Government's Baseline Scenario (Reference): The baseline demand outlook in the 5th Basic Plan for Long-term Electricity Supply and Demand was applied by extending it until 2030 (MKE and KPX, 2010).

Demand Reduction Scenario through Electricity Price Realization (A): This scenario was constructed to raise the electricity price for household use by 1% (based on real prices) each year to alleviate the burden on the home while raising the electricity price for industrial use with a larger portion of electricity consumption each year by 3% in 2012-2015, 2% in 2016-2020, and 1% in 2021-2030, taking urgency into account. The price for households in 2030 will increase by 21% compared to 2009 (similar to the level of OECD countries in 2009), while the price for industrial use in 2030 will increase by 37% compared to 2009 (similar to the level of OECD/European countries in 2009). The reduction of electricity consumption due to price increases was analyzed by applying price elasticity, i.e. -0.66 for electricity for industrial use (Kim, 2009) and -0.576 for electricity for household use (Jung and Park, 2010). The electricity demand outlook to which price elasticity was applied is similar to the government's target demand outlook presented in the 5th Basic Plan for Long-term Electricity Supply and Demand with electricity demand increasing by an annual average growth rate of 1.44%.

Scenario for Achieving the OECD Average Electricity Consumption Level (B): The electricity consumption per capita was set to achieve the level that meets the 450 ppm scenario of the OECD countries by 2030 through the reinforcement of demand management policy as well as realization of electricity prices (IEA, 2011).

Scenario for Achieving the OECD/European Countries' Average Electricity Consumption Level (C): The per capita electricity consumption was set to achieve a level that meets the 450 ppm scenario of the OECD/

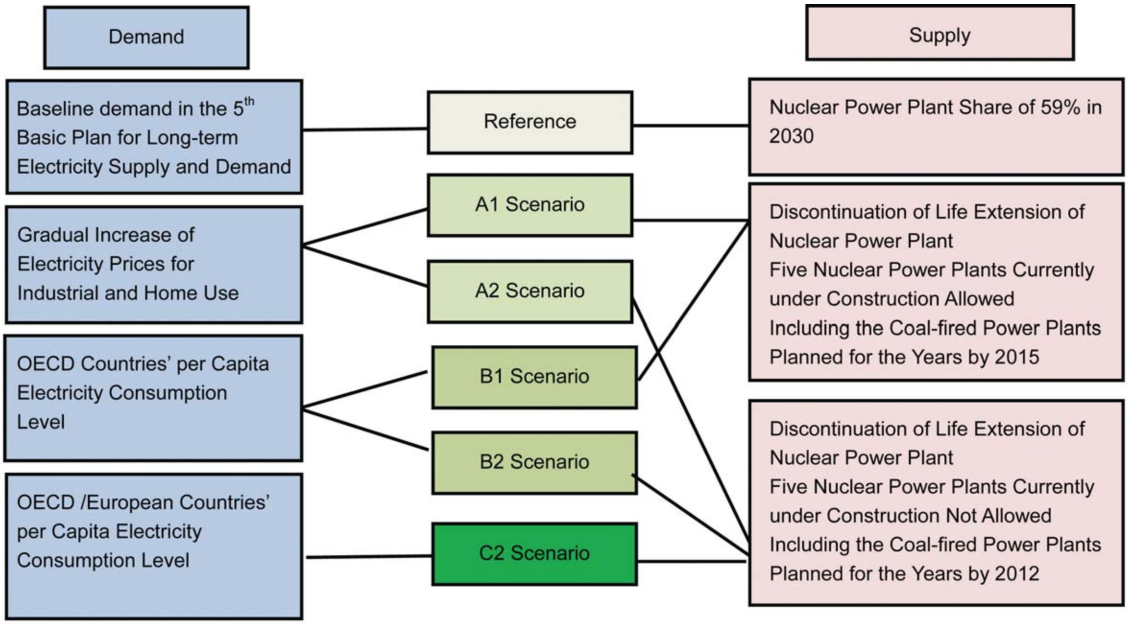

Fig. 1. Overview of Scenarios for an Alternative Electricity System by 2030.

European countries by 2030 through the reinforcement of the demand management policy as well as the realization of electricity prices (IEA, 2011).

The three supply scenarios were as follows.

Reference: Renewable energy plants at the level of implementing a renewable portfolio standard (RPS) system were added under the assumption that electricity is produced to meet the government's baseline demand outlook in the 5th Basic Plan for Long-term Electricity Supply and Demand, while the power generation share of nuclear in 2030 is approximately 59%. There are no plans for abolition of nuclear power by 2030, and the lifetimes of obsolescent nuclear power plants are extended (MKE and KPX, 2010).

Supply Scenario 1: Only the five nuclear power plants that are currently under construction are reflected, and there is no construction of additional nuclear power plants. The supply of renewable energy will be expanded. Coal-fired power plants planned for the years after 2015 will not be introduced (only the coal-fired power plants planned before 2015 will be allowed). Nuclear power plants and coal-fired power plants will be phased out after operating for 40 and 30 years, respectively.

Supply Scenario 2: Only the nuclear power plants and coal-fired power plants that have been built as of 2012 are operated. Nuclear power plants and coal-fired power plants will be phased out after operating for 40 and 30 years, respectively.

3. RESULTS

3.1 Electricity Mix

The annual average growth rate of electricity demand between 2009 and 2030 is 2.56% in the Reference scenario, 1.44% in A1 and A2 scenarios, −0.14% in the B1 and B2 scenarios, and −1.51% in the C2 scenario.

The existing nuclear power plants and the five nuclear power plants currently under construction are operated in the A1 and B1 scenarios. In the A2, B2, and C2 scenarios only the nuclear power plants completed as of 2012 are operated, while the necessary electricity is supplied by renewable energy and NGCC power generation (see Fig. 2). In the Reference scenario, 59% of the power will be generated by nuclear power plants by 2030 followed, in order, by coal, gas, and renewable energy. The power generation rate of the nuclear power plants that will be operating in 2030 is 59% (Reference), 24% (A1), 15% (A2), 33% (B1), 21% (B2), and 27 % (C2). In this case, the number of the nuclear power plants that will be operating in 2030 is expected to be 46 units in the Reference scenario (assuming that there is no abolition of nuclear power plants until 2030[1]),

[1]Currently there are 23 nuclear power units that are being operated or have been constructed, 5 units that are under construction, and 6 units for which construction plans have been determined. In case of governmental plan, 2 newly proposed sites (Yeongdeok and Samcheok) are required.

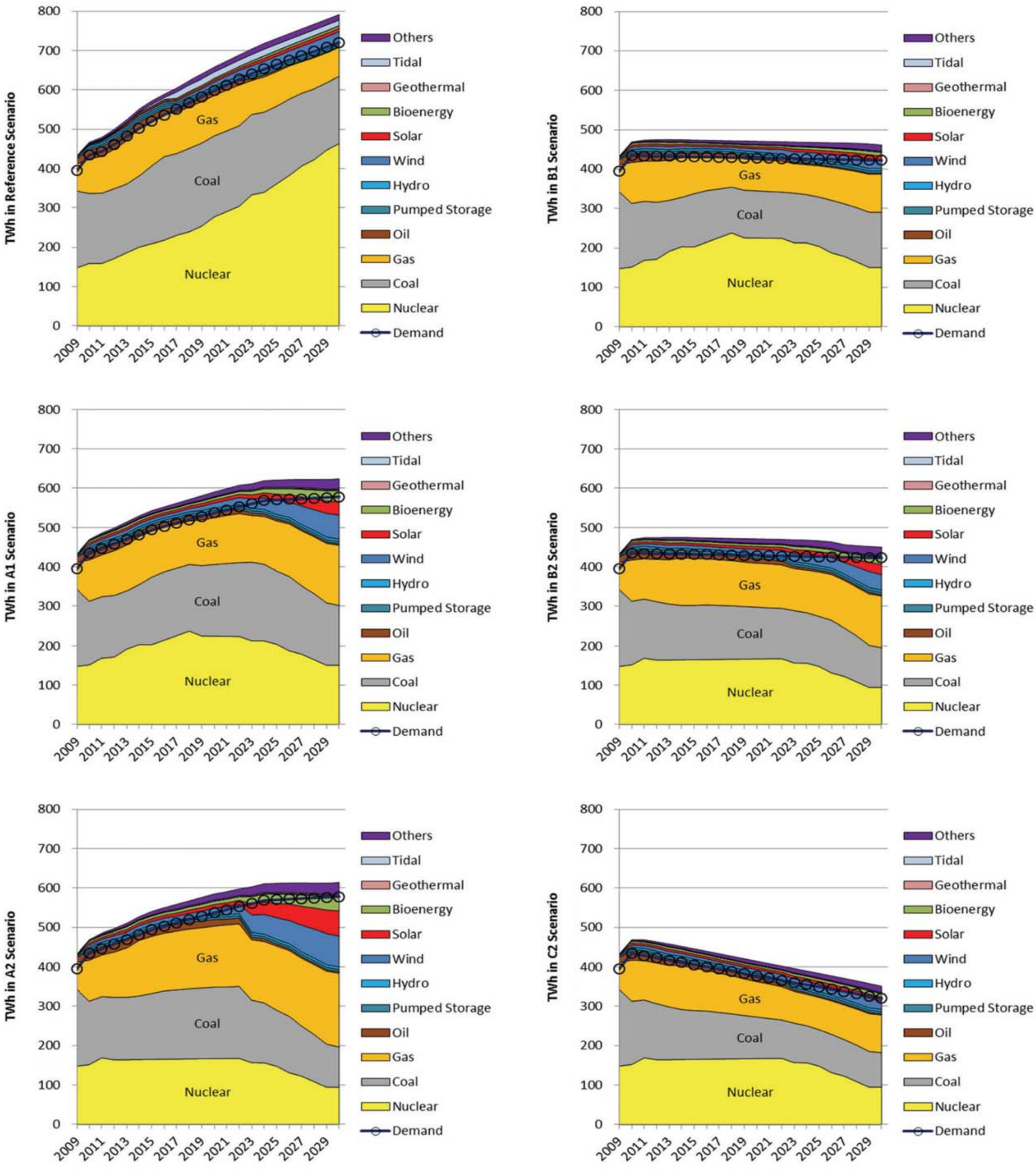

Fig. 2. Electricity Demand and Generation Outlook by Scenario. Others include byproduct gas, fuel cell and IGCC.

17 units in the A1 and B1 scenarios (when 40 years is assumed as the life of a nuclear power plant, the nuclear power plant installations will be 0 in 2057), and 11 units for A2, B2, and C2 scenarios (nuclear power plant installations will be 0 in 2052).

The power generation share of renewable energy by scenario is 8% (Reference), 22% (A1), 31% (A2), 11% (B1), 21% (B2), and 14% (C2). The annual average growth rate of the power generation of renewable energy required during the period between 2010 and 2030 is in the order of A2 (19.6%) > A1 (17.7%) > B2 (15.8%) > Reference (13.5%) > B1 (12.5%) > C2 (12.5%). In the A2 scenario with the largest power generation share of renewable energy, fast distribution of renew-

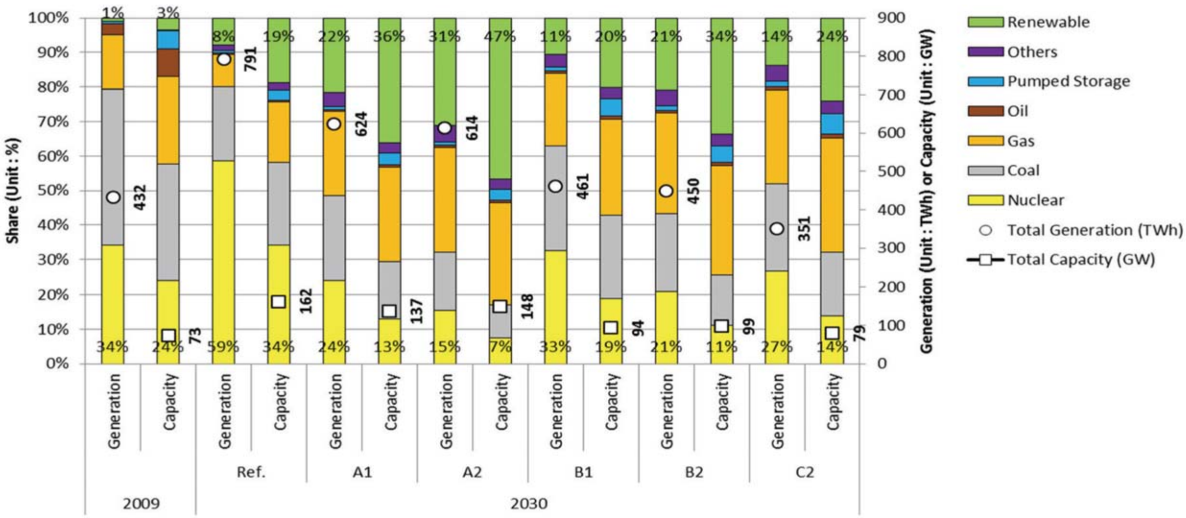

Fig. 3. Electricity Mix in Years 2009 and 2030 by Scenario.

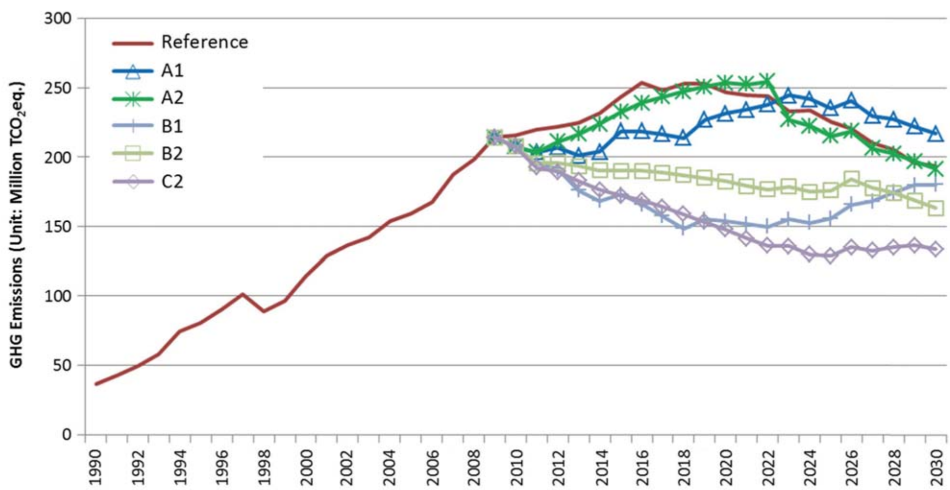

Fig. 4. GHG Emissions Outlook from Power Generation Sector (1).

able energy is needed to make up for the power generation share of nuclear power and coal-fired power generation after 2023. In the Reference scenario, the power generation share of wind and tidal power accounts for the largest part, while each of renewable energy sources such as the wind, solar, biomass, and hydropower evenly forms a part in the alternative scenarios. The power generation share by renewable energy in 2030 was analyzed to be in the range of 5-18% of the economic potential for renewable energy in Korea (MKE and KEMCO, 2010).

The capacity share in 2009 was 24% nuclear power and 3% renewable energy. In the Reference scenario in 2030, the capacity share from nuclear power will account for 34% and renewable energy for 19%. In the rest of the scenarios, the capacity share from nuclear power ranges from 7% (A2 scenario) to 19% (B1 scenario), while the capacity share from renewable energy ranges from 20% (B1 scenario) to 47% (A2 scenario) (see Fig. 3).

The Korea Photovoltaic Industry Association (KOPIA, 2011) investigated the maximum installable capacity of photovoltaic cells considering the largest area where solar cells can be installed. The ratio of maximum installable capacity of photovoltaic cells by scenario is A2 (61.0%) > A1 (34.9%) > B2 (25.6%) > Reference (12.9%) > B1, C2 (11.8%). Therefore, the power generation of renewable energy in each alterna-

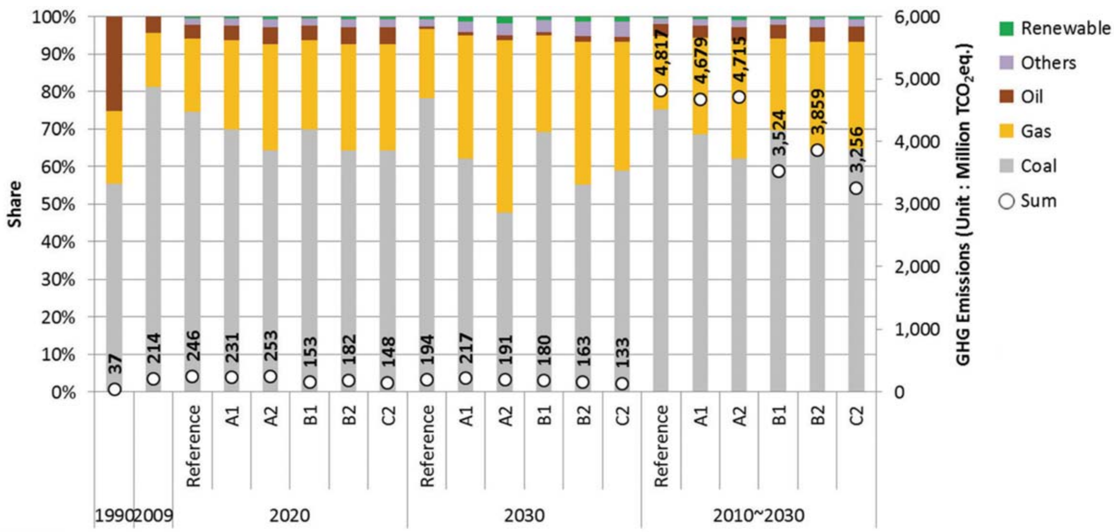

Fig. 5. GHG Emissions Outlook from Power Generation Sector (2). Others include by-product gas, fuel cells, and IGCC.

tive scenario seems to comply with the domestic natural and technological conditions.

3. 2 Greenhouse Gas Emissions

The results of analyzing the GHG emissions from power plant operation in 2030 showed that emissions in the Reference scenario increase until 2016 and then decrease by about 10% as compared to 2009 with the expansion of nuclear power plants. However, in the alternative scenarios, it was found that GHG emissions in the A1 scenario increase by 1% in 2030 as compared to 2009 with the transitional increase of NGCC power generation, and in the rest of the alternative scenarios, they decrease by 10-38% (see Fig. 4). However, the cumulative GHG emissions from 2010 to 2030 were analyzed to be lower in the alternative scenarios than the Reference scenario (see Fig. 5).

3. 3 Cumulative Cost

The total cumulative costs of the power generation sector from 2010 to 2030 were analyzed to be 104% (A1), 114% (A2), 80% (B1), 88% (B2), and 76% (C2) as compared to the Reference scenario. Physical costs were analyzed rather than opportunity costs. Capital costs for installations, operation and maintenance costs, fuel costs, and GHG emission costs are reflected in the cumulative cost. The efficiency improvement costs, costs for decommissioning nuclear power plant and post-treatment, land rental costs, and costs for backup installations are not reflected. In the cost items, fuel costs account for the largest part at 57-64%. The reason that the cumulative costs are higher by approximately 14% than those of the Reference scenario, even

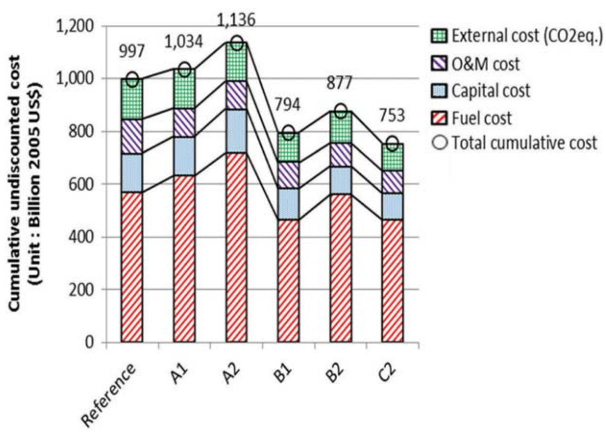

Fig. 6. Cumulative Cost by Cost Item.

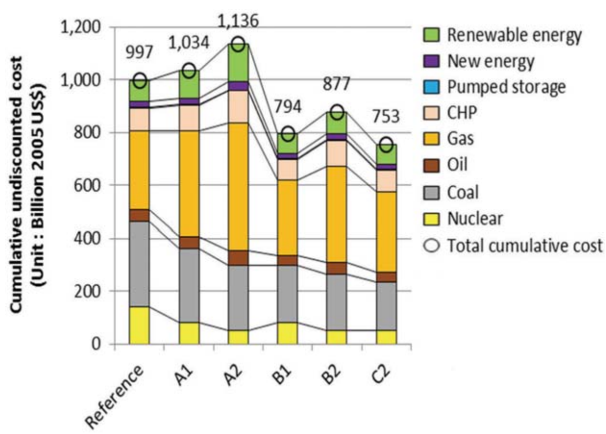

Fig. 7. Cumulative Cost by Generation Technologies.

Table 1. Employment Effect by Scenarios (Unit: Thousand person, %).

	2009	2030					
		Reference	A1	A2	B1	B2	C2
Sum	100.4 (100)	218.1 (100)	274.7 (100)	321.4 (100)	245.1 (100)	271.6 (100)	257.3 (100)
Nuclear	39.3 (39.1)	123.4 (56.6)	40.1 (14.6)	25.1 (7.8)	40.1 (16.4)	25.1 (9.2)	25.1 (9.7)
Coal	40.8 (40.6)	35.7 (16.4)	31.6 (11.5)	21.4 (6.6)	29.2 (11.9)	21.1 (7.8)	18.4 (7.1)
Oil	2.8 (2.8)	0.5 (0.2)	0.7 (0.3)	0.8 (0.2)	0.7 (0.3)	0.8 (0.3)	0.7 (0.3)
Gas	14.4 (14.3)	15.5 (7.1)	32.1 (11.7)	39.4 (12.3)	20.3 (8.3)	27.5 (10.1)	20.1 (7.8)
Pumped storage	0.8 (0.8)	1.6 (0.7)	1.6 (0.6)	1.6 (0.5)	1.6 (0.7)	1.6 (0.6)	1.6 (0.6)
Renewable	2.2 (2.2)	30.4 (13.9)	91.2 (33.2)	149.1 (46.4)	30.6 (12.5)	66.4 (24.5)	30.2 (11.7)
Others	0.1 (0.1)	11.1 (5.1)	23.3 (8.5)	30.1 (9.4)	9.6 (3.9)	16.1 (5.9)	9.4 (3.7)
Efficiency	– (0.0)	– (0.0)	54.0 (19.6)	54.0 (16.8)	113.0 (46.1)	113.0 (41.6)	151.9 (59.0)

in A2 scenario with the highest cumulative costs, is that fuel costs increase due to the expansion of NGCC power and capital costs increase due to the expansion of renewable energy supplies (See Figs. 6, 7).

3.4 Employment

Direct and indirect employment effects in the power sector were analyzed by applying the employment factors per power generation by energy source to the power generation by scenario. When the direct and indirect employment factors of Wei *et al.* (2010) were applied, the employment effects in 2030 were analyzed to be 126% (A1), 147% (A2), 112% (B1), 125% (B2), and 118% (C2) compared to the Reference scenario. It was found that nuclear power creates the largest employment effects in 2030 in the Reference scenario while renewable energy sources create the largest employment effects in A1 and A2 scenarios, and that the employment effects occur mainly through the efficiency improvements in the B1, B2, and C2 scenarios (see Table 1). Even when the number of jobs in the nuclear power sector decreases, the number of jobs in the sectors of efficiency improvements, renewable energy, and NGCC power increases.

4. CONCLUSIONS

Korea is establishing plans for electricity supply and demand every two years. Since the Fukushima nuclear accident, safety of nuclear power plants has been the most important issue, and the main concern is whether to maintain or discard the policy of nuclear power plant expansion. This study suggests the realization of electricity prices primarily in order to slow down the rapid growth rate of electricity demand. This should reduce the reference demand outlook for electricity to the level of target demand outlook in the 5th Basic Plan for Long-term Electricity Supply and Demand through the realization of electricity prices in the industrial and household sectors. Reference scenarios expanding the share of nuclear power in the electricity mix to 59% in accordance with the government's target for 2030 and the alternative scenarios to meet electricity demand through renewable energy and NGCC power while adding only nuclear power plants currently under construction, or abolishing even those plants, were established. The effects on GHG emissions, total cumulative costs, and jobs were analyzed according to the scenarios.

After the Fukushima nuclear accident, Japanese government published strategy to reduce its electricity production in 2030 by 10% compared to 2010 and to achieve zero dependence on nuclear power plants by the 2030s, expanding the share of renewable energy (EEC, 2012). In Korea, the electricity target demand in the 6th Basic Plan for Long-term Electricity Supply and Demand of Korea by 2020s is expected to increase more than the baseline demand in the 5th Basic Plan for Long-term Electricity Supply and Demand, and the decision for constructing new additional nuclear power plants has been postponed until the 2nd basic energy plan is established (MKE and KPX, 2013)[2]. Although thermal power generation and renewable power generation installations are being expanded, this is becoming controversial as it has become known that the forecasts of GHG emissions from the power generation sector will exceed the government's GHG emissions target in the transformation sector.

The role of renewable energy is expected to be even greater in the post-Fukushima era from the aspect of stabilizing GHG emissions, creating green jobs and making up for the power generation share of nuclear power plants. Because this study assumed that per capita income in 2030 would increase by approximately 2.1 times compared to that in 2009, it was found that the total cumulative cost increases up to 14% more than the Reference scenario by replacing nuclear power plants with NGCC and renewable energy could be affordable. Although this study analyzed direct and indirect employment effects, employment effects are expected to be larger if induced employment effects are also considered (Wei *et al*., 2010; MKE, 2008).

The Energy Alternatives Forum delivered the proposal of the civil society on the electricity mix to the national policy decision makers at a critical time during Korea's parliamentary and presidential elections (Energy Alternatives Forum, 2012). It is significant that the civil society established multiple scenarios for electricity supply and demand using a bottom-up energy system analysis model and further enhanced the content of energy policy debate by proposing them in a domestic reality where the government's scenario for the electricity supply and demand has been dominating the discussions. A roadmap for electricity price realization, expansion of research, development, and deployment for renewable energy technologies, establishment of an organization dedicated to renewable energy, and ambitious target for long-term renewable energy in the power generation sector will be important elements in the expansion of renewable energy in the future. Further studies on the demand management costs and on the grid integration of large-scale renewable energy and storage technologies are needed in the future.

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