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Impact assessment of CO_2 mitigation options in Korea using energy system analysis model

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Abstract

The Korea Electric Power Research Institute (KEPRI) has performed a study to analyze the deployment impact of CO_2 mitigation options in the power generation sector in Korea, with IEA Clean Coal Centre. The goal of this study is the identification of the viable technology and legal options for CO_2 mitigation, and the impact assessment of the options for the Korean power generation sector.

The MARKAL modeling package of IEA/ETSAP was used as an appropriate tool to make the database of Korean energy system in the model and assess the effects of the options. Several scenarios were made to study the effect of CO_2 emission reductions on the Korean power generation sector, and these were classified as the Base Scenario, New Technology Scenario, Carbon Tax Scenario, Total Carbon Emission Cap Scenario, and mixtures of the scenarios.

Under the base scenario based on the National Electricity Plan of Korea, the future power generation will be dominated by nuclear and coal power plants, with some of natural gas fired plant and a very small proportion of renewables. However, with increasing pressure to mitigate CO_2 emissions, the analysis results of all four scenarios and combination of the scenarios showed that Korea would have to adopt a little different approach. An extensive modeling work was, therefore, undertaken to analyze the impact of various measures on introduction of new technologies and policies in order to achieve significant CO_2 emissions reduction. As results of this work, we found estimated average cost for a ton carbon mitigation and estimated amount of CO_2 emission reduction by application of each scenario including constraint of lower limit of coal power generation for security of energy supplies in Korea. The results obtained are to be suggested as recommendation in establishing a sustainable energy portfolio within the Korean power generation sector.

Keywords : CO_2 mitigation options, Energy system analysis, MARKAL model, Scenario Analysis, Korean electric power sector

1. KESP (Korean Energy Strategy Project)

The Korean Electric power Research Institute (KEPRI) plays a role to provide information and research results to KEPCO and its subsidiary power generation companies, regarding climate change mitigation options. In this context, KEPRI has performed works for electric power sector in Korea to support long-term CO_2 mitigation strategies for the development of a portfolio of options to manage the large reduction of CO_2 emissions that will be necessary in the electric sector. This will offer a pathway for addressing greenhouse gas (GHG) emissions from the electric sector while identifying those factors that must be addressed to manage the risk that this approach represents. Factors being addressed in defining the future energy mix include carbon management options, the introduction of

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advanced power systems and the addition of renewables into the overall energy mix. Since the reduction of CO_2 emissions is increasingly a matter for international cooperation, KEPRI has undertaken a series of initiatives to establish better links with other research organizations active in the areas of fossil fuel usage and power generation. As part of this remit, KEPRI has undertaken a joint project with the IEA Clean Coal Centre, which was named as the Korean Energy Strategy Project (KESP) and was entitled 'The development of a strategy for CO_2 mitigation for coal fired power generation in the Korean electricity industry'.

The project was designed to consider the impact of internal and external factors on the viability of the various options for introduction of power generation technologies, with an emphasis on the potential for near zero emissions coal fired power generation within the overall energy mix for Korea. This included the analysis of those prospects together with the provision of recommendations for research, development and demonstration of CO_2 mitigation techniques for coal fired power generation in the Korean electricity industry together with an assessment of the benefits of international cooperation for such activities. In the context of this project, short term was considered to be of 10 years duration, medium term was 10~30 years, while long term was 30~50 years. The approach adopted was to quantify the current power plant status in Korea, determine the likely increases in capacity demand for a range of scenarios and from there consider the likely energy mix and technologies required to ensure that such demand could be provided on a sustainable basis. From this position, the outcomes were analyzed and recommendations were made.

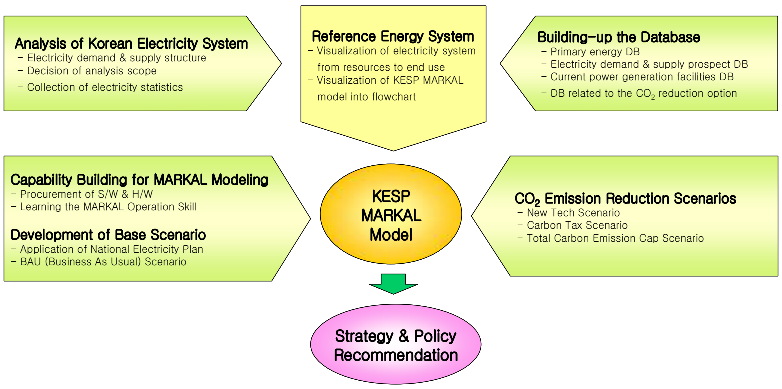

Figure 1 Overview of the model development

2. Energy system modeling and MARKAL

The power generation sector of the highest emitter of CO_2 within the Korean industrial sector will need to take measures to reduce such emissions. It is essential to assess the cost-effectiveness and the effect on both the electricity industry and the national economy of possible measures before any are adopted. Thus this study was intended to analyze the CO_2 emission reduction effect and the associated costs to the Korean electricity system if technical and political measures should be introduced to limit CO_2 emissions arising from power generation. The major targets of the model development were as follows (refer to Figure 1);

- to build up the basis for the analysis of the CO_2 emission reduction potential in the Korean electricity industry,
- to assess sustainable ways for CO_2 emission reduction that can be introduced into the Korean electricity industry,
- to investigate the effects of the several proposed scenarios for CO_2 emission reduction,
- to provide advice on strategies and policies for cost-effective CO_2 emission reduction in the Korean electricity industry.

After extensive discussions with various EU and Korean modeling experts, we selected the MARKAL modeling package of IEA(International Energy Agency)/ETSAP(Energy Technology Systems Analysis Program) as being appropriate for their needs. The team then took out a license for the MARKAL modeling package with the nominated organization, namely Decision Ware Inc. Subsequently, the Korean researchers have proceeded to develop their model in accordance with the approach set out in Figure 2. The Korean members of the project team familiarized and received operation techniques of MARKAL by cooperation of the ECN(Energy research Center in the Netherlands). This covered the drawing-up of a basic MARKAL, LP modeling and procedures for ANSWER software. This allowed the researchers to set up the basic framework of the KESP MARKAL model.

Following this initial training scheme, the project team sought the assistance of Korean MARKAL experts to guide them in the acquisition of special input data, data processing, and establishment of KESP Reference Energy System (RES) and scenarios. With the support of the experts, the project team put in the data to the ANSWER, established the prototype KESP RES, and modeled several scenarios for CO_2 mitigation. Subsequently, following assistance from the International Energy Agency (IEA) with the provision of various data sets, the researchers fine-tuned the model and completed the intended program of studies. [1,2,3] This comprised;

- Design of Reference Energy System of the Korean electricity industry,
- Development of Base Scenario model that fits to the current National Electricity Plan and could be used as a reference model for the comparison with CO_2 emission reduction scenarios,
- Development of CO_2 emissions reduction scenarios, such as the imposition of a carbon tax, the introduction of a total carbon emission cap and the introduction of new power generation technologies (e.g. advanced PF and CCS),
- Investigation of the optimum scenario, which can reduce CO_2 emissions most cost-effectively in the Korean electricity industry,
- Suggestions for strategies and policies to put the optimum scenario into practice.

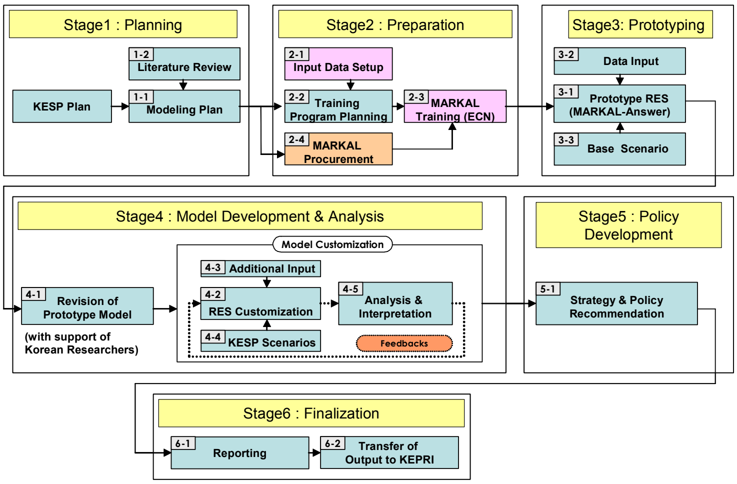

Figure 2 Schematic of the modeling approach

Table 1 Description of scenarios

	Features
Base Scenario	Only technologies either current in 2004 or included in the National Electricity Plan were included. Current trend for renewables introduction was reflected in the model. Constraints for some technologies were set according to the resource limit and geographical limit.
New Technology Scenario	Twenty likely and speculative new technologies using coal and gas, like IGCC, IGFC and CCS, were added to the Base Scenario for application within the lifetime considered in the model. CCS was included within these new technology variants.
Carbon Tax Scenario	Various carbon taxes (\$13, \$25, \$50, \$75/tCO_2) were imposed for both the Base Scenario and the New Technology Scenario. Effect of carbon tax was analyzed when lower generation limit was set on coal-fired power plant.
Total Carbon Emission Cap Scenario	Various total carbon emission caps (120%, 100%, 80%, 60% compared to the 2004 level) were imposed on the Base Scenario and New Technology Scenario. Effect of total carbon emission cap was analyzed when lower generation limit was set on coal-fired power plant

3. Energy system modeling and MARKAL

Four scenarios, which were considered the most likely by KEPCO in Korea, were developed to study the effect of CO_2 emission reductions on the Korean electricity industry, as in Table 1. These were defined as the Base Scenario, New Technology Scenario, Carbon Tax Scenario, and Total Carbon Emission Cap Scenario. Thus the Base Scenario assumes that the current electricity policy based on the National Electricity Plan is maintained. The New Technology Scenario considers the introduction of new power generation technologies which are expected to be used including CCS techniques. The Carbon Tax Scenario is the scenario where a tax on CO_2 emissions is levied. The Total Carbon Emission Cap Scenario takes into account the setting of a maximum level of CO_2 emissions. Subsequently, once the more promising scenarios were identified, possible strategies and policies were considered that might allow such scenarios to be established successfully. As part of this work, we also considered the correlation of the factors for CO_2 emission reduction in the Korean electricity industry. As the main objective of modeling was to analyze the influences of carbon emission mitigation options on the development of the national electricity system, the scope was limited to the Korean electricity generation and supply system and the related heat production and supply system. The period of analysis was set at 40 years from 2004 to 2044.

4. Results of scenario analysis

4.1 Results of base scenario analysis

Input data to establish the base scenario were obtained from official Government publications [4,5,6,7] as well as other yearbooks of statistics independently published by various industrial sectors. Overseas input data was obtained from IEA reports which were most reliable [1,2,3].

The initial key requirement was to establish the base scenario and to compare its output with that for the National Electricity Plan. Following tuning of the model, the electricity system estimated in the Base Scenario agreed very well with the one presented in the National Electricity Plan. There were some differences, up to 8%, in the period to 2009. This reflected the impact of certain constraints like the difference of plant construction time and capacity within the National Plan that are not compatible with the technology selection approach adopted in the MARKAL program. After these constraints were nullified, the difference fell to less than 2.5%, which is considered insignificant in terms of this particular project. Consequently, the results of the Base Scenario can be used with confidence as the standard for the comparison with the results of the other scenarios considered in this project and also as the basic data for other MARKAL analysis on the Korean electricity market in the future. The base scenario was developed from the assumption that the current conditions and plan of the electricity industry would continue without change, as defined in the National Electricity Plan [5]. It did not include any carbon emission mitigation efforts such as the introduction of advanced power technologies, carbon tax and total carbon emission cap.

This base scenario analysis showed that the overall power generation capacity would increase from 59.98GWe in 2004, to 81.68GWe in 2009 and then to 118.58GWe in 2044. When the different fuel sources were considered, the model indicated that coal-fired power plants comprised about 29% of the overall capacity in 2004 and about 32% in 2044. In the period around 2014, the percentage increased to about 42%, which reflects the impact of certain constraints applied to the model and, for the period 2014 to 2019, the overall plant margin was higher than strictly necessary. The LNG power plant capacity increased continuously to 2044 as the total electricity demand increased, contributing about 23~27% of the total capacity. After the constraint on the nuclear power plants was removed from 2014, the capacity of nuclear power facilities increased to meet the rising base-load demand, representing about 28% of overall capacity in 2004 and 32% by 2044.

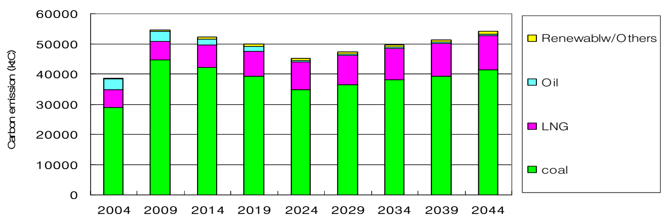

Figure 3 Carbon emissions due to fuel type used in the power generation sector (Base Scenario)

The carbon emissions were projected to increase from 38,633×10^3tC/year in 2004 to 54,844×10^3tC/year in 2009, and then to 54,170×10^3tC/year in 2044. The emission intensity increased from 0.1176kg-C/kWh in 2004 to 0.1285kg-C/kWh in 2009, but then decreased steadily to 0.0860kg-C/kWh by 2044. The overwhelming impact of the coal fired plant is shown in Figure 3.

4.2 Results of new technology scenario analysis

This scenario examined the impact of seeking to introduce new coal and new gas fired power generation technologies, some of which included CCS, into the power plant mix. The basis of their possible introduction was on economic grounds only without any political incentives to meet as yet undefined environmental limitations for CO_2 emissions. Since this study is focused on the mitigation of carbon emissions from the power sector, the introduction of new, advanced technologies were considered for only fossil fuel. The new technologies considered in this study comprised 13 new coal power technologies, 7 of which included CCS, and 7 new gas combined cycle technologies, 3 of which included CCS. They were those researched by the IEA in their study of prospects for CO_2 Capture and Storage [8].

This scenario resulted in almost the same energy mix and total capacity as those for the Base Scenario, Figure 4, although the replacement of existing fossil fuel fired technologies with highly-efficient new technologies resulted in about a 1.93% reduction in the total system cost over the period 2004 to 2044. The total power generation capacity mix hardly changed, year on year from that for the base scenario, Figure 4, although as power technologies of relatively higher efficiency were adopted, the quantity of gas power technologies needed was slightly reduced. As a result, when actual generation was considered, the total carbon emissions over the period of 2004 to 2044 were reduced by about 2.9%, from 446.7 million tons of carbon (MtC) to 433.7 MtC. This scenario demonstrates that more efficient fossil fuel technology can be introduced in the appropriate circumstances and will result in some decrease in CO_2 emissions. However, without some powerful drivers, the introduction of such technology coupled with CCS, which is seen as the best technical option to achieve a significant reduction in CO_2 emissions, will not occur. This is because the efficiency losses associated with CCS make the technologies economically unattractive unless either some form of financial incentive is applied or environmental regulations to severely constrain CO_2 emissions are introduced.

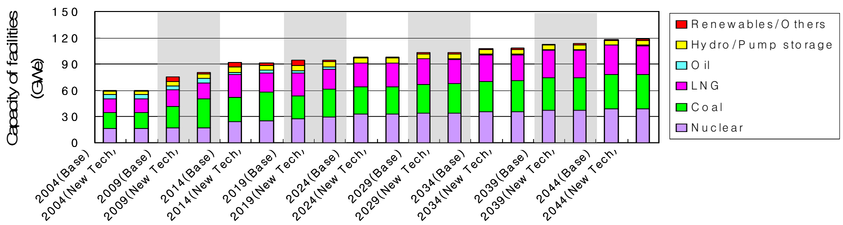

Figure 4 Growth in power system capacity (base scenario vs. new technology scenario)

4.3 Results of carbon tax scenario analysis (CTAX)

This scenario considered on a sequential basis the sensitivity of the carbon tax approach by assessing its impact at four levels, namely US\$13, US\$25, US\$37, and US\$50/tCO_2, taking into consideration the carbon taxes applied in the Reference Plan for the Korean National Electricity Plan. To put these levels in context, when the burden of the carbon tax is compared to the fuel price, the carbon tax is equivalent to 56 ~ 216% of the fuel price for coal power technology while it is 9 ~ 34.7% for gas power technology. In comparison to the Base scenario, where the carbon tax was US\$37/tCO_2 or below, there was no significant impact on either the overall power plant capacity or the fuel mix. This suggested that under the expected situation within the Korean power sector, these levels of carbon tax were too low to cause a perturbation in fossil fuel power plant technologies selection. However, for CTAX-50 with a carbon tax of US\$50/tCO_2, the capacity of coal power facilities was reduced by 38% compared to CTAX-37, while the increase in gas power generation was 48% in comparison to the base scenario for 2044.

As the carbon tax level increased, power generation by gas power technology relatively more expensive than coal power technology increased, resulting in the increase of total system cost by up to 4.6% in CTAX-50. For the various levels of carbon tax, the total carbon emissions decreased by 5.6 to 20.2%, compared to the Base scenario.

4.4 Results of new technology + carbon tax scenario analysis (NCTAX)

The combined effects of new technologies and carbon tax were analyzed. The impact on the overall capacity and on the technology mix was greater than for all previous options considered. Thus the higher the carbon tax, the greater is the driver for the higher efficiency, lower carbon technologies to be introduced. There was an increasing introduction of new coal based technologies equipped with CCS, from about 2019 onwards, such that by 2034 all the existing coal power technologies were replaced with ever more advanced coal power technologies equipped with CCS. Regardless of the carbon tax level, gas power technology maintained a capacity level similar to that of the Base scenario but the competitive superiority of each technology varied with carbon tax level. As the carbon tax increased, the total carbon emissions over the period 2004 to 2044 decreased by 7.5% to 47.5, compared to the Base scenario. In particular, for NCTAX-50 where all coal power technologies were completely replaced with new coal technologies with CCS, the decrease in carbon emissions was very significant. Thus from 2034 onwards, when CCS technology was largely applied, the CO_2 emission levels were reduced to 25% or less of that of the Base scenario.

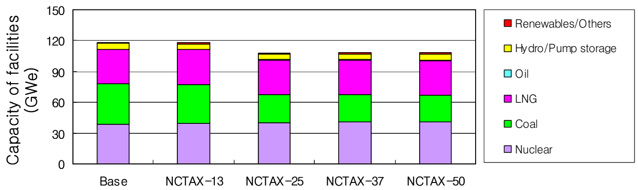

Figure 5 Capacity by fuel type in 2044 (Base scenario vs. NCTAX scenario)

4.5 Results of low limit on coal power generation + new technology + carbon tax scenario analysis (LNCTAX)

While the carbon tax was effective in constraining carbon emissions, it inevitably resulted in the reduction of coal fired technologies in favour of either gas power technologies or carbon neutral technologies such as renewables. From the perspective of security of energy supplies, a balanced portfolio of fuels is to be preferred. Within Korea, the current view is that for this sector an energy mix that is dominated by nuclear and coal with some gas and renewables would appear to be a realistic mix provided that carbon emissions can be constrained through the use of high efficiency plants equipped with CCS. Therefore this approach was assessed by applying a constraint to the Carbon Tax with New Technology scenario; such that the lower limit on coal fired power generation was 30%.

For these scenarios, compared to the Base scenario, the overall capacity remained effectively constant. However, there were significant changes in the types of coal fired plant introduced with increases in the level of carbon tax. Thus new coal power technologies with CCS became competitive as the carbon tax level increased. Subsequently, for the latter scenario, very high efficiency advanced CCS technology was introduced in 2029 and its capacity steadily increased to become the predominant coal based technology in the LNCTAX-50 scenario (29.44GWe in 2044). As the carbon tax level was increased, the total carbon emissions gradually decreased in comparison to the Base scenario, i.e. 5.3% (LNCTAX-13), 7.5% (LNCTAX-25), 9.0% (LNCTAX-37), and 34.8% (LNCTAX-50). The big change between the last two scenarios is a result of all coal power technologies being replaced with new power technologies with CCS. The other impact was that when the system was constrained such that coal fired plant maintained a minimum of 30% of operational capacity, the introduction of a carbon tax promoted the earlier introduction of new coal technologies equipped with CCS but delayed that of new gas technologies with CCS.

4.6 Results of total carbon emission cap scenario analysis (CToT)

The use of a total emissions cap as an alternative means to limit CO_2 emissions was next considered. The sensitivity of this approach was examined by setting the total carbon emission cap at 120%, 100%, 80%, 60%, and 40% of the emissions level in 2004. For scenarios CToT-120 to CToT-80, as the total carbon emission cap became tighter, gas power technology increasingly replaced coal power technology within the capacity mix while the annual load factor of competitive gas power technology increased, resulting in an increase in overall utilisation and a corresponding decrease in total capacity, Figure 6. However, to achieve even lower target levels of carbon emissions (CToT-60 and 40) was not possible just through a replacement of coal by gas fired technology as the coal fired plant had just about been eliminated from the grid. Consequently the model suggested that as well as gas power capacity continuing to increase there would need to be a very significant increase in the use of nuclear power and a very significant introduction of renewables.

The consequence of this approach was to massively increase the use of zero emission technologies (nuclear and renewables) as well as the (lower carbon) LNG technologies, at the expense of coal. As in the carbon tax scenarios, these total carbon emission cap scenarios indicated that gas power would replace coal power unless other alternative fuel technologies became available. Also, when the cap was particularly severe, then the capacity mix required appeared to be unrealistic and relatively expensive.

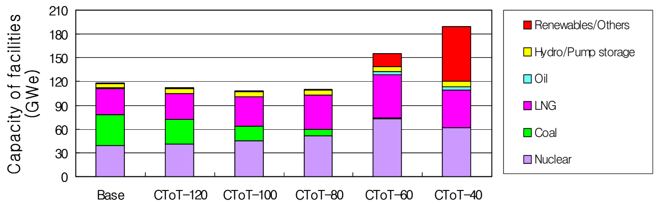

Figure 6 Capacity by fuel type in 2044 (Base scenario vs. CToT scenario)

4.7 Results of new technology + total carbon emission cap scenario analysis (NCToT)

Figure 7 shows some change in overall capacity and fuel type as the total carbon emission cap became more severe. Thus the capacity of coal power technology facilities decreased by close to 40% when the cap was decreased from 120 to 100%. However, at the same time there was a strong driver for advanced technology with CCS to be introduced. That is, the stronger the emission cap, the earlier CCS technology was introduced and the more advanced the technology that was introduced. The other point to note is that as the total carbon emission cap became stronger, power generation by gas power technologies replaced power generation by coal power technologies.

In this analysis, coal power generation decreased but gas power generation increased instead. As a result, total carbon emission was mitigated 7.7% and 37.8% for NCToT-120 and NCToT-40, respectively. The use The initial key requirement was to establish program. In these NCToT scenarios, if only new power technologies with CCS were compared it appeared that coal power technology was adopted more rapidly, achieved higher capacity and had a higher load factor than gas power technology. It implies that as the total carbon emission cap was tightened, new coal power technologies with CCS, which have the capability of mitigating more carbon emission to produce same amount of electricity, are necessary to meet the cap.

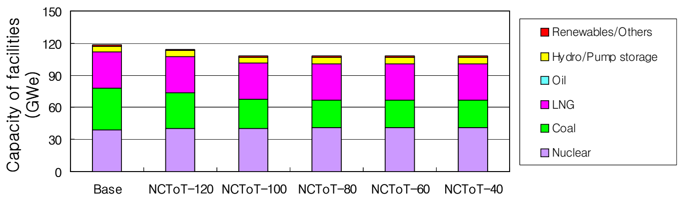

Figure 7 Capacity by fuel type in 2044 (Base scenario vs. NCToT scenario)

4.8 Results of low limit on coal power gen. + new technology + total carbon emission cap scenario (NCToT)

As for the carbon tax scenario, it is necessary to take into account security of supply concerns, which require a certain capacity (30%) of coal fired power plant to be maintained on the grid. The capacity for each fuel type technology was relatively constant although there were significant differences in the load factors and for the times at which advanced technologies with CCS were introduced. In comparison to the NCToT scenarios, the LNCToT scenarios promoted the introduction of new coal power technology with CCS but delayed that of new gas power technology with CCS. Consequently there was a greater cost associated with the LNCToT scenarios compared to the NCToT scenarios to achieve the same carbon emission mitigation effect.

In the LNCToT scenario, unlike for NCToT, due to the lower limit on power generation by coal power technologies being set at 30%, new power technologies that could meet the emissions cap replaced the existing power, resulting in an increase in power generation by new technologies with CCS. Due to early appearance of coal power technology with CCS, power generation by gas power technology with CCS was delayed in comparison to the NCToT scenario. That said, the carbon emissions level was very similar.

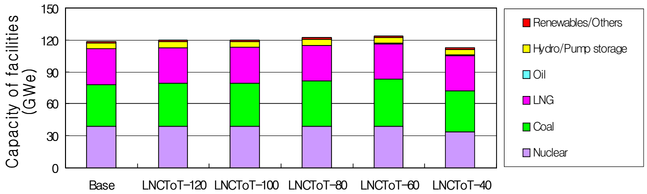

Figure 8 Capacity by fuel type in 2044 (Base scenario vs. LNCToT scenario)

5. Conclusion

The MARKAL modelling activity has provided information on future projected power demand and on the future mix of power generation technologies (nuclear, natural gas, coal and renewables), together with a sensitivity analysis of those projections to the imposition of environmental drivers such as a carbon tax and a carbon emission cap. This has allowed KEPRI to develop scenarios for achieving various levels of CO_2 mitigation within the power generation sector options. It has also indicated, with the imposition of a number of environmental drivers, the timescales for when advanced technologies, including CCS, will need to be available for sustainable introduction into the power plant mix. At the same time, the sensitivity analysis has also shown the considerable uncertainly inherent within the scenarios. For example, the prime technology choice in many scenarios was gas fired combined cycle power plant, based on the IEA input parameters. However gas prices have risen significantly since those numbers from 2004 were selected and such rises would certainly have some adverse impact on gas technology relative competitiveness. Another issue is the lack of mature CCS techniques, which again will introduce some uncertainty into the relative technology competitiveness. Finally, there is as yet the lack of a comprehensive framework to establish such technologies on a commercial basis.

Thus it is strongly recommended that more diversified scenarios for carbon emission mitigation in the electricity industry should be analyzed and the outputs compared to those already examined. From this, the more promising (i.e. more effective and sustainable) options should be identified, which may well comprise combinations of a number of options. This should form the basis from which a plan for a national carbon emission mitigation implementation system could be determined. From this starting point, it should be possible to suggest systematic policies that will allow the plan to be implemented successfully.

Acknowledgements

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