Technological Advancement and Implication for Optimal Carbon Mitigation Portfolio in Korea Power Sector

- A scenario analysis using a bottom-up energy system model -

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Abstract

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Technology is widely considered to be one of the decisive factors governing the interaction between energy, environmental and economic systems. While most pollution problems are byproducts of using existing technology within economic activities to meet human needs, new technology may also provide alternative means to meet the same human needs with less harm to the environment. When searching for solutions to a long term environmental problem such as climate change, the significance of technological innovation is quite prominent since future technological progress may play an important role in ameliorating what in the short run appears

to be a serious conflict between economic activity and environmental goals, due to the lack of cost-competitive technology alternatives. The positive prospect for future technology development brings many to believe the long-term and ultimate solution to climate change will be realized through technological change.

The overarching goal of this thesis is to investigate the role of technological advancement in managing carbon mitigation and achieving the transition to a low carbon electricity supply system in Korea. Given diverse low carbon technology options, a comprehensive assessment of technological advancement potential, its implication for the development of a cost-effective carbon mitigation technology portfolio, and its role in managing mitigation cost would provide guidance in setting the policy direction to low carbon system transformation. It would also help design energy and technology policies directed toward climate-friendly technology development or deployment such as defining priorities for research, and development (R&D) funding and public support for technology deployment and diffusion.

Korea — ranked the 7th largest GHG-emitting country in the world in 2010 with 570 million tonnes of CO_2 equivalent ($MtCO_2e$) from fuel combustion—, the power sector is one of the biggest players both as an energy supplier and GHG emissions source. Korean electricity sector generates about 475TWh of electricity which accounts for 19.3% of total final energy consumption in 2010; this reflects a rapidly growing industry when looking at the 4% share in 1970. This sector is one of largest GHG sources which emit about 238 $MtCO_2e$ in 2010 accounting for 41% of GHG emissions from fuel combustion. Given that many research institutes and government agencies project the continuous rising of electricity consumption in the future, the electricity sector will be the most important sector under any carbon reduction policy.

The thesis developed a Korean power sector model in the MESSAGE (Model for Energy Supply System Alternatives and their General Environmental impacts) modeling framework. MESSAGE is a bottom-up, technology-rich systems engineering optimization model for medium- to long-term energy system planning, energy policy analysis, and scenario development and analysis related with energy and environmental issue. The model provides technology-specific response strategies for achieving a given policy goal by solving for the least-cost portfolio of supply technologies and their deployment over time. The MESSAGE of Korean power sector was developed in a way to fully account the vintage structure of energy capital and near-term capacity expansion plan to reflect a short-term rigidity of long-lived, capital-intensive electricity supply system. The optimization feature of the model and reality-based model calibration would provide more realistic scenario results when assessing the role of technological advancement in the electricity sector transitioning to a low carbon one from the system wide, inter-temporal cost optimization perspective.

The way of representing technological advances in the study is a various set of cost reduction and performance improvement of low carbon technologies. The portfolio of low carbon technology under consideration in this study include those technologies which already passed beyond the demonstration project, are commercially available in the global market, and are considered in the Korean government's 25-year horizon plan for electricity supply and demand. The prospect for the rate of cost decrease and performance improvement is adapted from various global carbon emission and mitigation scenario analyses in the literature. To incorporate the uncertainty surrounding future technological advancement and the stringency of carbon mitigation target, various combinations of carbon mitigation pathways and the rate of technological advancement was considered as alternative scenario assumptions.

The analysis demonstrates several important points.

First, the analysis identifies that carbon mitigation costs can be reduced by 30% to 100% through technology advancements. The range, dependent on the stringency of carbon mitigation and the extent of technology advancement, is equivalent to annual cost savings of 4 to 8 trillion KRW over the next 40 years compared with when the status of technology advance is frozen at present level. This estimate can serve as a reference for economic benefit of technological advances against which economic cost of policy is balanced when technology development or deployment policy is designed.

Second, cost-competitiveness of zero-emitting variable renewable (varRE) technologies is not ensured by technology advancement alone, but by the combination with aggressive decarbonization policy goals. Although the economy of individual varRE technology can reach as low as so-called grid parity level, a complementary backup system which is required to ensure reliable operation of the overall power system, imposes an additional implicit cost on these technologies. Although the economy of individual varRE technology can reach as low as so-called grid parity level, a complementary backup system which is required to ensure reliable operation of the overall power system, imposes an additional implicit cost on these technologies. Such implicit costs of varRE technologies can be offset by aggressive carbon mitigation policy goals. Thus, the discrepancy in the economy of a technology between the stand-alone and system integration perspective should be carefully addressed in this type of analysis to avoid an overestimation of the role of varRE technologies.

Third, fuel substitution into natural gas utilized by advanced combined cycle technology is a robust carbon mitigation measure regardless of stringency of carbon constraint and the degree of technology advance of low carbon technologies. That is, the expansion of natural gas in the generation mix is a 'no-regret' technology choice even under the combined uncertainty of technology advancement and policy target for carbon mitigation. This finding is supported by the reasoning addressed in the previous paragraph on the weakness of varRE technologies as carbon mitigation options. Relatively clean natural gas without any intermittent problem becomes more cost competitive under a carbon constrained world. CCS technology is also an attractive mitigation option if relative competitiveness among a broad range of low-carbon technologies is frozen at the current level. However, if the rate of advance for CCS is slower than that of other low carbon alternatives, as much of the technology scenario literature estimates, CCS technology would lose its competitive edge to other alternatives.

Finally, a significant challenge for a large scale deployment of low carbon technologies lie ahead regardless of technological advance. Depending on the carbon abatement policy goals, low carbon generation share needs to reach to 8% to 11% by 2030 and 28% to 41% by 2050, a fast and significant increase from 1.7% in 2010. If the most ambitious decarbonization target (i.e. 50% reduction by 2050 from the current level as in 'mit50%') is pursued, an unprecedented deployment of low carbon technologies, a steady growth at the rate of 10% per year, is required

over the next four decades. Technology advance will only alleviate the cost to achieve this transition. An effective policy response to such challenge is to make an immediate change in current policy direction for electricity supply portfolio. The later into the future this policy change is delayed, the greater the challenge and associated costs of carbon mitigation would be.

Keywords: technological advancement, electricity power sector, carbon mitigation, bottom-up optimization energy model, low carbon technology, energy and technology policy

Chapter 1. Introduction

1.1 Climate Change: A Policy Problem

The establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 has brought climate change issues to the forefront of international and domestic energy and environmental policy discussion among scientist, policymakers, and political leaders during the past two decades. The international agreement, whose ultimate objective is the stabilization of GHG concentration in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate system (United Nations, 1992), presents one of the grand challenges for humanity in the twenty-first century.

The grand challenge stems from the fact that many of the activities that generate GHG emission are also responsible for the economic well-being of humanity. Inaction or not-enough action in emission reductions may result in significant anthropogenic interference with the climate, triggering climate impacts such as rising sea levels and weather patterns change, ecosystem impacts such as habitat loss and species extinction and impacts on agriculture, human health, settlement and mobility (Intergovernmental Panel on Climate Change, 2007). Conversely, aggressive action in emission reduction is likely to incur a significant burden on the world’s economies, because the large portion of anthropogenic carbon is emitted by the combustion of fossil fuels to provide energy inputs to economic activity. Some fear the environmental and socioeconomic costs of inaction while others are more fearful of the economic consequences of trying to avoid climate change. Policymakers face such dilemma and the economic analysis of climate change deals with the fundamental difficulty of choosing the timing and extent of cuts in carbon emissions in such a way that the overall net costs (i.e. cost of carbon control minus benefit of avoided climate-related damage from carbon control) incurred by society are minimized.

Despite the stumbling of two-decade long international climate negotiation and no consensus yet on what constitute “safe” levels of atmospheric CO_2, little doubt is shared among scientific community and political leaders that stabilizing concentrations within the 100- to 200-year time-frame will necessitate drastic and sustained cuts in carbon emissions below current levels (Intergovernmental Panel on Climate Change, 2007). More recently, limiting global mean temperature rise to 2°C above pre-industrial levels (“2°C target”) seems to have developed into a widely accepted goal (Copenhagen Accord, 2009; Council of the European Union, 2005; G8, 2009) which requires significant short- to medium-term action and would require “our willingness to share with all countries the goal of achieving at least a 50% reduction from current global emission by 2050”(G8, 2009).

Undertaking such a drastic carbon emission cut necessary to slow climate change is likely to impose economic costs on society, changing patterns of energy production and use, and associated technologies in ways that adversely affect the welfare of consumers in economies that use large quantities of energy currently from carbon-emitting fossil fuels.

There are a number of reasons what makes this drastic and sustained cut in carbon emission hard and expensive.

First, the world today relies predominantly on carbon-emitting fossil fuels to supply its energy needs. These fuels currently satisfy 86% of world primary energy needs (IEA, 2012e) and lead to the release of more than 30 billion tons of CO_2 in 2010 along with significant quantities of other GHGs (IEA, 2012a). Any attempt to curb the CO_2 emission from fossil fuels will lead to the increase of aggregate energy price by substituting currently expensive alternative low- or zero- carbon energy for relatively cheap fossil fuels. The increase of energy price will last until alternative carbon-free energy and associated technologies come into existence that has a clear cost advantage over fossil fuels.

Second, the energy system from production to use and associated technologies and infrastructure is capital intensive and its lifetime usually last a few decades. The transformation of energy system into low-carbon one requires complete turnover of existing energy-related capital stock which is heavily fossil fuel-based. The more drastic emission cut is pursued the earlier retirement of fossil-fuel based energy capital is required. The premature retirement of energy-related capital and its replacement with low-carbon one requires new investment in low carbon energy capital and incurs great burden on an economy. The rigidity and inertia of energy system and associated capital thus imply the carbon control, by nature, is a long-term issue.

Third, energy is used in every sector of the economy and human activities. Increases in the cost of fossil fuels have economy-wide effects on production costs, the level and growth of output, and income and standards of living. Given many developing countries around the world seek to develop their economies and to attain higher standards of living, limiting CO_2 emission will be a daunting task and challenge.

One pivot in the cost-benefit analysis of climate change is to analyze the economic costs of carbon controls and the cost-effectiveness of various policies or technology portfolio in achieving a given carbon control target. Many climate change policy analyses only address the cost aspect of abating GHG emissions setting aside the environmental and socioeconomic benefit of abating GHGs. Uncertainty and long-term nature of the benefit (i.e. avoided damage from climate change by abating GHGs) may make the estimate of benefit elusive and the global stock pollutant nature of GHGs can make it hard to fully incorporate the benefit side of carbon control into national level climate policy consideration.

The focus of this thesis is on the economic cost of carbon control. From a sovereign state perspective more realistic and pending policy question regarding climate change response are how much a society can commit to carbon control and how to achieve a commitment level in a cost-effective way. More specifically this thesis investigates the role of technological change on the economic cost of carbon control and the development of optimal mitigation technology portfolio.

Of all the factors that hinder or facilitate the process of reducing emissions, new technology plays what is perhaps the most important role. Technology is widely considered to be one of the decisive factors governing the interaction between energy, environmental and economic systems. While most pollution problems are byproducts of using existing technology within economic activities to meet human needs, new technology may also provide alternative means to meet the same human needs with less harm to the environment. When searching for solutions to a long term environmental problem such as climate change, the significance of technological innovation is therefore quite prominent. Future technological progress may play an important role in ameliorating what in the short run appears to be a serious conflict, due to lack of competitive technology alternatives, between economic activity and environmental quality. The positive prospect for future technology development makes many to believe the long-term and ultimate solution to climate change will be realized through technological change whether it is for climate mitigation or adaptation. Given that 80% of global heat-trapping GHGs are being emitted in a way to produce and consume energy, technological development on energy technology gets much attention from climate change research community.

1.2 Role of Technological Change in Carbon Mitigation

From the beginning of human civilization technology has been positioned at the center of economic activity and human being's surrounding and has made it possible for human society now to produce 70 trillion USD (U.S. dollar) of new goods and services annually. As schematically illustrated in Figure 1 technology has shaped how the human being utilizes natural resource from its surrounding and satisfied its needs and desires by providing necessary inputs and services to economics activities and human wellbeing. Technology has also played defining roles as a cause of, and solution to various environmental problems. Technology, as a cause to environmental impact, has imposed a social cost on economy while as a solution it has managed the environmental harm and made tackling those harms more affordable by providing alternative options. In this sense, it can be said that economies and societies have evolved as a result of technological change (Grübler, 2003)[1]. A long progression of inventions – steam engines, electric motor, internal combustion engine, automobile, vacuum tube, commercial aviation, television, nuclear energy, microchip, just to name a few - has changed people's lives.

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[1] Technology and Global Change describes how technology has shaped society and the environment over the last 200 years. This book gives a comprehensive description of the causes and impacts of technological change and how they relate to global environmental change.

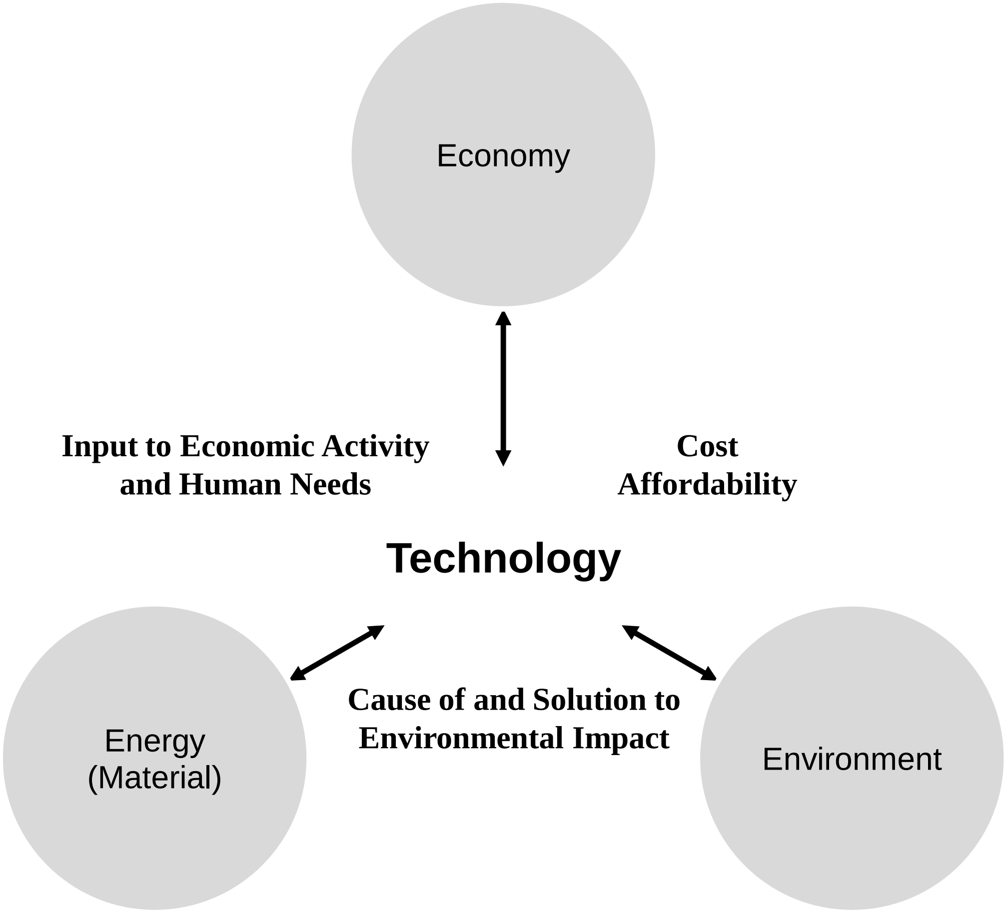

Figure 1: Schematic view of role of technology in intertwined relation between energy, environment, and economy

When it comes to energy production and use, our society has moved from a reliance on wind, water, animal power, and wood to reliance first on coal, and then petroleum, natural gas and nuclear as shown in Figure 2 which illustrates the evolution of global primary energy consumption by different energy sources during the past 150 years. Such dynamics has been closely related with the development of associated energy supply and demand technologies by making it possible to extract resources, to convert one energy form into another, and to provide a useful service such as mobility, machinery work, process heat for industry, illumination, cooling, heating for human comfort. While technology has defined the way in which energy is produced and used for economic activities, the evolution of technology also has been a major cause of and solution to various environmental problems. Technological progress has held keys to pollution abatement in the course of economic growth and also to reducing the costs of pollution abatements. If we look at the history of pollutants like particular matter (PM), leads in fuels, volatile organic compounds (VOCs), and more recently SO_2 and NO_x, technologies and fuels have been developed that are able to reduce pollution per unit of energy use and even with rising energy consumption, we have seen dramatic reductions in emission levels thanks to technological change (Grubb et al., 2002).

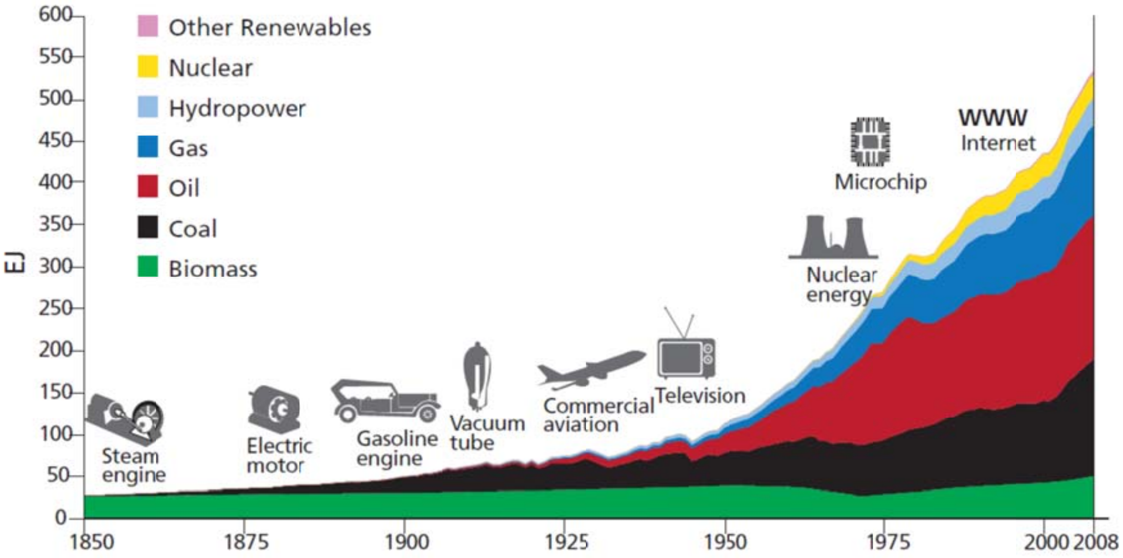

Figure 2: Total global primary energy consumption in the period of 1850-2008 (Source:GEA (2012a))

Given the influence of technology and its dynamics on shaping economic activity, defining energy supply and demand, and being cause of, and solution to environmental problem, technological change has drawn much attention in the climate change discussion, which is one of the most important environmental problems human society is facing now. Given the long-term nature of both climate change and technological change, the direction and extent of technological change have profound implication for future carbon emissions and any response strategies to climate change.

There are several aspects involved to explain why technological change is important in carbon mitigation.

First, technological change seems to be the only malleable variable among other driving forces for carbon emissions. Given the combined pressures of population and economic growth which is hardly a policy control variable for the purpose of climate change mitigation, the radical reductions in carbon emissions that would be required to stabilize the atmosphere in the next century can only be achieved if technologies with much greater efficiency in energy use and carbon free supplies can be improved substantially.

Second, technological change may also play an important role in technical attainability and economic affordability of carbon control targets. Determining the technical feasibility of how deep cuts in carbon emission can be made on what time schedule (i.e. timing of abatement) depends on the availability of wide range mitigation technologies portfolio and their deployment potential in the energy and economy system.

Finally, technological change also governs the affordability of a carbon control target by affecting the abatement cost. Improvement of low carbon supply technologies and energy use efficiency in terms of economic cost and technical performance would tend to alleviate the burden of carbon control in a society. Figure 3 illustrates the implication of technological change for technical attainability and economic affordability of carbon abatement. Depending on technological change, a society can achieve a given carbon control target at less cost and can achieve more stringent mitigation target at the same cost. The harmonized consideration of technical feasibility and economic affordability will serve for the mitigating goal setting by policymakers and technological change influence both aspects of policy decision criteria.

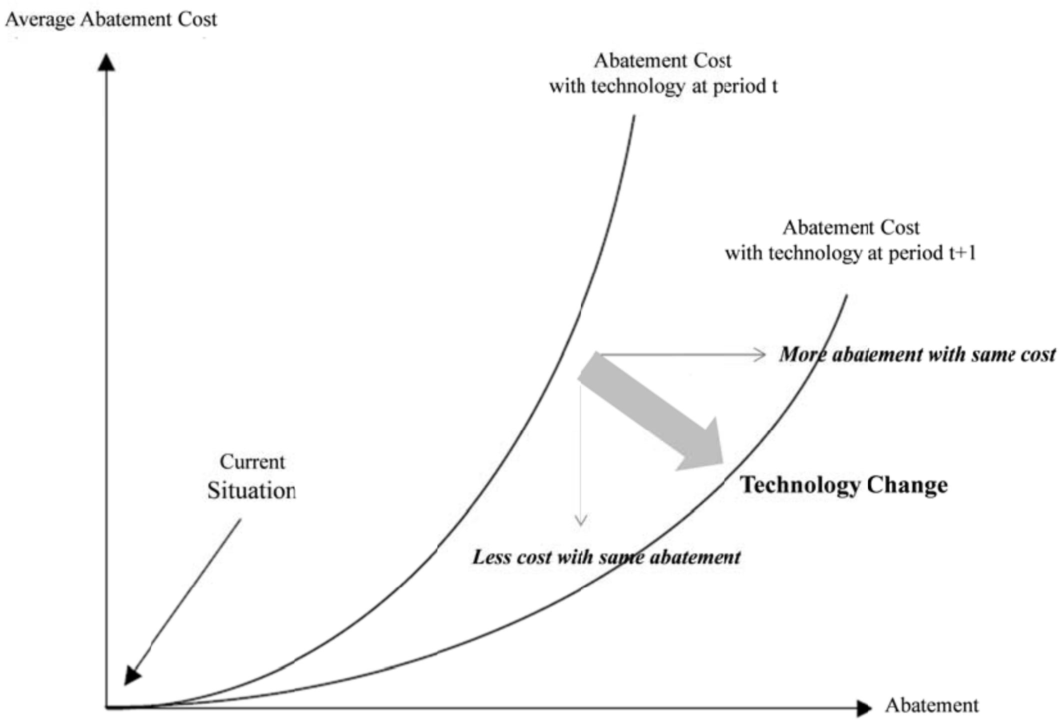

Figure 3: The implication of technological change in pollution abatement cost
(Note: modified from Grubb (1997))

1.3 Objective and Scope

The specific objective of the thesis is to investigate the role of technological advancement in managing carbon mitigation and achieving a transition to low carbon electricity supply system in Korea. Given diverse low carbon technology options, a comprehensive assessment of technological advance potential, its implication for the development of cost-effective carbon mitigation portfolio, and its role in managing mitigation cost would provide an important guidance in setting policy direction to a low carbon transformation. It would also help design energy and technology policies directed toward climate friendly technology development or deployment such as defining priorities for research, and development (R&D) funding and public support for technology deployment and diffusion.

Korean power sector is one of the most important energy sectors both in terms of its contribution to final energy mix and GHG emissions. The sector generates about 475TWh of electricity which accounts for 19.3% of total final energy consumption in 2010 rapidly growing from 4% in 1970. The sector is one of largest GHG sources which emitted about 238 $MtCO_2e$ in 2010 accounting for 41% of GHG emissions from fuel combustion. Given that many research institutes and government agents project the continuous growth of electricity consumption in the future, the electricity sector will be the most important sector under any carbon reduction policy.

The thesis developed a Korean power sector model in the MESSAGE (Model for Energy Supply System Alternatives and their General Environmental impacts) modeling framework. MESSAGE is a bottom-up, technology-rich systems engineering optimization model for medium- to long-term energy system planning, energy policy analysis, and scenario development and analysis related with energy and environmental issues. The model provides technology-specific response strategies for achieving a given policy goal by solving for the least-cost portfolio of supply technologies and their deployment over time. The MESSAGE of Korean power sector was developed in a way to fully account for the vintage structure of energy capital and near-term capacity expansion plan to reflect a short-term rigidity of long-lived, capital-intensive electricity supply system. The optimization feature of the model and reality-based model calibration would provide more realistic scenario results when assessing the role of technological advancement in the electricity sector transformation into low carbon one from the system wide, inter-temporal cost optimization perspective.

The way of representing technological advance in the study is a various set of improvement in cost and performance of low carbon technologies. The portfolio of low carbon technology under consideration in this study include those technologies which already passed beyond the demonstration project, are commercially available in the global market, and are considered in the Korean government's 25-year horizon plan for electricity supply and demand. The prospect for the rate of cost decrease and performance improvement is adapted from various global carbon emission and mitigation scenario analyses in the literature. For the quality check purpose of applying the rate of technology advancement from scenario literature into Korea-specific situation, technological learning rates for different electricity technologies were estimated based on empirical data in Korea and were compared with estimates from other literature. To incorporate the uncertainty surrounding future technological advancement and the stringency of carbon mitigation target, various combinations of carbon mitigation pathways and the rate of technological advancement was considered as alternative scenario assumptions.

The body of the thesis consists of four chapters. Chapter 2 overviews the types of models used to assess the economic effects of climate policy and different methods for representing technological progress (both exogenous and endogenous). Also key issues associated with energy/environmental policy design and instrument choice in ways to promote technology innovations are outlined. In last part of Chapter 2, the concept of technological learning and its empirical evidence in electricity technology both in literature and in Korean power sector is presented. Chapter 3 starts with the introduction of historical development and current status of Korean power sector in terms of supply, demand, and GHG emissions. This chapter also assembles the economy and performance data of currently utilized technologies on which the model is calibrated in order to generate more realistic scenario results. Later part of Chapter 3 introduces the MESSAGE modeling framework and its application in the literature as well as the structure of Korean power sector mode. Chapter 4 presents key scenario assumptions with their quantifications as well as the results of scenarios performed with the model. Scenario results are presented in several aspects such as relative contribution of individual technology or measure to carbon mitigation, cost implication of technology advancement, and optimal technology portfolio and necessary transformation of electricity supply system. Finally, Chapter 5 concludes by summarizing the key finding from the analysis, drawing some policy implications from the key finding and discussing future work to be undertaken with the model developed in this thesis

Chapter 2. Modeling Technological Change in Climate Change Policy Analysis

2.1 Models for Climate Change Policy Analysis

A model is a simplified characterization of a system that captures the important elements of how the system works for a particular problem at hand. Economic models of climate change represent a complex system where intertwined relation occurs between energy, environment and the economy. Models of complex socioeconomic systems require simplifying assumptions on system boundaries and system relationships. One of the key determinants of the system relationship is technology and its future change. Economic models of climate change, with a time horizon of many decades, rely on some metric of technological change to capture the evolution of technical progress over long periods. This future evolution will affect the scale of human economic activity, how economic actors produce and use energy, and their environmental impact.

Economic models of climate change are generally classified into two categories: bottom-up and top-down. They differ mainly with respect to the emphasis placed on a detailed, technologically-based treatment of the energy system, and a theoretically consistent description of the general economy (Loschel, 2002).

The bottom-up models

The bottom-up models for climate change policy analysis are usually a partial model of the energy sector describing emissions from energy production and consumption in detail. They do not incorporate a complete model of economic activity to which the energy sector provides inputs, and thus lack interaction between energy sector and the rest of economy. In general, they are technology - or energy-engineering - based linear activity models with detailed description of large number of energy technologies to capture substitutions and penetration of energy carriers and associated technologies from the primary, through the conversion and distribution, to the provision of energy services to the end-use sectors.

The bottom-up models can be roughly classified as simulation and optimization model depending on whether the model computes the least-cost system transformation subject to various systems constraint[2]. In optimizing bottom-up models, a rich description of various technologies with cost and performance characteristics are used to compute the least-cost methods of meeting a given energy demand subject to various systems constraint such as exogenous emission reduction targets. They generally begin by assuming that a set of advanced technologies either does or will exist, with predetermined cost and efficiency characteristics. They embed new technologies and model the penetration of these technologies via competition with old and existing ones based on costs and performance characteristics. Technological change occurs by the process of technology substitution.

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[2] For a list of bottom-up energy system models and is classification, see Connolly et al. (2010)

They then compare the world as it is now to the world that would exist if the assumed technologies were to be commonly used. Thus, their depiction of climate change policy will depend strongly on the assumptions they make regarding new technologies.

Because of the partial coverage of energy system and the narrow emphasis on the comparative cost and performance of individual technologies, these models usually do not reflect many other aspects of the economy's response to climate change and climate change policy, such as broader price-induced changes in energy demand, or the way households work or save. They are poorly suited, therefore, to estimating the societal economic cost of climate change or related policies. Instead, their strength lies in analyzing the energy sector specific technological response to climate change and for carbon mitigation with associated energy system transformation and in illuminating the economic value of possible technological improvements.

The top-down models

The top-down models place emphasis on a theoretically consistent description of the general economy and are predicated on "market equilibrium" as a way to achieve overall economic efficiency. These models use a set of equations to describe the complex web of interaction between producers and consumers. They do not rely on direct and detailed descriptions of the energy system and associated technologies. Rather, they describe the energy system (similar to the other sectors) in a highly aggregated way by means of neoclassical production functions that capture substitution possibilities between production factors through substitution elasticity (Loschel, 2002).

Computable general equilibrium (CGE) models, a kind of top-down models, have become the standard tool for the analysis of the economy-wide impact of GHG abatement policies on resource allocation and the implication for incomes of economic agent across sectors (Grubb et al., 1993). General equilibrium which a CGE model seeks provides a consistent framework for investigation price-dependent (or induced) interactions between the energy system and the rest of economy. This feature of CGE models is important when assessing the economy-wide impact of climate policy since carbon abatement polices not only cause direct adjustments on fossil fuel or GHG markets; they also produce indirect spillovers to other sector of markets which, in turn, feed back to the economy.

The top-down models do not necessarily provide details about design, costs, or performance of specific technologies. Rather, they start with a set of initial conditions based on the current state of the economy, and then extrapolate from past experience to look at the future implication of major economic and technological forces. As they contain little or no explicit technological detail, many top-down models represent technological change in terms of a single societal rate at which energy efficiency will continually improve in the future, a rate usually based on observed values in the past. This exogenous depiction, therefore, requires the modelers to make an assumption regarding the value of this ongoing, “autonomous”, improvement .

Other top-down models have attempted to replace this “exogenous” assumption with a more detailed representation of the very process by which technology is created and adopted by firms in the economy. This approach starts by assuming that the amount of innovative effort in the economy is a direct function of current and anticipated economic conditions, and is called endogenous technological change, because technological change is projected within the model

Hybrid Model

There has been also various try to mix these two broad types of representation of the energy sector and the general economy. A top-down representation of the economy is linked with a bottom-up description of technologies in energy market. Bohringer (1998) presented how a synthesis of top-down and bottom-up approaches can be used in a CGE modeling for a hybrid description of economy-wide production possibilities where energy sectors are represented by bottom-up activity analysis and the other production sectors are characterized by top-down regular functional forms. Messner and Schrattenholzer (2000) linked a macroeconomic model (MACRO) with a detailed energy supply model (MESSAGE). MESSAGE-MACRO link consistently reflects the influence of energy supply costs as calculated by the energy supply model in the optimal mix of production factors included in the macroeconomic model.

Wing (2006) incorporated technology detail into the electricity sector of a computable general equilibrium model of the US economy to characterize electric power's technological margins of adjustment to carbon taxes and to elucidate their general equilibrium effects.

Integrated Assessment Model (IAM)

Models of climate change policy analysis recently try to approach climate change modeling in a very comprehensive way by gathering knowledge from diverse scientific fields. So-called Integrated Assessment Models (IAMs) of climate change combines environmental or climate sub-models with energy system or economic models.

IAMs can be divided into two broad categories, which vary according to the purpose of policy analysis. Policy evaluation (or simulation) IAMs evaluate the effect of an exogenous policy goal (e.g. a stabilization of atmospheric GHG concentration at certain level) on climate, energy, and economic systems as done in Riahi et al. (2007) with IIASA (International Institute for Applied Systems Analysis) IAMs framework.

In contrast, policy optimization IAMs have the purpose of finding the efficiency or cost-efficient climate change policy and simulating the effects of an efficient level of carbon abatement as done in DICE model (Nordhaus, 1994). Since this is a complex process, such models typically have relatively simple economic and climate sectors.

Models[3] of climate change policy analysis differ with respect to where analytical emphasis is placed (e.g. system boundary or interactions under consideration within the system) and how technology and its dynamics are represented. Even though the specific class of a model is important for GHG mitigation cost projections, recent model studies show that different

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[3] For survey of the literature and overview of modeling methodology and classification, see Connolly et al. (2010), Gillingham et al. (2008), Loschel (2002), Grubb et al. (2002), and Edmonds et al. (2000)

modeling approaches are less important than model differences in assumption on technology and its dynamics over time. Indeed, the difference in the descriptions of technological progress in models, which will be covered in following section, seems to be the most important explanation for the inequality between top-down and bottom-up models in the assessment of economic costs of GHG emissions (Loschel, 2002).

2.2 Review of Representing Technological Change in Climate Policy Models

Modeling technical change in climate policy analysis is one of the most complex and salient question. The treatment of technological change in climate policy modeling is widely considered to be one of the most important determinants of the results of climate policy analyses such as future projection of GHG emission, the cost of mitigation, the timing of abatement, and policy instrument choice for the effective GHG mitigation etc. Unfortunately, the complex mechanism by which the processes of technological advancement work are neither understood clearly nor captured easily in modeling frameworks, creating significant difficulties for modelers and various modeling results.

The remainder of this section introduces the different methods in literature of treating technological change in climate policy model, provides an overview of how to conceptualize these methods in modeling framework, and reviews the pros and cons of each method.

Exogenous Technological Change

In a broad classification, methods of treating technological change in climate policy modeling can be dichotomized into exogenous and endogenous one. In former approach the most common and widespread use until recently, technological change is considered an exogenous variable defined outside modeling boundary- simply an autonomous function of time. The exogenous approach incorporates technological change as a non-economic variable that is defined outside the model and excludes the linkage between other socio-economic and policy variables in the model. It regards technology innovation as “manna from heaven” and can show mere effect of technical change, but not how technology development occurs in the dynamics with policy interventions.

One of simple practical way of exogenously representing technological change in climate policy model is to include an autonomous energy-efficiency improvement (AEEI) parameter, which increases the energy-efficiency of the economy by some exogenous amount each year. The use of an AEEI parameter is particularly common in more aggregated and top-down models such as DICE (Nordhaus, 1994). AEEI has the primary advantage of simplicity and transparency, and in addition reduces the risk of model nonlinearities, multiple equilibriums, and permits ready sensitivity analysis with different AEEI values (Gillingham et al., 2008).

The inclusion of backstop technologies can also be classified as a form of exogenous technological change. Backstop technologies are typically low- or zero- carbon energy sources that may be already known, but are not yet commercialized or widely deployed due to relatively high cost. If the price of energy under an economic and policy condition (e.g. GHG abatement policy and corresponding price increase of carbon emitting energy) becomes high enough, the backstop technologies will penetrate the market by substitution for GHG emitting technologies and prevent the price of energy from rising further.

Modelers often assume that the cost of the backstop technologies is decreasing with time at its own autonomous rate. This assumption effectively implies that if the backstop comes into effect, then technology is improving solely as a function of time. Even though the autonomous rate of cost reduction and performance improvement of backstop technologies is exogenously given, the time profile of backstop technology deployment and corresponding technology portfolio over time can be endogenously determined with a least cost criteria in a bottom-up energy system optimization model like MESSAGE (GEA, 2012b).

The exogenous representation of technological change draws the criticism that it is unrealistic to assume that technologies will remain largely unaffected by policy over the longer time horizon typical for climate policy assessments and that it fails to incorporate the dynamics between the policy and technological change which is a key factor affecting the cost and timing of carbon control policy.

Endogenous Technological Change (ETC)

In ETC approach, more recent development, a feedback mechanism by which policy changes the direction of technological change toward carbon-saving one is incorporated in modeling framework. A feedback which ETC incorporated occurs through channels such as energy prices, research and development (R&D) activities, or accumulated production experience, i.e. learning by doing (LBD)

The fundamental distinction between exogenous approach and ETC is that with exogenous representation production possibilities depend only on passage of time, whereas with ETC, these possibilities can depend on a variety ways of past, present, and/or future expected prices and policy. Table 1summarizes the distinction with associated characteristics and implication of technological change representation in climate policy analysis models.

Table 1: Distinction between and implication of exogenous and endogenous technological change
(Source:Grubb et al. (2002))

	Technological Change Process	
	Exogenous	**Endogenous**
Defining characteristic	Independent of energy market conditions or expectations	Responsive to energy market conditions or expectations
Relationship to technology supply vs. demand	Predominantly “supply push”	Predominantly “demand pull”
Dominant stage of technology development	Initial invention, declining in applied technologies	Innovation and development of applied technologies
Potential sources of technological change	Inventors, university research, government research and development	Corporate research and development, learning by doing, scale economies
Representation in energy-economy modeling	Overall efficiency improvement (AEEI) and technology cost and performance assumptions (Backstop technology)	Price-, R&D-, Learning-induced technological change
Mathematical Implications	Usually Linear	Nonlinear, complex
Optimization implications	Single optimum with standard techniques	Potential for multiple equilibria, perhaps very diverse, complex techniques
Policy instruments and cost distribution	Efficient instrument is uniform Pigouvian tax + government R&D	Efficiency response may involve wide mix of instruments, targeted to reoriented industrial R&D and spur market-based innovation in relevant sectors. Potentially with diverse marginal costs
Abatement Timing Implications	Defer abatement to await cost reductions	Accelerate abatement to induce cost reductions

There are two broad methods of representing ETC in the climate policy analysis model. On the one hand, usually adopted in top-down macroeconomic models, technological progress is modeled as a product of explicit investment in R&D. In response to a policy, a profit maximizing firm has an incentive to invest in R&D and as a result knowledge stock is accumulated and this accumulation of the knowledge stock in turn drives TC (Buonanno et al. (2003), Goulder and Schneider (1999), Goulder and Mathai (2000), (Popp, 2004, 2006)

On the other hand, bottom-up system engineering models treats TC in LBD process ((Grubler and Messner, 1998), (Manne and Richels, 2004), (Messner, 1997)). In this approach technology progress is described as a function of accumulating experience with production and the use of the new technology. Climate polices can cause firms to introduce new or different production methods in order to conserve higher-priced carbon-based fuels. As firms gain experience with these processes, they may learn how to employ them more cheaply. LBD commonly measured in the form of learning or experience curve in terms of how much unit costs declines as a function of experience or production.

Table 2 summarize the modeling of technological change in a sample of climate change policy models and highlights the variety of approaches in different types of models.

Depending on which approach is chosen, the implication of TC for climate policy considerably varies (Goulder and Mathai (2000)). In general, LBD-based approach shows strong impacts on the cost and timing of carbon policy. LBD approach assumes that a set of advanced technologies either does or will exist, and that improvement of those technologies will be achieved without cost. These characteristics of LBD approach tends to results in significantly lower near-term emission and dramatic reductions in the cost of emission reductions. On the contrary, R&D approach, in general, tends to produce more modest cost savings and has little impact on the timing of abatement. Investment in R&D to increase knowledge for technology advance is a cost-incurring-process by a profit maximizing economic agent. The cost of new investment in R&D may crowd out other forms of R&D. The crowding-out effect limits the potential contribution of ETC which is great in LBD approach.

Table 2. Technological change characteristics in selected climate policy models

Model	Model Category	Representation of technological change	Reference
MESSAGE	Bottom-up(ES)	EN(LBD) EX	Grubler and Messner (1998) Riahi et al. (2007)
ERIS	Bottom-up(ES)	EN(R&D)	Barreto and Kypreos (2004)
MARKAL	Bottom-up(ES)	EN(LBD)	Barreto and Kypreos (1999)
POLES	Bottom-up(ES)	EN(LBD)	Kouvaritakis et al. (2000)
NEMS	Bottom-up(ES)	EX/EN(LBD)	EIA (2003)
MERGE	Bottom-up(ES)	EN(LBD)	Manne and Richels (2004)
PACE	Top-down(CGE)	EX	Bohringer (1998)
GREEN	Top-down(CGE)	EX	Burniaux et al. (1992)
MIT-EPPA	Top-down(CGE)	EX/LBD	Jacoby et al. (2006)
GOULDER	Top-down(ME) Top-down(CGE)	EN(LBD,R&D) EN(R&D)	Goulder and Mathai (2000) Goulder and Schneider (1999)
DICE/RICE	IAM	EX	Nordhaus (1994)
R&DICE	IAM	EN(R&D)	Nordhaus (2002)
MACRO	CGE/IAM	EX	Manne and Richels (1992)
IMAGE	IAM	EX	Alcamo (1994)
ICAM-3	IAM	LBD	Dowlatabadi (1998)
MESSAGE-MACRO	Hybrid	EX	Messner and Schrattenholzer (2000)

Acronyms:
Model Category: ES, energy technology and system model; CGE, computable general-equilibrium model; ME, macroeconometric model; IAM, integrated assessment model
Technological Change: EN (endogenous); EX (exogenous); LBD (learning by doing); R&D (research and development)
Source: (Edmonds et al., 2000; Gillingham et al., 2008; Kahouli-Brahmi, 2008)

2.3 Policy Design and Instrument Choice for Technology Innovation

Regardless of how the process and mechanism of technological change in the model is represented, there is widespread agreement that large scale GHG emissions reduction would require innovation and massive adoption of GHG-reducing energy technology and fundamental change in the global energy system in the long run. A key question to a policy maker is then how to design a policy or a combination of policies in a way to motivate technological innovation in the market.

It has become less disputable that market-based approaches are superior over traditional forms of regulation for a nationwide carbon control program. The market-based environmental policy intervention, such as carbon cap and trade systems and carbon taxes, generate incentives by establishing a price on carbon emission that will affect which new low-carbon technologies will be developed and how rapidly and deeply they will diffuse. The induced effects of environmental policy on technology can therefore have substantial implications for policy design and instrument choice[4]. For this reason, the environmental economics and policy literature, both from theoretical, empirical, and modeling perspective, has driven much effort to understand the relationship between environmental policy and technological change (Fischer and Newell, 2008; Fischer et al., 2003; Jaffe et al., 2002; Kemp, 1997; Newell et al., 2006).

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[4] The importance of environmental policy design and instrument choice is not just limited to its relation with technological innovation. For a general overview and comparison of environmental policy instruments see Harrington et al. (2012). For a broader implication of environmental policy choice and its effect on policy evaluation criteria see Goulder and Parry (2008).

Even economic theory has a strong argument that pricing carbon emission through tax or cap and trade system provide an incentive for firms to develop and adopt less carbon emitting technology, some rationales and motivations exist, due to market failures associated with technology innovation and diffusion, which may justify additional technology policy options to achieve a given emission goal in economically efficient way. Jaffe et al. (2005) phrases 'a tale of two market failures' to describe concomitant interaction between markets failure associated with environmental pollution and market failures associated with the innovation and diffusion of new technologies. They suggest these combined market failures provide a strong rationale for a portfolio of public policies that foster emissions reduction as well as the development and adoption of environmentally beneficial technology.

Following sub-section describes a brief market failures associated with each stage of the technology innovation process and various rationales or motivations for additional technology options[5]

Stage of Research, Development, and Demonstration (RD&D)

Knowledge Externalities. R&D is a set of firms' activities associated with discovering new knowledge and applying that knowledge to create new and improved products, processes and services. From firms' perspective, R&D is an investment activity to make returns on that. The economics literature on R&D, however, points to the difficulty firms face in capturing all the

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[5] A brief review on the market failures associated with each stage of the technological change process and various rationales is based on Jaffe et al. (2005); Newell (2007)

benefits from their investments in innovation, which tend to spill over to other technology producers and users. The public-good nature of knowledge and associated market failure of imperfect appropriation can lead to underinvestment in innovation effort (Arrow, 1962) and this motivates policies that directly target R&D. On flip side, the free-ride issue of knowledge market justifies coordinated public support of R&D: once created new knowledge or technology can be used by many people at little or no additional cost. Thus, the positive externality of innovation and new knowledge lead to social rates of return to R&D substantially in excess of the private rates of return (Griliches, 1992). The benefit of knowledge spillover is not limited in domestic level. The Clean Development Mechanism, one of key features of the Kyoto Protocol, is based on the virtue of international technology spillover in reducing emission in cost effective way. Also a technology-oriented international agreement to address climate change as an alternative to mandatory GHG reduction targets has been recently studied (de Coninck et al., 2008)

Uncertainty in investment environment. Investors like certainty. The importance of certainty is more prominent in investment decision in long-lived energy assets. In the context of long-term environmental problems such as climate change, the huge uncertainties surrounding the future impact of climate change and thus the magnitude and credibility of the policy response would seems to exacerbate underinvestment of private sector in GHG-reducing technology. In other word, the development of climate-friendly technologies has little market value absent a sustained, credible government commitment to reducing GHG emissions.

Similarly, rationales for public support of technology demonstration program tend to point to the large expense; high degree of technical, market and regulator risk; and inability of private firm to capture the rewards from designing and constructing first-of-a-kind facilities.[6]

Stage of Technology Deployment

Even a new technology is proven to be technical feasible through RD&D process, there are couples of barriers which prevent adoption and diffusion of the new technology, and market problems which can be addressed better with technology deployment policy.

Information Asymmetry. A typical example of information problem at the diffusion stage of new technology innovation is the landlord-tenant problems (in general economic term, principal-agent problems). A builder or landlord has no incentive to pay for efficiency improvement capital if the tenant pays the energy bills and therefore capture any resulting cost savings.

Spillover Effect. Like knowledge spillover without incurring cost on the beneficiary, the benefit of learning from experience of a new technology (e.g. technology improvement by learning-by-doing (LBD) or learning-by-using) also spills over to other producers without fully compensating to the early adopters. LBD is one of important channels through which technological improvement occurs. Thus, incentives for early adoption will be diluted and investment in learning-by-doing will fall short of what is optimal for society as a whole.

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[6] For more detail see Loschel (2002)

Network Effect. If a product becomes more valuable to an individual user as other users adopt a compatible product, network externalities exist. In particular, within large integrated energy systems where technologies are interrelated from energy production, through transmission, to distribution infrastructure, the network effect is prominent and deployment polices aimed at improving coordination and planning can be justified.

Given market barriers and failures addressed above, strong arguments are often made for additional public support and incentives to accelerate the technological innovation. A broad array of policy options specific to each stage of technology innovation process have been employed and suggested as presented in Table 3

However, some critics argue against public support or intervention for technology innovation. They often claim that government is ill-positioned to pick winners among a broad array of technological possibilities and vulnerable to political fist such as pork-barrel spending. Even recognizing the associated market problems in knowledge creation and diffusion of new technology, they argue that the cost and waste associated with government intervention outweigh the benefit that technology policy originally intends to accrue. Also such public programs are often driven by other interests rather than addressing market problems and end up with higher cost to the economy of reaching the environmental goal (e.g. recent debates on ethanol subsidy in U.S.). Thus, critics argue that decision about how and where to invest in technology innovation are best left to a private sector motivated through broad incentive provided through a price mechanism on environmental externalities (Norberg-Bohm, 2002).

Table 3: Summary of technology policy instrument
(Source: Alic et al. (2003)

Direct Government Funding of Research and Development (R&D)	• R&D contracts with private firms (fully-funded or cost-shared) • R&D contracts and grants with universities • Intramural R&D conducted in government laboratories • R&D contracts with industry led consortia or collaborations among two or more of the actors above
Direct or Indirect Support for Commercialization and Production; Indirect Support for Development	• Patent protection • R&D tax credits • Tax credits or production subsidies for firms bringing new technologies to market • Tax credits or rebates for purchasers of new technologies • Government procurement • Demonstration projects
Support for Learning and Diffusion of Knowledge and Technology	• Education and training (technicians, engineers, and scientists; business decision-makers; consumers) • Codification and diffusion of technical knowledge (screening, interpretation, and validation of R&D results; support for databases) • Technical standard-setting • Technology and/or industrial extension services • Publicity, persuasion, and consumer information (including awards, media campaigns, etc.)

Based on these criticisms, it's worth emphasizing that any additional technology policy within a comprehensive portfolio of environment policy should be designed with features addressing a specific market problem identified and be implemented in a manner which ensures benefit exceeds cost. Public funding program for basic and applied R&D project typically eludes the criticism. Studies typically find that U.S. federal energy R&D investment have yield substantial direct economic benefits as well as external benefits such as pollution abatement and knowledge creation (Norberg-Bohm, 2002). Thus, public R&D program should be targeted toward RD&D project which serves for basic knowledge generation and be designed to hasten knowledge spillover across sectors. Research contracts and grants to national labs, universities, other non-profit institutions fit to this category. Another key element that a successful public R&D program should feature is to leave specific R&D decisions to private sector on the most productive area of investment. Tax credits for private R&D allow such flexibility for private sector avoiding unnecessary government involvement in "picking winner" or administrative burden. On the other hand, tax credit approach should well specify the targeting R&D so that any irrelevant type of R&D is excluded from tax credits.

The benefits of technological innovation come only with widespread adoption, and because adoption and learning are mutually reinforcing processes, the policy portfolio should support diffusion of knowledge and deployment of new technologies beyond research and discovery.

As the development of environmental policy instruments has evolved from mandatory command-and-control type measures to more flexible market-oriented ones the same trends has been observed for technology policy instrument. There are several principal motivations behind the broad embrace of economic-incentive or market-based policy instruments. First, the cost-effectiveness of any types of environmental/technology policy instrument can typically be increased by incorporating trading system. Second, market-based instrument provides better incentive for technology innovation. For example, technology standard which is designed to guarantee a particular level of performance in an individual technology (e.g. energy efficiency standard such as CAFÉ) or an aggregate penetration level or market share (e.g. market share standards such as renewable portfolio standard) equipped with intertemporal banking and borrowing systems would ensure incentive for further technology innovation and transition. With this type of design feature the goal of a given technology policy, either via standard or subsidy system, can be met in a least cost way.

Arguments against government intrusion into the market gain more solid ground when the target of technology policy moves toward adopting and deployment stage because government discretion in selecting particular technologies and the political influence of stakeholders become greater. However, it should be noted that these arguments, which are more relevant to politics, institution, and practical implementation, are somewhat positioned outside pure economic policy analysis.

It’s less disputable that long-term solution to mitigation of GHG emissions will come from technological change and it would reduce the overall cost of climate policy. Technology policies aimed directly to fostering the development and adoption of new technology is an effective measure to hasten the change because technology development and diffusion involves their own externalities when they are left on ‘invisible hand’ of market. Policy incentive should be provided in both RD&D and diffusion/deployment stage, but with more care in latter stage. Policies should be carefully designed and implemented to address associated market problems while leaving much discretion to private sector on how/where to invest.

However, it should be noted that the technology policies alone cannot adequately respond to global climate change. They must be complemented by regulatory and/or carbon pricing policies. The goal of technology policies in the context of climate policy is not *per se* at the development and deployment of climate friendly technology itself. The ultimate goal is to reduce GHG emissions. Thus, an effective climate policy should provide not only 'carrot' (incentive to use new technology provided by technology-oriented policies), but also 'stick' (disincentive to use old technology provided by direct emission control policy). A broad portfolio of climate change policy needs to balance these two incentives to meet the policy goal in a cost-effective way.

2.4 Technological Learning

The technological learning – or alternatively, learning effect – is a concept which describes an empirical observation that a technology's performance improves as experience with the technology accumulates. A long-recognized concept, technological learning first was quantified for the aircraft industry (Wright, 1936). He noted that unit labor costs in airframe manufacturing declined with accumulated experience, as measured by cumulative output. Learning effect, in its most common formulation, is quantified as unit production costs decrease by a certain value known as the learning rate for each doubling of cumulative production.

Several drivers or mechanisms of technological learning which justify the observed decrease of the unit production costs in the literature have been identified: Learning-by-doing, learning-by-researching, learning-by-using, learning-by-interacting, and economies of scale (for more detailed explanation and related literature for each mechanism, see Kahouli-Brahmi (2008)). Although all these mechanisms in theory can attribute to the empirical observation of technological learning, it is not easy to quantify all these patterns. Nevertheless, in order to evaluate the cost decrease prospects and performance improvements of novel technology, the theoretical and empirical literature makes reference to the learning-by-doing by means of "learning" or "experience" curve modeling. Learning curves implicitly take into account in a reduced form all the parameters that influence the total cost of a product as it moves through the development stages toward becoming a mature technology. Learning curves have the advantage of employing an empirically quantifiable concept to allow current prices and activity to influence future technology possibilities in a relatively straightforward manner.

The customary form to express the learning curve is by using an exponential regress (Argote and Epple, 1990):

$$C(Q) = aQ^{-\propto}$$

Where, C is the cost of unit of production, investment or capital, a is the cost of the first unit produced, Q is the cumulative capacity or production and α is the elasticity of learning, which defines the effectiveness with which the learning process takes places. Above equation enables to determine the progress rate or, alternatively, the learning rate:

$$\text{Progress Ratio} = 2^{-\propto}$$

$$\text{Learning Rate} = 1 - 2^{-\propto}$$

The progress ratio is the rate at which the cost declines for each doubling of the cumulative production. For example, a progress rate of 80% means that the unit costs are reduced to 80% of their previous level after each doubling of cumulative capacity or production. In other words, for each doubling of cumulative production, unit cost of production decreases by 20% which indicates 20% of learning rate. Figure 4 illustrates the graphical representation of the experience curve with progress ratio for photovoltaic (PV) modules on the world market for the period 1976-1992. The data, plotted on the double-logarithmic scale with cumulative PV sales in x-axis and unit price (in constant 1992 US$) of PV modules in y-axis, indicate a steady and progressive decrease in unit price through cumulative sales. However, it should be noted that ever-decreasing unit cost with cumulative experience is not realistic. With every consecutive cumulative capacity doubling, the cost decrease obtained would tend to be smaller than in the previous one as the technology approaches its maturity and markets are saturated.

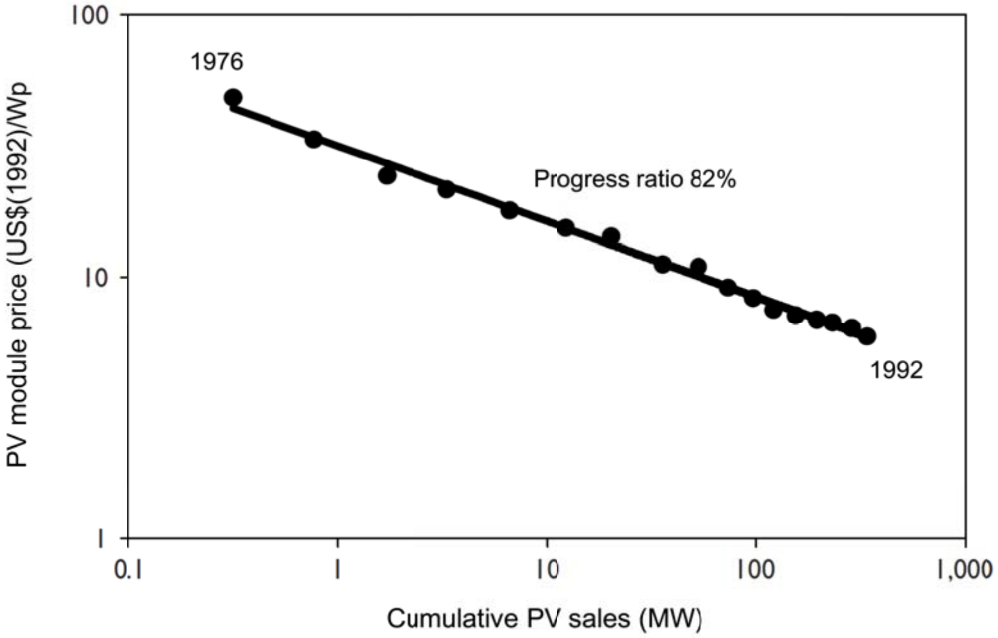

Figure 4: Experience Curve for photovoltaic modules on the world market, 1976-1992
(Note: Adopted from Willarns and Terziari (1993))

The estimated learning rates has been increasingly incorporated in models to assess long-term energy strategies and related greenhouse gas emissions. Early modeling efforts approximated learning curves by simple time series in an effort to avoid computational and methodological difficulties. Modelers have specified cost reductions over time both for individual energy technologies (Nakićenović et al., 1998b) and for groups (technology clusters) of similar technologies (Yohe, 1996).

It is more common practice that technological learning is incorporated in bottom-up models because they are more suitable for energy system analysis where they provide particular attention to specific technological options. The parameter most commonly affected in bottom-up models by the learning effects is the investment cost of energy technology. Investment cost of energy technology is one of key decision variables in bottom-up optimization energy model which typically seek to minimize the costs of serving an exogenous energy demand subject to technological and environmental constraints, by choosing which technology to install.

It is a common practice to incorporate technological learning in bottom-up models based on the fundamental idea by which current investments in new low-carbon energy technologies are more expensive than those in fossil energy technologies which are mature and experience less cost reductions and it is expected subsequently that the cost trajectory of emerging low-carbon technology decreases when the cumulative installed capacity increases to reach some threshold of cost reduction. This approach has allowed examining the importance of technological advance and evaluating the magnitude of the impacts of advance and the associated availability of low- to zero-emitting technologies (Clarke et al., 2007). More specifically, many previous researches first find out the optimal deployment schedule of low-carbon technology options with associated investment amount (Riahi et al., 2012), second put forward the economic, environmental and technological policies to support the large-scale diffusion of emerging energy technologies (IEA, 2012c, e), and third evaluate the value of technological learning (Richels and Blanford, 2008).

This study takes the same approach as these literatures to the representation of technology advancement. The purpose of this dissertation is not focused on how to represent the process of technological learning into the model, but the assessment on the role of technology advancement for the costs of emission control and for the optimal carbon mitigation portfolio. The following subsection surveys the literature quantifying learning rates associated with different energy technologies and presents Korea-specific empirical study of learning rates for a selected electricity generation technologies.

2.4.1 Empirical Evidence Electricity Generation Technology

There is rich literature on quantifying observed learning rates associated with energy technologies. The great majority of published learning rate estimates relate to electricity generation technologies (Köhler et al., 2006; Kahouli-Brahmi, 2008; McDonald and Schrattenholzer, 2001; Neij, 2008). These studies mainly draw attention to the significant variability in estimated rates between different energy technologies as shown in Figure 5 which presents experience curves and learning rate estimates of several energy technologies in the literature. Kahouli-Brahmi (2008) complied 77 empirical studies and estimated a wide range of learning rates from 1% to 42% cost reduction. Köhler et al. (2006) estimated learning rates of different technologies and time periods which span a very wide range, from around 3% to over 35% cost reductions associated with a doubling of output capacity. McDonald and Schrattenholzer (2001), by estimating learning rates for 26 data sets, concluded that unit cost reduction of 20% associated with doubling of capacity has been typically for energy generation technologies.

The fact that learning rates are highly variable and seem to depend, to a large extent, on technology, the data point and the time period illustrates the need to better understand the underlying elements and issues inherent in the learning curve modeling. Despite the variability of learning rate estimates many studies assert that while the mature technologies such as coal, oil and lignite conventional technologies present relatively low learning rates of 4% on average, the new renewable energy technologies such as solar photovoltaic energy exhibit high rates, which are around 20% on average (Kahouli-Brahmi, 2008).

Some studies have even reported negative learning rate for technologies when they have been subject to costly regulatory restrictions over time (e.g. nuclear, and coal if flue gas desulphurization costs are not separated), and price-based (as opposed to cost-based) learning rates in some periods reflecting aspects of market behavior.

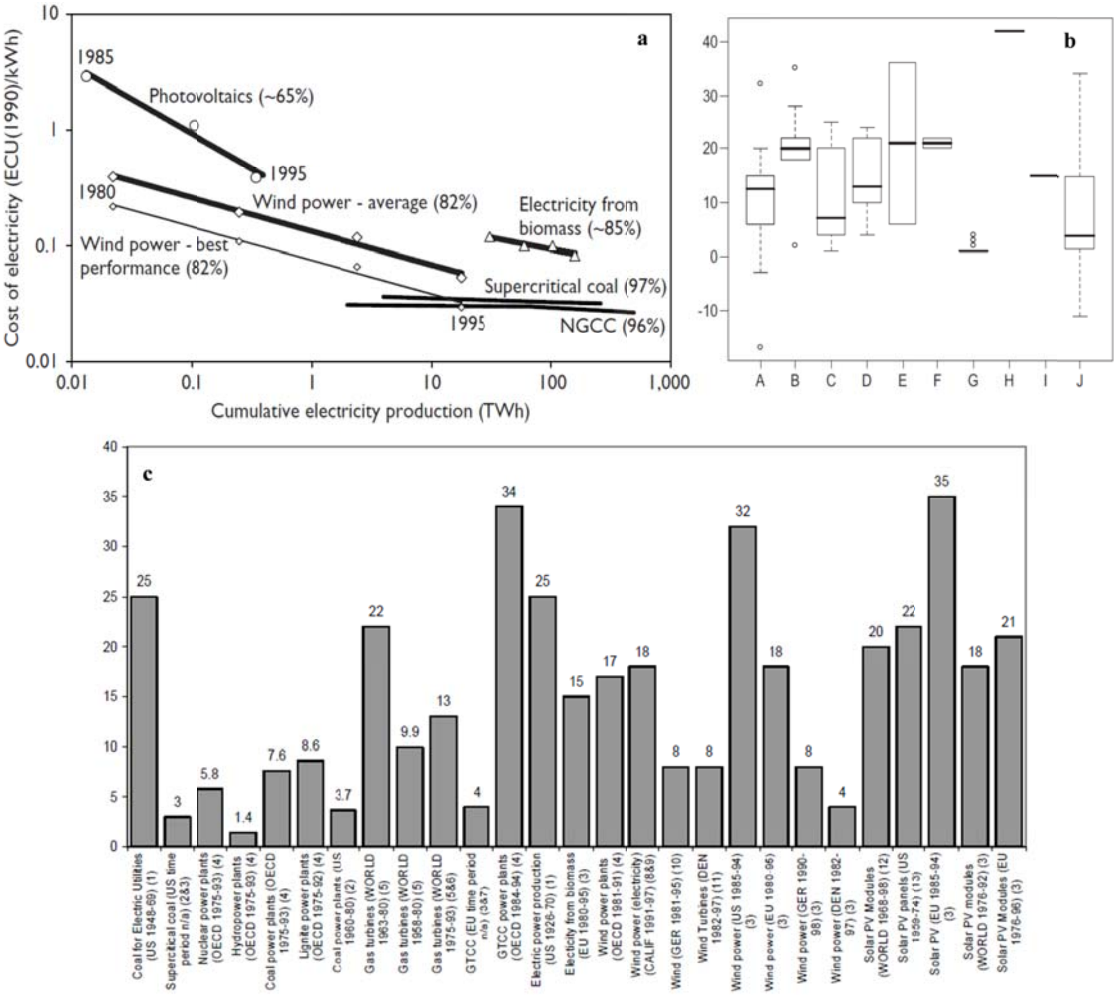

Figure 5: Experience curves and learning rate estimates of several energy technologies in the literature

(Note: (a) Learning curves and estimates of progress ratio in parenthesis for electricity technologies in EU, 1980-1995 (Source: Wene (2000)). (b) Learning rate estimates in electricity production technologies (Source: Köhler et al. (2006). (c) Range of learning rates estimates of several energy technologies (Source: Kahouli-Brahmi (2008): (A) Wind energy, (B) photovoltaic energy, (C) coal, oil and lignite energy, (D) gas turbine, (E) nuclear energy, (F) ethanol, (G) hydropower energy, (H) waste to electricity, (I) electricity from biomass, (J) GTCC.

2.4.2 Empirical Evidence in the Korean Power Sector

Table 4 lists estimated learning rates for several electricity generation technologies in Korean power sector and Figure 6 illustrates corresponding experience curves with estimated learning rates. The main purposes of the estimation for this thesis, which as far as I know the first attempt in this kind using Korea-specific data, are first to see if the observed learning trends in Korean power sector are consistent with other literatures, and second to explore where Korea technology experience positions in a wide range of variability observed in the literature.

It seems that Korea has followed the similar technology progress pattern as found in other regional or global trends. The estimated learning rates for different technologies which account 54 GW of cumulative capacity (compared with 78GW total installed capacity in 2010), range from -2% to 18%. The technologies which are relatively mature, both in domestic and international market, and subject to regulatory restriction show a negative (i.e. -2% for nuclear) or modest (2% for coal) learning rate in terms of cost decrease for each doubling of cumulative capacity. Conversely, emerging low-carbon technologies, except wind, show relatively fast learning rate (i.e. 18% for solar_pv and 10% for fuelcell) [7]. The estimated learning rates for different technologies are well suited within the range of variability in the literature.

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[7] It should be noted that the data coverage for emerging new and renewable technologies is very limited. Thus, there is still a possibility that the estimated learning rates for these technologies are over or underestimated. Another issue related with underlying data is the definition of performance measures, that is, dependent variable in experience curve model. I used the construction cost (KWR/kW) from the original data set as a proxy of technology specific investment cost. If the construction cost in the original data includes other costs such as land acquisition, it would add further uncertainty on estimated learning rates.

Table 4: Estimated learning rates for electricity generation technologies in Korean power sector

Technology	Time Period	Estimated Learning Rate (%)	R^{2} [a]	Cumulative capacity(MW) counted in estimation [b]	Total Installed capacity (MW) in 2010
Solar_PV[c] (Photovoltaic)	2006-2011	18	0.63	22	511
Wind (Onshore)	2004-2011	1	0.01	55	377
Fuelcell	2006-2011	10	0.82	12	36
Nuclear	1978-2011	-2	0.02	18,766	18,766
Coal Power Plant (Bituminous)	1972-2008	2	0.02	22,580	23,080
NGCC (Natural gas combined cycle)	1979-2010	1	0.01	12,663	16,378

Note: All underlying data on dependent variable (construction cost in 2010 KRW/kW) and independent variable (cumulative capacity in MW) comes from KPX (2012). Construction costs (i.e. proxy of investment cost) are converted to constant 2010 KRW/kW using GDP deflator from current KRW/kW in original data set (For more detail see Appendix A)

[a] R^2 expresses the quality of the fit between the data and the estimated learning curve. However, R2 values in different lines should not be compared because samle sizes are different.

[b] Availality of contruction cost in original data set for Solar_PV, Wind, and Fuelcell makes the data coverage limited.

[c] Only plants whose total installed capacity greater than 0.5MW is considered.

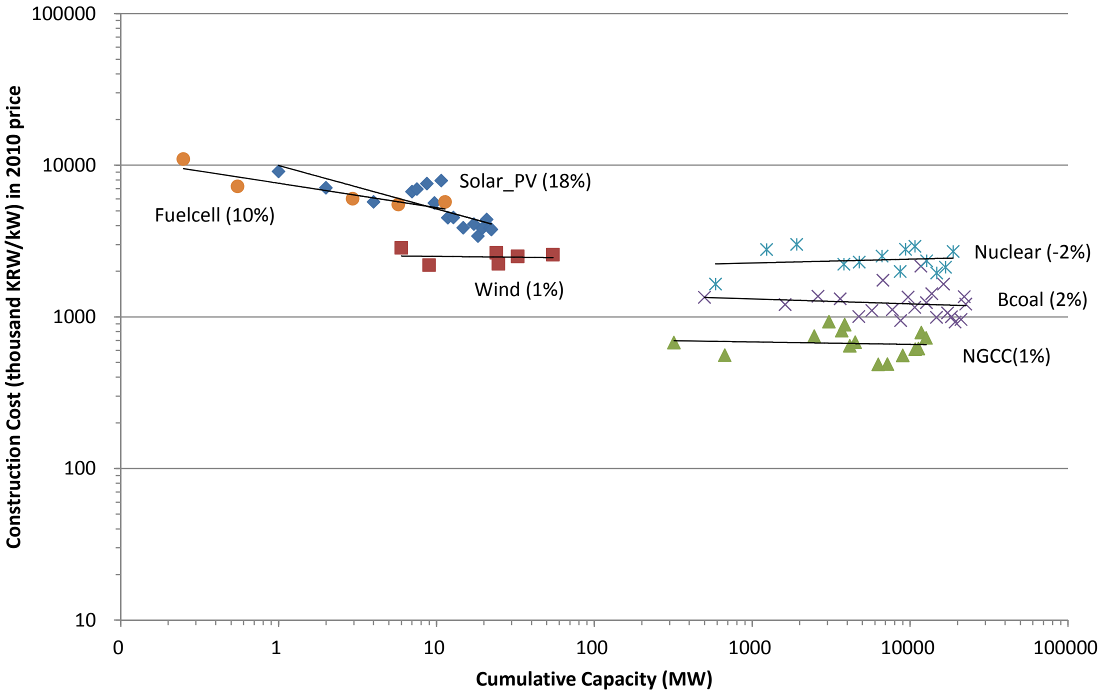

Figure 6: Experience curves and estimated learning rates in parenthesis for electricity generation technologies in Korean power sector

A few general implications can be drawn from the comparison. First, there seems to be a cross-country spillover effects in energy technology. The import-export movements of energy technologies and the international transfer of associated knowledge and practice have become more and more considerable. It is then expected that the cross-country spillover effects of energy technology influence the level of technological learning rates in a country. Second, the spillover effect may justify the application of the global market trends of technological advancement in a country specific energy-environment modeling exercise. Especially the adoption of future technology advancement prospect from global energy and emission scenario analysis, where future prospect is based on empirical dynamics of past as well as expert judgment, may provide a shortcut to an inherently uncertain task of projecting future technological progress. This type of shortcut will serve for a study like this thesis where the main purpose is to explore the role of technological advancement in carbon control cost and in the optimal carbon mitigation portfolio rather than the precise prediction of the rate and the direction of technological change.

Chapter 3. Korean Power Sector and Modeling Framework

3.1 Overview of the Korean power sector

3.1.1 Power Supply and GHG Emissions

Korean power sector[8], a highly centralized system, generated 54.1 GWyr (474 TWh) of electricity in 2010, an average increase of 6.1% per year since 2000 and 81% greater than in 2000. More than 70% of electricity was generated from coal (42%) and nuclear (31%) as base demand technologies, complemented with natural gas (20%) and oil (3%) for an intermediate and peak demand. The share of electricity from hydro and alternative energy source is 1.7% (0.8% from hydro and 0.9% from alternative[9]).

Electricity generation from gas-fired plants increased by 240% over the past ten years, from 3 in 2000 to 11 GWyr in 2010 while output from coal-fired plants has doubled from 11 to 23 GWyr in the same period. Once dominated source of electricity generation, oil gradually faded out with only 1 GWyr generation in 2010 while the production of nuclear electricity increased by 36% over the past ten years. Figure 7 illustrated a longer historical development of

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[8] All statistics for Korea power section comes from Electric Power Statistics Information System (EPSIS) (KPX, 2013a) unless otherwise indicated.

[9] Alternative energy sources includes solar, wind, land filled gas (LFG), offgas, biogas, fuelcell, waste, and tide

generation mix and corresponding GHG emissions in the Korean power sector between 1970 and 2010.

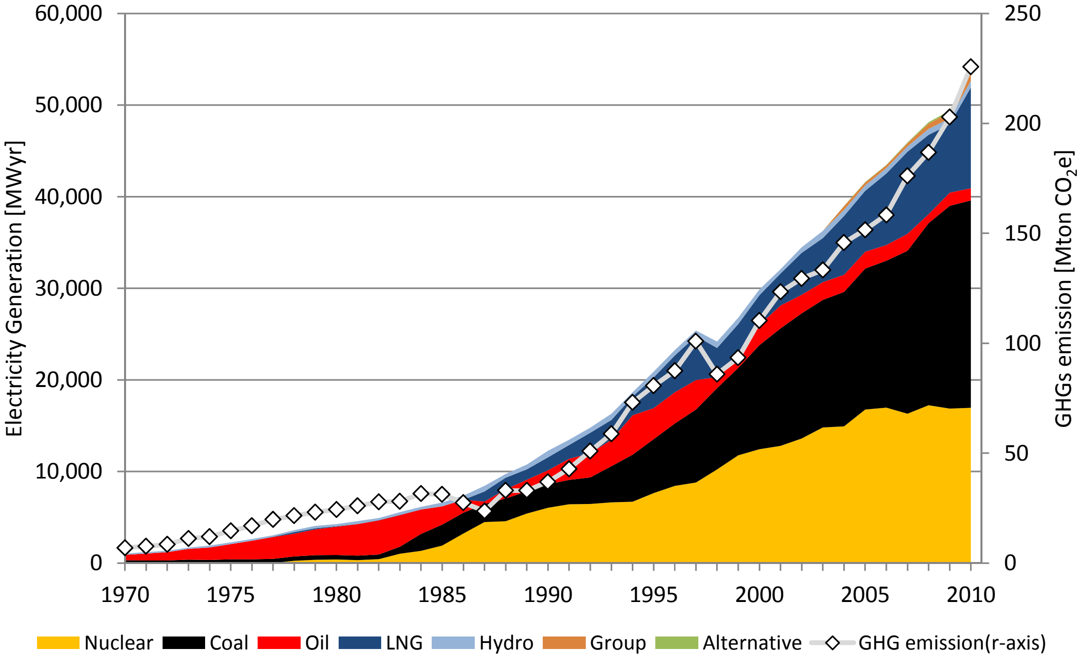

Figure 7: Electricity generation by source and GHG emissions, 1970-2010

With a drastic increase of electricity demand coupled with fossil fuel dominance in generation mix, the GHG emissions from electricity sector more than doubled over the past ten years, from 110 in 2000 to 226 $MtCO_2e$ in 2010[10]. Emission rate of CO_2 from unit of electricity generated in Korea has been almost constant between 500 and 550 gCO_2/kWh over the past two decades. It can be attributed to a steady increase of nuclear electricity which counteracted

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[10] Author's own calculation. Each fuel consumption in physical unit (KPX, 2013a) were converted into energy unit with low heat value (LHV) for each fuel (KEEI and MKE, 2010)

against the continuing growth of electricity demand and fossil fuel dominance in generation mix. Figure 8 presents the development of CO_2 emission rates of electricity across selected countries and regions between 1990 and 2010. Korean power sector currently generates electricity in cleaner way than world average, but dirtier way than most Annex I countries or regions under Kyoto Protocol. Unless a significant reduction in electricity demand occurs, CO_2 emission rate of electricity is a key indicator to the level of de-carbonization in any country's electricity system.

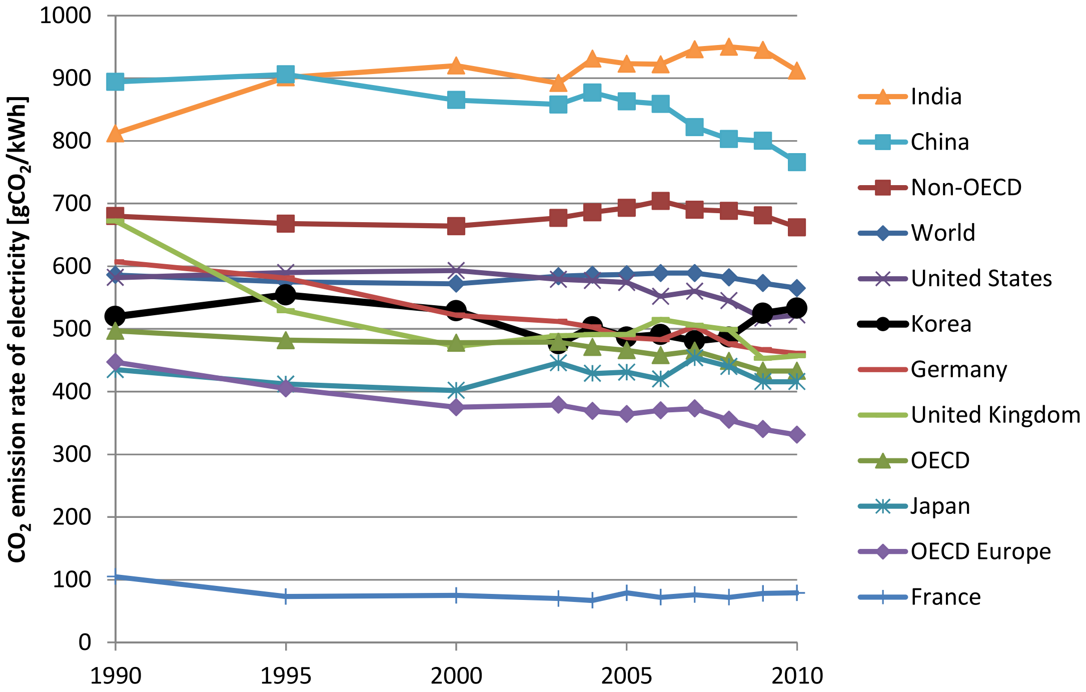

Figure 8: CO_2 emission rate of electricity in a selected countries and regions, 1990-2010 (Source: IEA (2012a))

Korea's installed capacity for electricity generation is 76GW[11] at the end of 2010. Of this capacity, coal (24.2GW) is the largest source, followed by natural gas (20.0GW) and nuclear (17.7GW). The generation fleet also contains oil (5.9GW), hydro (1.6 GW), and various alternative energy capacities (1.8GW).

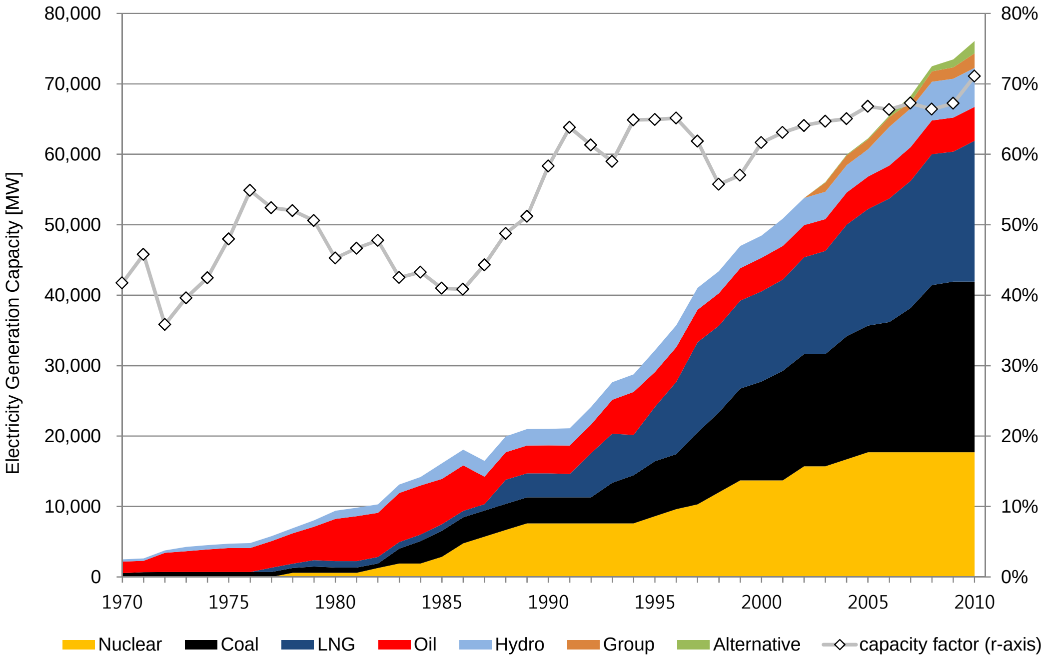

Figure 9: Electricity generation capacity by source and system wide capacity factor, 1970-2010

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[11] With 4GW capacity of auto-producers who sell a small portion of their electricity to the grid operator, the total installed capacity increase into 80GW. But the auto-producers are excluded in this thesis

Figure 9 illustrates the development of installed capacity of electricity generation by source and system-wide capacity factor[12] over the past four decades. Even fluctuated the system-wide capacity factor improved over time which indicates the overall system has been more efficiently utilized. However, it should be noted that higher annual capacity factor doesn't necessary guarantee the security of system year round, especially, when peak demand occurs with a tight margin of operational reserve as evidenced by a load-shedding event in September 2011.

The vintage of current 76GW capacity is evenly distributed over time. About 27% of current capacity is older than 20 years with 37% between 10 to 20 years old while 38% is less than 10 years old as shown in the left panel of Figure 10. The right panel shows the breakdown by source of more than 20 years old capacity. More than half (11GW) of aged capacity is base load demand technologies such as nuclear and coal.

What technology and energy source would replace these relatively obsolete capacities as well as what new technology portfolio would be added in coming decades to serve a growing electricity demand has a huge implication for the future transformation of electricity generation system and any GHG emissions control strategy.

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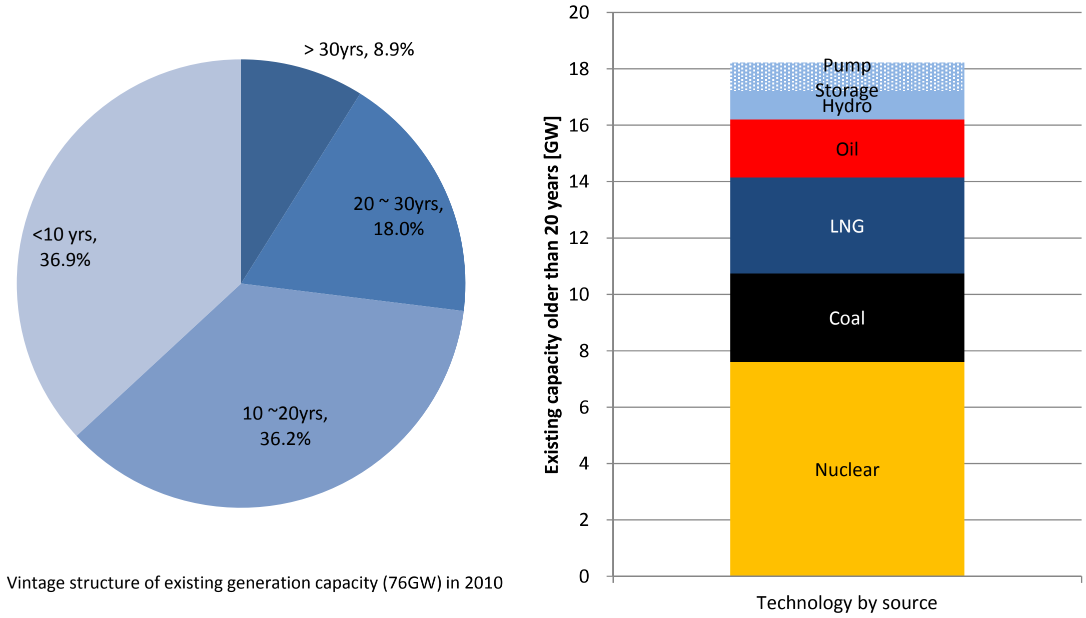
[12] Capacity factor is a measure of how often an electric generator with a fixed capacity operates for a specific period time. The system wide capacity factor presented in the figure is a simple proportion of total output of electricity to the total installed capacity in a year. Technology-specific capacity factor will be presented in the later section of this thesis



Vintage structure of existing generation capacity (76GW) in 2010

Figure 10: Vintage structure of existing electricity generation capacity in 2010
(Note: Labels in left panel indicates age and % of total)

Even having been growing fast over the past few years, due in part to the last administration's green growth initiative, new and renewable energy sources plays still a very minimal role in electricity generation mix accounting only 1.7% (0.9 GWyr) from the total generation and 4.4% (3.4GW) from total installed capacity in 2010. Figure 11 shows the breakdown of electricity generation from new and renewable sources (left panel) and corresponding capacity (right panel) in 2010. Accroding to the renewable portfolio standard (RPS) that Korean government enforces for electricity sector as of 2012, the definition of new and renewable includes some non-renewable energy source such as land-filled-gas, fuelcell, waste, and offgas[13]. This non-interantional standard renewable sources account about one thrids of electricity generation from new and renewable sources in 2010. Korean government lately proposed an ambitious plan to deploy new and renewable electricity capcities which increases to 32GW (about 20% share from the total installed electricity capacity) by 2027 (MKE, 2013a).

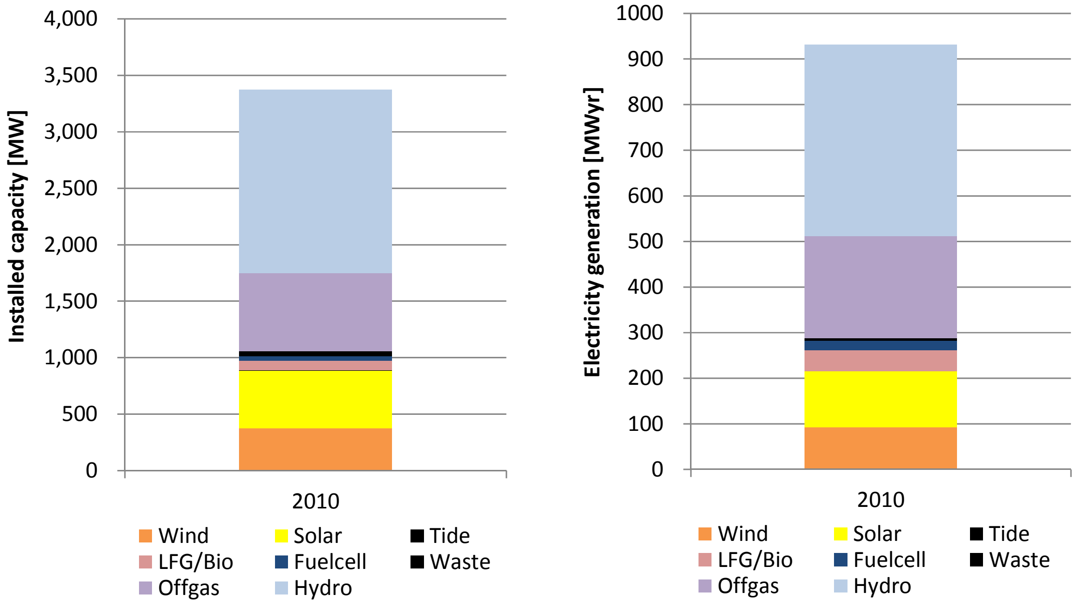


Figure 11: New and renewable electricity capacity and generation in 2010

With interantional standard on the defintion of renewable energy source applied, the share of renewable electricity in Korea is the lowest among IEA member countries (IEA, 2012b). Figure 12 shows the evolution of non-hydro renewable electricity generation share across a selected

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[13] Even electricity generated from Integrated Gasification Combined Cycle (IGCC) and Carbon Capture and Storage (CCS) technologies is counted under the current RPS scheme in Korea

countries or regions over the past two decades. Korea's renewable share is about 0.6% while OECD average is about 5%.

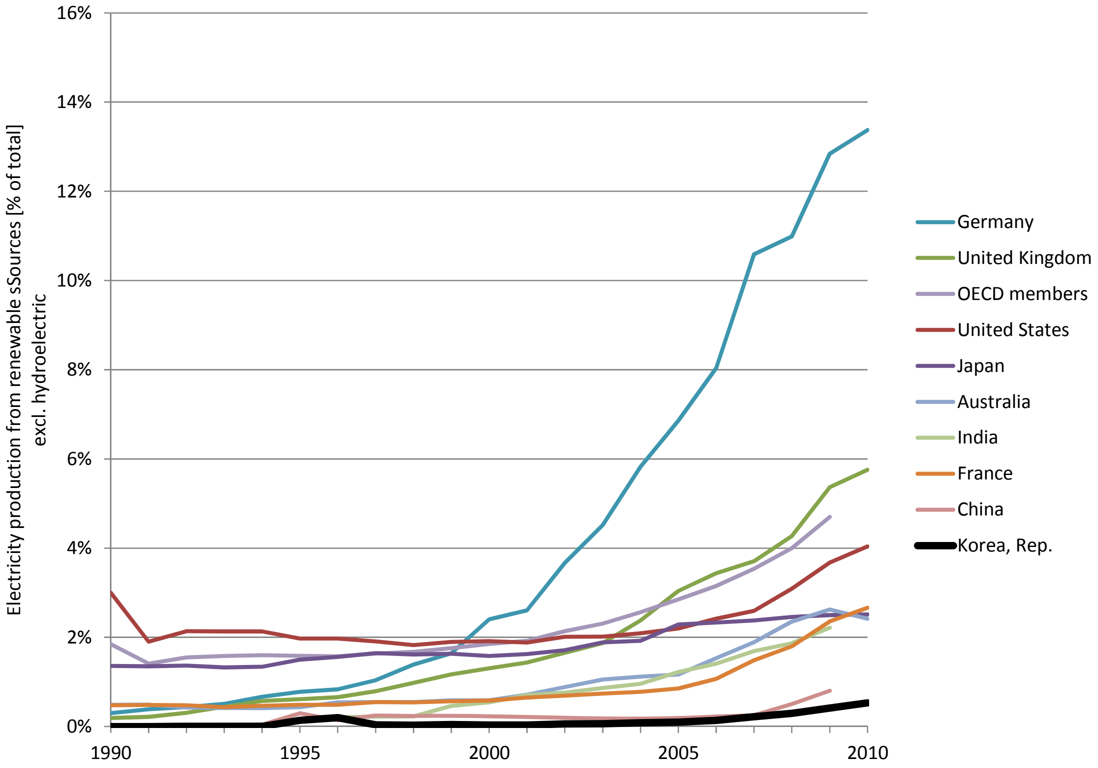

Figure 12: Electricity production from renewable sources in selected countries, 1990-2010 (Source: World Bank (2013))

3.1.2 Electricity Demand

In 2010, total electricity consumption was 49.6 GWyr (434 in TWh), half of which (49% or 213 TWh) was consumed by industry. The commercial and public services sector consumed 150 TWh (35%) and the residential sector 61 TWh (14%) with other sectors consuming the remaining volumes. Even though the general pattern of diminishing annual growth rate has been observed in recent years, electricity consumption has still been growing significantly at the rate of 6.2% p.a. (per annual) over the past decade. Industry sector drives the overall increase of electricity consumption at 7.9% p.a. while commercial (5.4%) and household (5.2%) follows next.

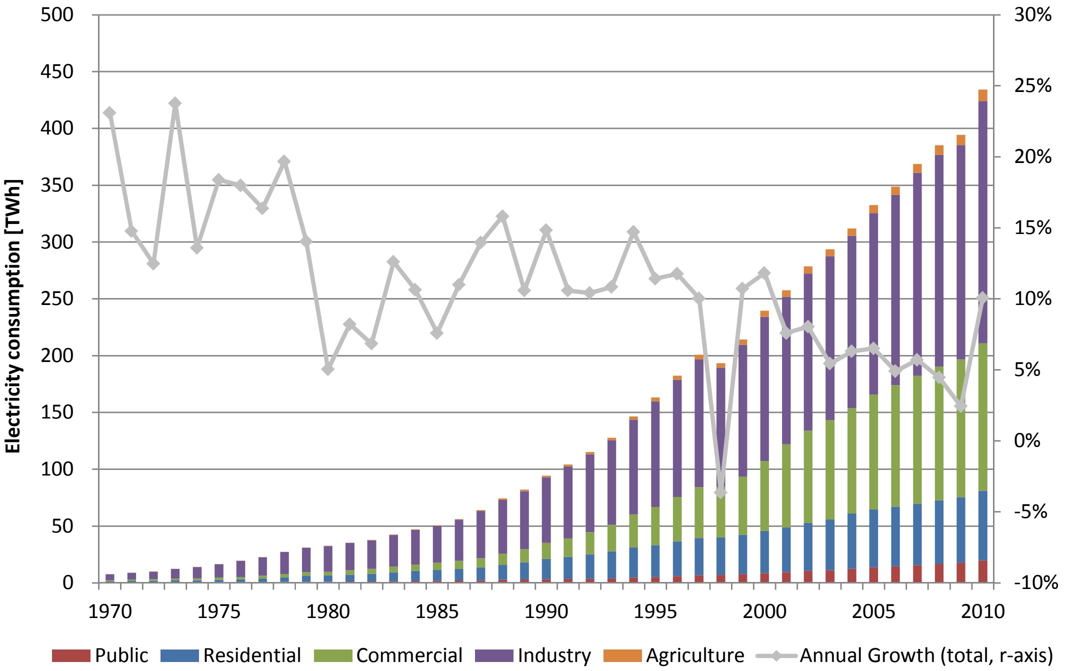

Figure 13: Electricity consumption by sector and annual growth rate, 1970-2010

In recent years, demand has tended to peak in winter owing to growth in demand for electric heating. In 2010, monthly peak demand varied between 55.2 GW and 71.3 GW with consumption higher in winter and summer because of the demand for heating in winter and air conditioning in summer. Growing electricity demand hastens the rapid electrification of final energy supply system by substituting away other energy sources such as coal and oil in building sector. The share of electricity in total final energy consumption has increased from 11% in 1990, through 13.7% in 2000, to 19.1% in 2010 (KEEI and MKE, 2012). The steady electrification in the economy has a signification implication for secure supply of electricity in coming decades.

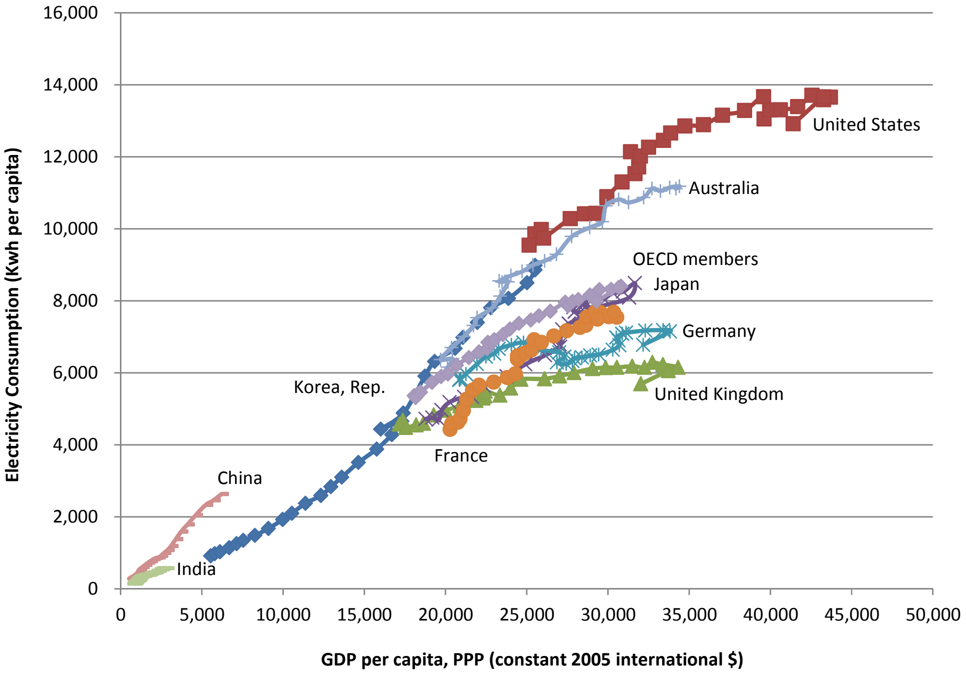

Figure 14: Cross country comparison of electricity consumption and income, 1980-2009 (Source: World Bank (2013))

Electricity consumption per unit of GDP in Korea was 35 MWh in 2010 compared to 30 MWh in 2000 (IEA, 2012b), while per capita electricity consumption was 9.4 MWh in 2010 compared to 5.6 MWh in 2000. Owing to its energy-intensive economy, electricity consumption per capita in Korea is a little higher than other IEA member countries (see Figure 14).

The amount of instantaneous electricity demand on any system fluctuates throughout the day. It also varies over the course of the year between a minimum base load and peak load. This aspect is demonstrated by a load duration curve that shows the number of hours that a given average hourly electricity load occurs in the system over the course of a year. Figure 15 shows the electricity load duration curve in 2010. These data indicates that the minimum demand (32.2GW) on the system is less than half of the peak demand (71.3GW). The generation, transmission and distribution infrastructure must be designed in a way that it can work reliably within this entire range. For example, the peak 10% of generating capacity (7.6 GW) is only required 1.2% of the time (105 hours out of 8760 hours) in 2010. In other words, the total hours when the system-wide operational reserve goes below 10% is 105 hours over the course of the year 2010. Securing funding for investment in generation capacity to meet peak demand can be difficult if market structures do not provide revenue security for such high value, low call-off generation. The dotted line in grey is a simplified load duration curve which curtails the year round electricity load into 7 regions and the reconstructed load curve will be applied into future electricity demand profile in the modeling practice in this thesis. More detailed description on simplified load curved will be presented in later section.

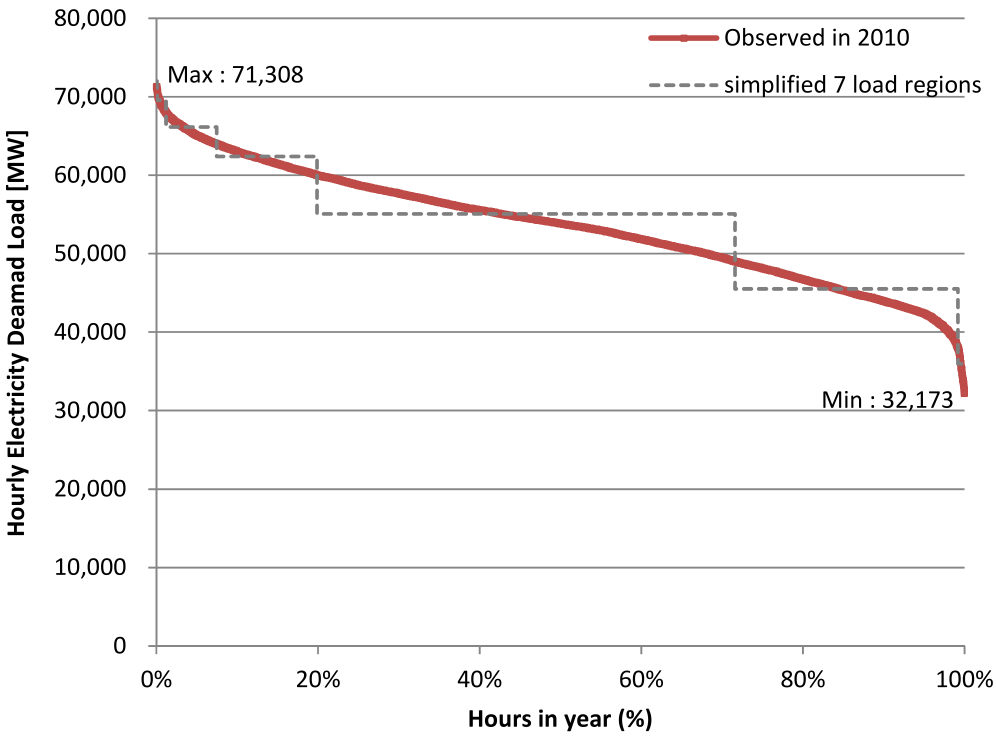

Figure 15: Hourly electricity load duration curve in 2010 and simplified 7 load regions (Source: Personal communication with Korea Power Exchange (KPX))

3.1.3 Economy and Performance of Electricity Technologies

Various economic and technical performance characteristics are key determinants of economic competitiveness of a technology among many alternative options. Table 5 identifies these characteristics of electricity generation technologies currently utilized in the Korean electricity system. Looking into these characteristics, technology by technology, can provide an image of technical and economic mechanism through which the electricity system operate to meet the overall and instantaneous electricity demand and concurrent environmental impacts such as GHG emissions.

The data are for a representative technology currently under operation, that is, an average of same kind of plants rather than an individual plant specific. The investment cost expressed in thousand KRW in 2010 price level per unit of output capacity is an average of plants constructed between 2005 and 2010. The operation and maintenance (O&M) cost is scaled to the investment cost by the same proportion of OECD average from IEA (2012e).

These data also can serve as a base year reference from which the prospect of future improvement for technology options can be drawn. If cost-effectiveness is a key decision criterion on what technology portfolio would best satisfy energy demand schedule subject to economic, technological and environmental constraints, as in a typical bottom-up energy system optimization model, these characteristics are key decision variables on which technology to choose.

Table 5: Cost and performance characteristics of electricity technologies in Korea in 2010

Technology	Efficiency[a]	Investment cost[b] [kKWR/kW]	O&M cost[c] [kKWR/kW/yr]	Capacity factor[d]	Life time[e] [years]
Anthracite Coal (Acoal)	0.35	1844	46	85%	40
Bituminous Coal (Bcoal)	0.39	1085	33	94%	35
Oil_steam	0.36	1866	56	28%	30
Diesel generator	0.41	1109	33	26%	40
LNG_steam	0.35	1109	33	29%	30
NGCC	0.46	753	19	57%	30
Nuclear	0.33	2409	60	96%	50
Large_Hydro	-	3013	72	24%	60
Small_Hydro	-	4741	90	63%	50
Onshore Wind (On_Wind)	-	2497	37	25%	25
Solar PV	-	3967	40	24%	25

[a] Gross thermal efficiency in 2010 (KPX, 2013a)

[b] Average in 2010 price of new power plants constructed over 2005-2010 (KPX, 2012)

[c] The proportion of operation and maintenance (O&M) cost to investment cost (OECD averge) from IEA (2012e) is used to estimate Korean-specific O&M cost

[d] Capacity factor in 2010 (KPX, 2013a)

[e] Adapted from various sources (IEA, 2010, 2012e)

In addition to the technology-specific economy and technical characteristics the cost of fuel as an input to a technology is also important factor affecting the economy of electricity generated from a technology. Figure 16 shows the trends of major fuel costs during the past decade in terms of thousand KRW in 2010 price per kWyr of input. Even there was some volatility of cost movement, the general pattern is observed that the costs of most fossil-based fuels have significantly increased while fuel cost for nuclear power has even decreased.

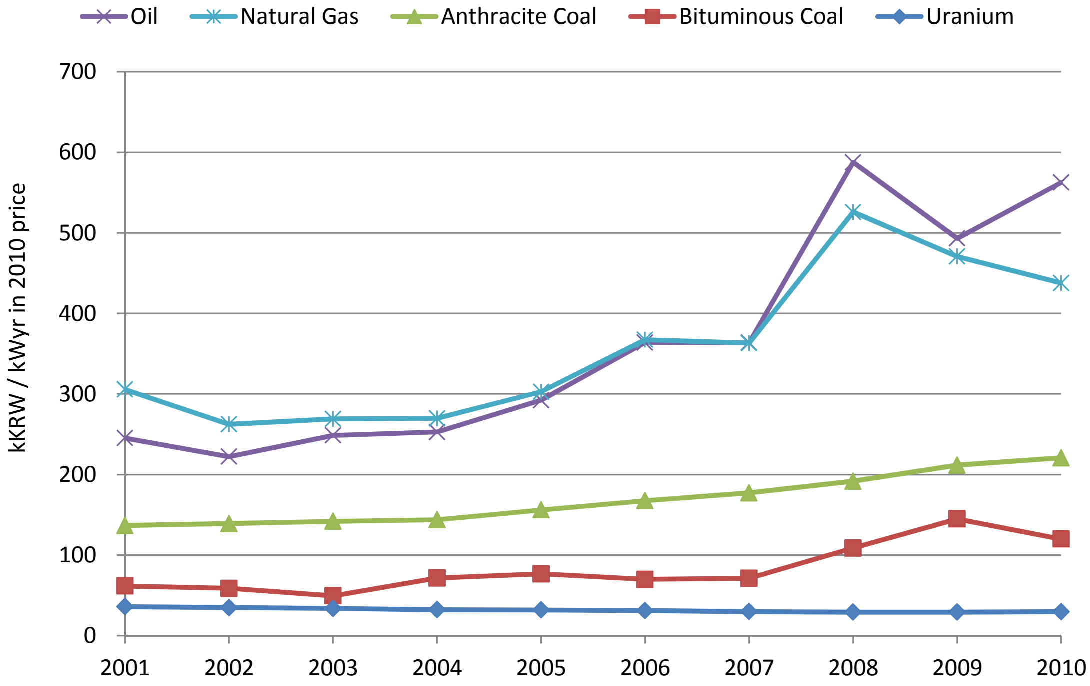

Figure 16: The price development of major fuels for electricity generation in Korea, 2001-2010 (Source:KPX (2013a))

The notion of levelized cost of electricity (LCOE) is a widely used tool for comparing the costs of different power generation technologies. LCOE corresponds to the present value of the average lifetime cost of electricity reflecting overnight capital cost, fuel cost, O&M cost, and an assumed utilization rate for each plant type (IEA and NEA, 2010). The formula used for calculating the levelized cost of electricity (LCOE) from a technology is:

$$LCOE = \frac{Inv \times \frac{dr(1+dr)^{r}}{(1+dr)^{r}-1} + OM}{\pi} + \frac{fuelcost}{eff}$$

Where,

Inv : investment cost per unit of capacity,
OM : OM cost per unit of output capacity per year,
dr : discount rate (i.e. 5.5%),
τ : technical plant life time,
π : plant capacity factor,
fuelcost : fuel cost as input to technology, and
eff : efficiency of technology

The first term of the RHS in the above formula is a capital-related LCOE with the second term for fuel cost. Figure 17 plots the calculated LCOE in 2010 across electricity generation technologies with its capacity factors. Red square indicates median value of capacity factor for each technology between 2000 and 2010 with upper error bar for maximum and lower bar for minimum value. All required variables for the calculation are based on the data presented in Table 5 and Figure 16. The range of LCOEs varies from 36 KRW/kWh to 250KRW/kWh. LCOEs of base load technologies such as nuclear and bituminous coal power plant (Bcoal) is at the lower end of the range while LCOEs of peak load technologies such as oil- and natural gas-fired steam generator is at the middle and high end of the range. Intermittent renewable technologies such as wind and solar generate electricity at relatively higher cost due to its high capital cost yet and low capacity factor. A reverse pattern is found for capacity factor of different technology. That is, cheap base load technologies are more utilized while expensive or intermittent technologies are less utilized. This general pattern may confirm that the supply side of current electricity system in Korea works in a way to minimize the overall cost of meeting energy demand under technical conditions.

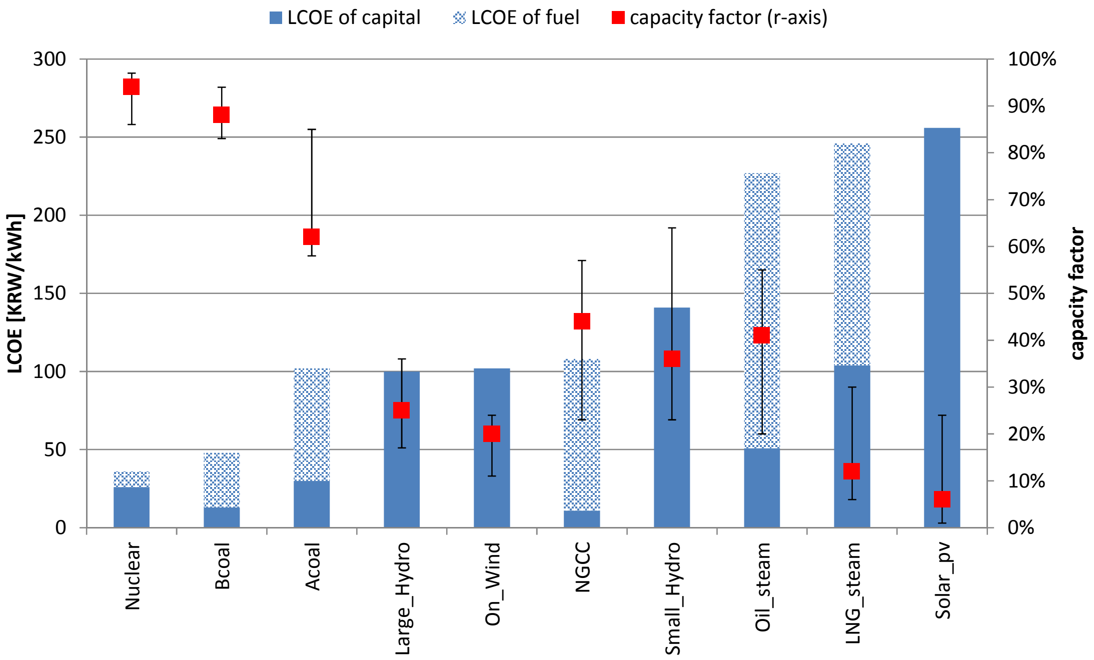

Figure 17: LCOE for individual technology and its capacity factor

(Note: Red square indicates median value of capacity factor for each technology between 2000 and 2010 with upper error bar for maximum and lower bar for minimum value)

3.2 Korean Power Sector Model

3.2.1 Introduction to MESSAGE

The thesis uses the MESSAGE (Model for Energy Supply System Alternatives and their General Environmental impacts) [14] modeling framework (Messner and Strubegger, 1995), a bottom-up energy system optimization model. MESSAGE is widely used for medium- to long-term energy system planning, energy policy analysis, and energy-environment linked scenario development and analysis. The model can provide a framework for representing an energy system and associated environmental impacts. It can describe an energy system with all its interdependencies from resource extraction, imports and exports, through conversion, transport, and distribution, to the provision of useful energy services (e.g. thermal comfort, illumination, appliance use, industrial process heat, and mobility, etc.) to various end-sectors (e.g. industry, residential, commercial, and transport sector).

MESSAGE finds the optimal flow of energy throughout the entire chain of an energy system, which is feasible in mathematical and an engineering sense, and at the same time the optimal investment choices on technologies that lead to the least-cost of all feasible energy mixes to meet a given energy demand and environmental constraints. Engineering feasibility is ensured by making energy flows consistent with model constraints on primary energy extraction, energy conversion and transport as well as on end-use technologies. Such energy flows and technology

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[14] In this section the general feature of MESSAGE modeling framework is introduced. More detailed description of MESSAGE of Korean power sector will be presented in the following section

choices are further determined by constraints on the rate of new capacity installation, the substitutability among energy forms, resource recoverability, renewable-energy potentials and environmental constraint if applicable. The optimization process thus can be likened to decision makers who invest in energy technologies characterized by different performance, cost and environmental characteristics in such a way to meet demands at least cost under the given technical, environmental, and economic constraints. Cost includes investment costs, operation and maintenance costs, fuel costs and any user-defined costs such as pollution costs. Calculating total cost, MESSAGE all accounts these specific costs of individual technology, energy forms, and environmental impact as the energy develop develops over time. Changes in the energy system are therefore endogenous, that is, the pace of structural change in an energy system is determined by shifts in energy mix and associated technology portfolio selected.

In the course of representing an energy system, MESSAGE can include a full accounting of the vintage structure of the long-lived energy capitals. The detailed representation of historical and future technology capacities and their lifetimes permit to address issues related to the timing of technology diffusion and substitution, and to represent inertia of the system for replacing existing facilities with new generation systems.

In the application of MESSAGE into energy-environment linked scenario analysis, the model's principal results can include technology-specific multi-sector response strategies for achieving given environmental goals such as GHG emissions and local air pollution. These strategies are identified by solving for the least-cost portfolio of technologies and their deployment over time that meet both the environmental goal and a given reference energy demand. The choice of the individual mitigation options across pollutants and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility.

MESSAGE has been used for many applied projects and scientific studies. Examples of these include the joint IIASA-WEC (World Energy Council) report on Global Energy Perspectives (Nakićenović et al., 1998a), the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000), and the IPCC third (Metz, 2001) and fourth assessment reports (Metz, 2007), and more recently Global Energy Assessment (Jefferson, 2013). MESSSAGE was also used to generate RCP-8.5 scenario (Riahi et al., 2011), one of the four Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011), currently being used to estimate further climate change in the context of the IPCC fifth Assessment Report.

3.2.2 Korean Power Sector Model in MESSAGE

The system boundary of Korean Power Sector Model (hereafter KPSM) built for this thesis in the MESSAGE modeling framework covers all public utility level supply technology, its capacity and electricity demand which is transmitted and distributed through a closed national grid system operated by Korea Electric Power Corporation (KEPCO). The system excludes auto-producers of electricity that mainly generate electricity to meet its own use and sell a small amount of electricity to the grid operator. Electricity consumption which is not provided by the grid system is also not counted in.

The reference energy system (RES), a simplified representative structure of the real world energy system, of KPSM is schematically shown in Figure 18. The upstream primary energy sector from which fuel and energy resource are supplied to the power sector is exogenously represented with only energy carriers and their costs. The downstream end-use sectors that consume the generated electricity from power sector through the grid system (i.e. Electric T/D) are also aggregated in one sector with exogenously given electricity demand.

KPSM includes a number of fossil, nuclear, renewable technologies as well as a new technology options which are expected to be available in the future such as CCS technologies. Listed electricity generating technology options which are the major building blocks of the RES should be interpreted as representative technologies rather than specific technologies that compete each other under varying circumstances. For all existing technologies, their capacity vintage profile has been implemented based on statistics to reflect their remaining life in the future.

The modeling time horizon is up to 2050 with 5 years step. The base year of the model is 2010 in which model's input and output is calibrated with all related statistics. The system wide discount rate of 5.5% is assumed for the calculation of the present value of total system cost over time horizon (i.e. the objective function of the model)

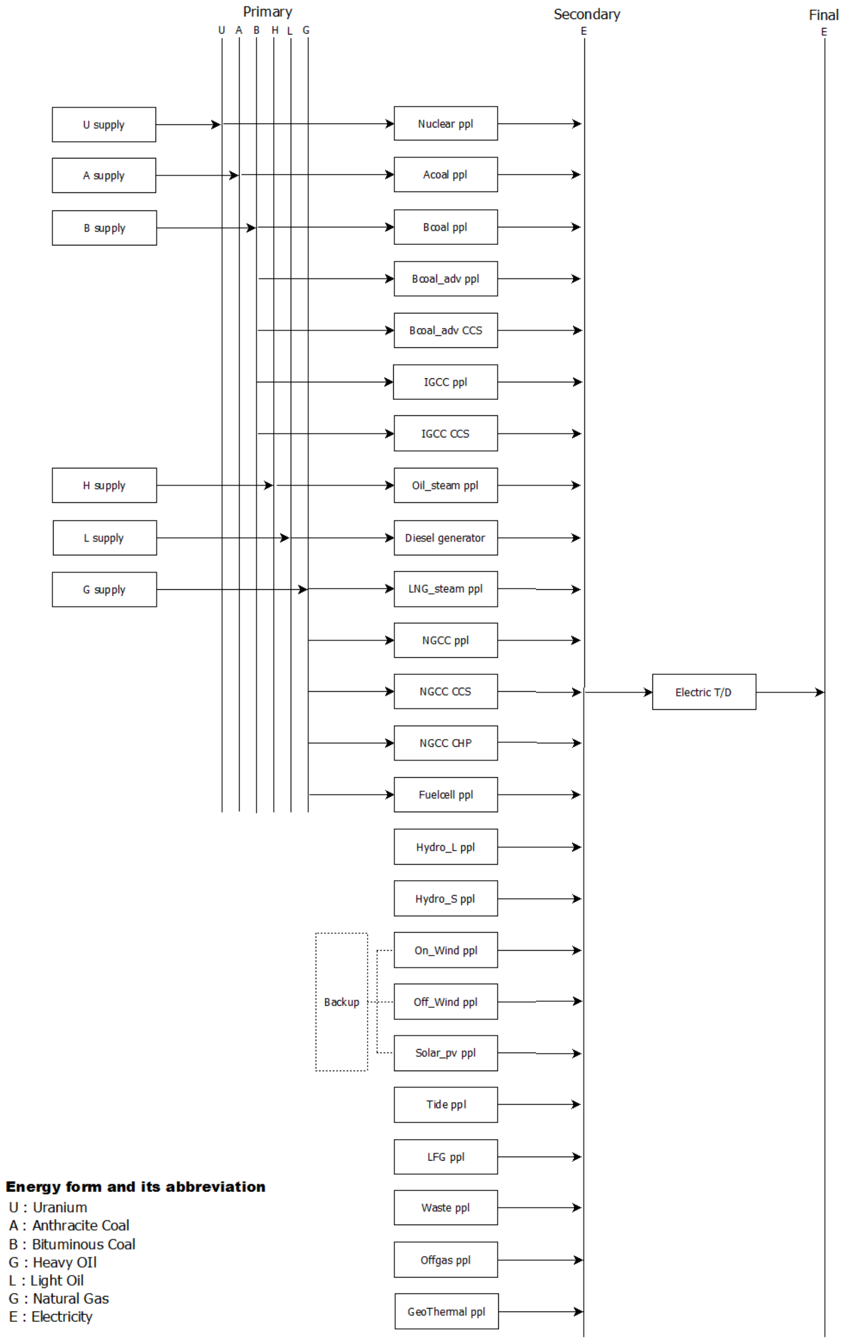

Figure 18: Reference Energy System (RES) of Korean power sector model (KPSM)

Chapter 4. Transition to Low Carbon Power System

4.1 Basic Scenario Assumptions

4.1.1 Electricity Demand Projection

Electricity consumption, energy demand in general, is one of the key factors which affect the transformation of the electricity system by determining the necessary generation capacity expansion and associated investment. Electricity demand is also a key determinant of environmental impacts from any electricity supply systems. Different electricity demands even with an identical supply system would impose different impacts on environment. The assumed schedule of electricity consumption to 2050 for this thesis is adopted from a wide range of projections in other scenario studies and government plans.

Figure 19 presents the historical development of total electricity consumption from 1970 to 2010 and a range of projections until 2050. Electricity demand projections plotted consists of three from governmental plans (MKE, 2010, 2013a) and three from Korea Energy Economics Institute (2011) showing a wide range of uncertainty. Among these projections[15] this study takes the baseline demand projection in the 5th BPE (Biannual Plan on Electricity Supply and Demand)

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[15] Plotted electricity projections are scaled up from observed electricity demand in 2010 with their original growth rates except two projections from 6th BPE. Three demand projections from government BPEs are available only up to 2024 or 2027. The projection for the rest of periods was extrapolated based on the trend analysis of annual growth rate in five-year step in original projection data.

(MKE, 2010), which places in the middle of wide range uncertainty, as a demand schedule for the reference scenario. It should be noted that a very simple approach was taken to the electricity demand projection in this thesis because the main objective is to assess the role of supply-side technological advancement in carbon mitigation. However, it doesn't means that the demand side management is less important than supply-side decarbonization when it comes to carbon mitigation.

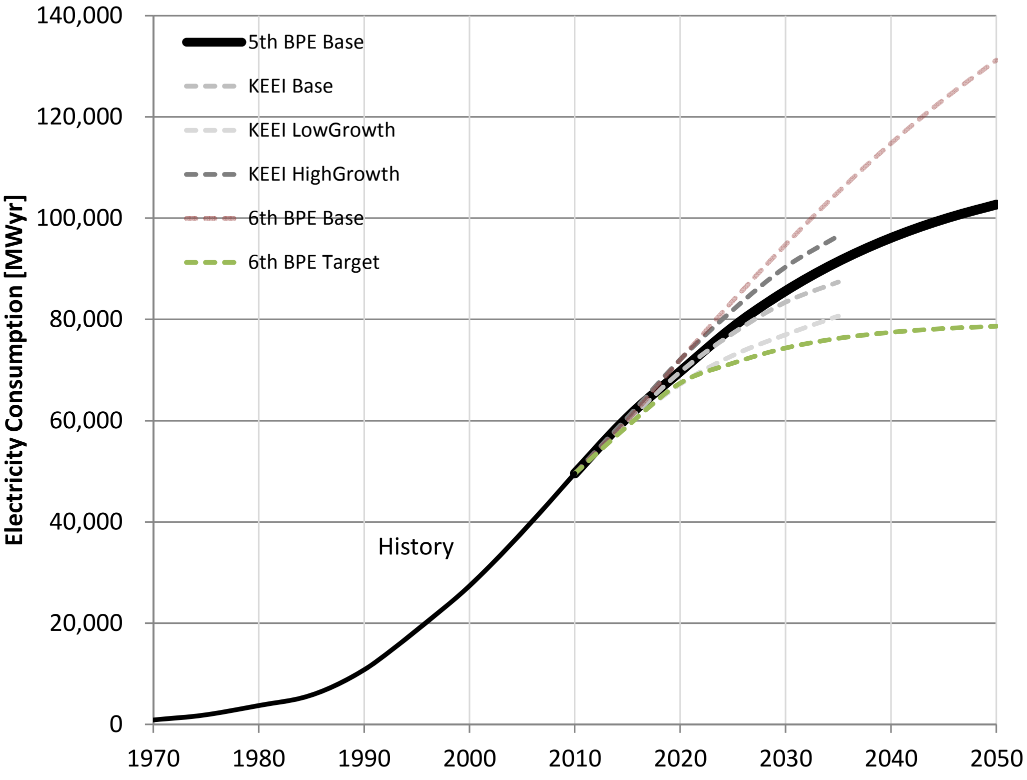

Figure 19: Historical development of electricity demand and the uncertainty of its future projections

According to the reference demand schedule, total electricity demand will reach about 700 TWh in 2030 (14,400 kWh per capita) and 900 TWh (18,700 kWh per capita) in 2050, respectively, 70% and 100% increase from the consumption level of 430 TWh (8,800 kWh) in 2010. The projection reflects a historical trend of a steady increase of electricity demand but with recent declining growth rates as shown in Table 6.

Table 6: Average annual growth of electricity consumption in 10 year period

Period	1970 ~ 1980	1980 ~ 1990	1990 ~ 2000	2000 ~ 2010	2010 ~ 2020	2020 ~ 2030	2030 ~ 2040	2040 ~ 2050
6th BPE Base					*3.81%*	*2.78%*	*1.93%*	*1.35%*
Reference	15.52%	11.19%	7.78%	4.8%	***3.47%***	***2.08%***	***1.16%***	***0.66%***
6th BPE Target					*3.12%*	*0.98%*	*0.41%*	*0.15%*

In addition to the total annual electricity demand, a simplified load duration curve over the course of each year, constructed based on the load curve in 2010 as identified in Figure 15, is implemented. The simplified load duration curve is composed of 7 regions. The share of time duration and electricity demand for each of 7 regions is defined in a way described in Table 7. For example, it is assumed that the highest load (i.e. in 1st load region) occurs for 7 hours out of 8760 hours during which about 0.1% of projected total annual electricity demand is required. The application of standard load duration curve into the future demand profile is based on the empirical observation that there is a close correlation between the shape of load curve and the total annual electricity demand (MKE, 2013a).

Table 7: Simplified 7 regions electricity load duration curve

Load Region	1st	2nd	3rd	4th	5th	6th	7th	Total
Hours	7	98	548	1,088	4,533	2,416	70	8,760
Share of Hours	0.1%	1.1%	6.3%	12.4%	51.7%	27.6%	0.8%	100%
Share of Demand	0.1%	1.4%	7.7%	14.3%	52.7%	23.2%	0.5%	100%
Demand in 2010 (MWyr)	504	6819	36,255	67,894	249,645	109,976	2518	473,611
Peak load in 2010 (MW)	72,000	69582	66159	62403	55073	45520	35971	-

4.1.2 Short-term Capacity Expansion Plan

In this study the short-term (by 2019) electricity technology capacity expansion from the government plan, the 6th BPE (MKE, 2013a), is assumed to be binding[16]. Since the construction of a utility-scale power plant takes at least 2 years for NGCC, 5 years for a coal power plant, and as long as 7~8 years for a nuclear power plant, it is assumed that new generation capacity

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[16] The planning horizon of the 6th BPE is from 2013 to 2027, but the study only considers that the capacity plan until 2019 is binding and irreversible. Also the capacity plan by 2019 excludes a so-called "policy capacity" which amounts to 3.5 GW in the 6th BPE.

scheduled to be online by 2020 is fixed and irreversible. Figure 20 shows the breakdown of technology type with its scheduled capacity additions until 2019. The total 65.5GW of new generation capacity will be installed between 2010 and 2019 with 21.5GW of coal, 22 GW of natural gas, 11GW of nuclear, and 10GW of renewable sources.

The implementation of the short-term capacity plan would restrict the movement of decision variables in the model and reflect the short-term rigidity of the system. Accordingly, any scenario results generated from the model would be more realistic.

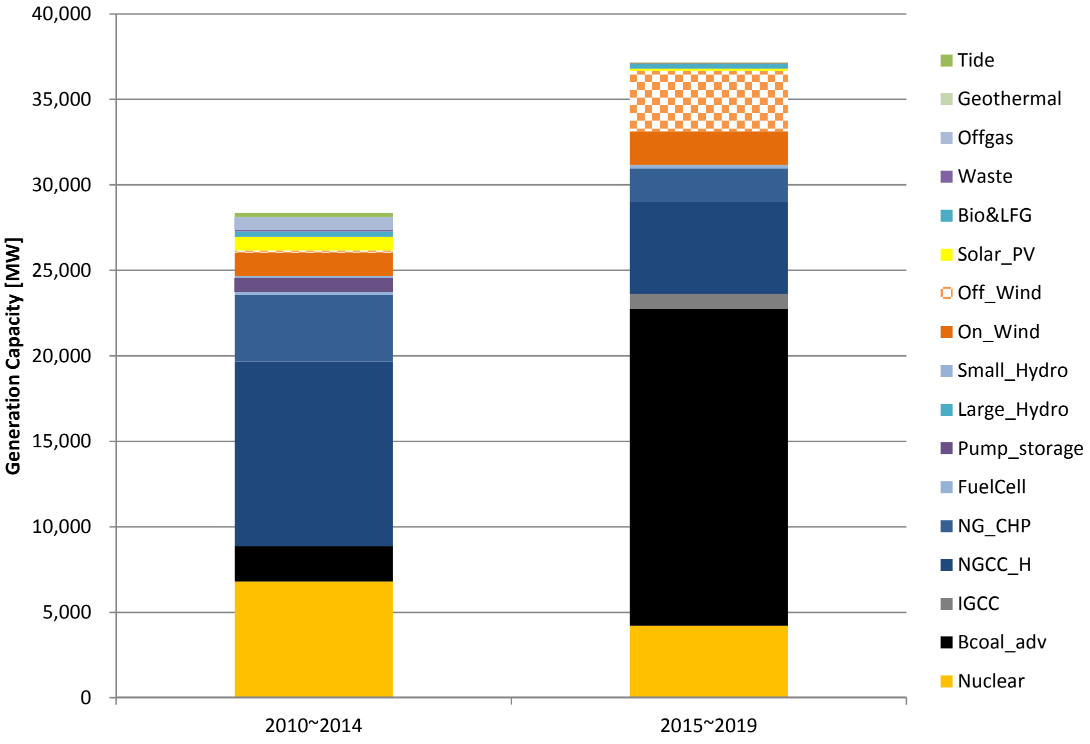

Figure 20: Electricity generation capacity plan in 6th BPE, 2010-2019

4.1.3 Technology Options and Future Advancement

When assessing a supply-side strategy to the carbon mitigation, what types of technology would be available in the future is a key factor determining any response strategy to carbon control. In particular, when the time horizon is long, as in this thesis and any other climate change policy analyses, the future technology portfolio is by nature uncertain. A portfolio of new technology as listed in Table 8 is considered. These technology options are currently under consideration in the latest government's BPE, and have already passed beyond the demonstration project phase, or are already being implemented somewhere at full industrial scale as delineated in Pacala and Socolow (2004). The full technology portfolio considered in the model is the combination of existing technologies listed in Table 5 and these new technologies. The current states of cost and performance characteristics of new technology portfolio are also presented in Table 8. All technology options are assumed to be available as of 2010 except CCS technologies whose first available year is 2025.

To implement future technology advance, potential efficiency improvement and investment cost reduction rate for individual technology are surveyed from various sources in the GHG emission scenario and modeling literature. The prospect of technology advance for Korea is benchmarked on that of OECD member states. The average rate from OECD countries of future cost decrease for individual technology were first assembled to avoid cross-country or regional variations, and then applied to the current level of investment cost for each technology in Korea. In other words, this study differentiates the current state of technology advancement in Korea from other regions by using indigenous cost and performance data, but adopts the future trends of technology advancement from an industrialized countries' prospect. The rationale can be supported by the consistency check of empirical technological advance using an experience curve model and learning rate estimate as presented in Chapter 2.4.

Two variants of technology advance were considered. The optimistic advance case is one where the greater rate of cost decrease in the surveyed literature is applied and the modest case adopts the middle value of investment cost in 2010 and that in 2050 from the optimistic advance case. Numerical assumptions on the investment cost and efficiency improvement are presented in Table 9.

Most new technologies under consideration are believed to be already commercially available and are in an early stage of large-scale diffusion. To mimic the conventional S-curve technology diffusion pathway, the exponential interpolation of investment cost from now to 2050 was applied to project the investment cost trajectory over time in which fast advance (i.e. cost decrease) occurs in early periods and the rate of cost decrease gradually attenuates in later periods when technology advance get matured as illustrated in Figure 21. O&M cost is assumed to follow the same trajectory. Figure 22 demonstrates the development of resulting LCOEs for two variants of technology advance case over time (left panel for modest advance case and right panel for optimistic case) which converts all related cost and performance characteristics of individual technology into a present value of average lifetime cost of electricity production.

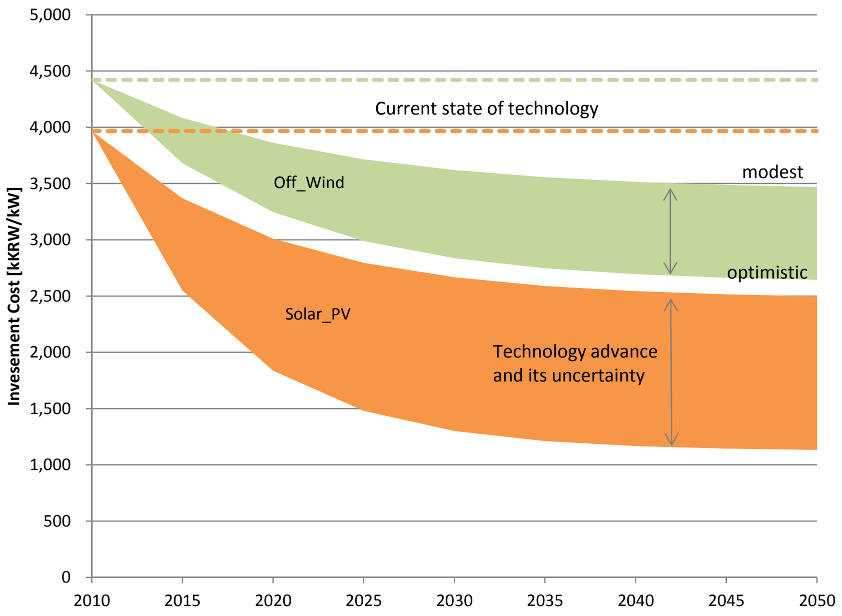

Figure 21: Illustration of technology advancement pathway and its uncertainty

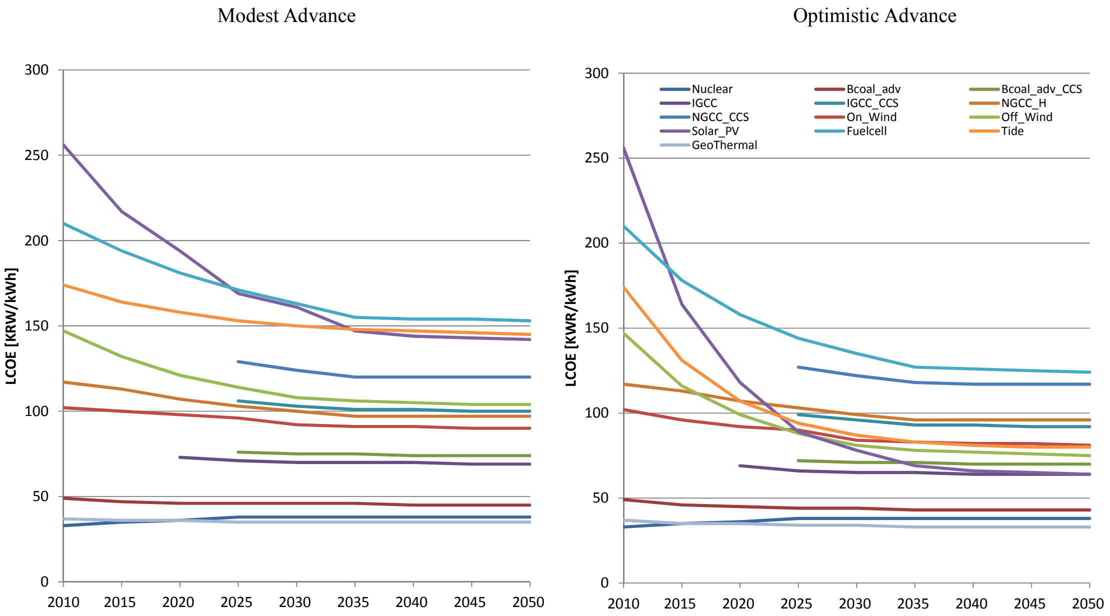

Figure 22: The development of LCOE over time across selected new technologies

Table 8: Cost and performance characteristics of new electricity technologies as of 2010

Technology	Efficiency[a]	Investment cost[b] [kKRW/kW]	O&M cost[c] [kKRW/kW/yr]	Capacity factor[d]	Life time[e] [yrs]
Bcoal_adv	0.46	1469*	44	85%	35
Bcoal_adv_CCS	0.35	2479**	74	85%	35
IGCC	0.48	3598*	126	85%	35
IGCC_CCS	0.39	5220**	183	85%	35
NGCC_H	0.58	904*	23	85%	30
NGCC_H_CCS	0.46	1627**	41	85%	30
Fuelcell	0.45	7090*	142	85%	20
On_Wind	-	2497*	37	25%	25
Off_Wind	-	4420**	133	36%	25
Solar_PV	-	3967*	40	15%	25
Tide	-	7389**	192	46%	30
Bio & LFG	0.30	3234**	97	70%	20
Waste	0.50	8726**	332	65%	30
Offgas	-	2254**	79	70%	20
Geothermal	0.15	2486**	50	70%	30

[a] Korea-specific data wherever available. Otherwise, adapted from OECD average in World Energy Outlook 2012 (IEA, 2012e)

[*] based on Korea-specific data (KPX, 2012, 2013b)

[**] investment cost data for these technologies are not available. Thus, scaled with a proportion to a cluster technology. The proportion adapted from OECD average in World Energy Outlook 2012 (IEA, 2012e)

[c] the same method as in Table 5

[d] OECD average in World Energy Outlook 2012 (IEA, 2012e)

[e] adapted from various sources (IEA, 2010, 2012e)

Table 9: Cost and performance assumption in 2050 in two technology advance cases

Technology	Efficiency or Capacity factor		Investment Cost [kKRW/kW]		
				2050	
	2010	2050 [a]	2010	Modest advance [b]	Optimistic advance [c]
Bcoal_adv	0.46	0.48	1469	1307	1145
Bcoal_adv_CCS	0.35	0.36	2479	2151	1823
IGCC	0.48	0.52	3598	3186	2773
IGCC_CCS	0.39	0.45	5220	4608	3997
NGCC_H	0.58	0.62	904	829	753
NGCC_H_CCS	0.46	0.51	1627	1431	1234
Fuelcell	0.45	0.60	7090	5022	2954
On_Wind	0.25*	0.26	2497	2282	2067
Off_Wind	0.36*	0.40	4420	3470	2520
Solar_PV	0.15*	0.17	3967	2499	1031
Tide	0.46*	0.46	7389	5383	3377
LFG	0.30	0.30	3234	2878	2523
Waste	0.50	0.50	8726	8345	7964
Geothermal	0.15	0.15	2486	2357	2227

[a] adapted from various sources (IEA, 2010, 2012c, e)

[b] middle value of invesment cost in 2010 and that in 2050 from the optimistic advance case

[c] adpated from the most optimistic cost reduction rate for OECD average from scenario literature (IEA, 2010, 2012c, e)

* indicate capacity factor

4.1.4 Other Scenario Assumptions

A linear program (LP)-based optimization model like MESSAGE can produce erratic behavior of any decision variable. For example, an output or the rate of deployment of a certain technology over a short period can sky-rocket or plummet so much that it doesn't seem to be plausible in reality due to other constraints which are not fully reflected in the mathematical model. Such "flip-flop" behavior or "winner-takes-all" behavior (e.g. a single least-cost technology option satisfy all energy demand) can be avoided by utilizing some features such as market penetration constraint. Also other reality-based decision criteria such as diversification of energy mix can be implemented in the model by introducing a user defined constraint. Following is a brief description of such constraints implemented in all scenarios under consideration.

Nuclear

The share of electricity generated from nuclear is upper-limited at 35% as of 2030. This assumption reflects the latest government nuclear policy outlined in the 1st National Energy Master Plan (NEMP) where 14 new nuclear reactors with 18.2 GW capacities is schedule to be constructed until 2024. As of 2030 new nuclear capacity installation is only allowed as much as to replace retired capacity while satisfying 35% generation from nuclear.

Natural Gas

The share of electricity generated from natural gas is capped at 35% to secure the diversification of energy sources in electricity generation.

Fuel price

Fuel price projection is not considered in the study. Current level of fuel prices as presented in Figure 16 are assumed to be maintained (i.e. relative price) over time.

Deployment of low-carbon technologies in reference scenario

Due to cost disadvantage in the absence of any carbon constraint (i.e. the reference scenario) the rate of deployment of low carbon technologies would slow down beyond 2020. To avoid the unrealistic reverse, a lower limit of market penetration constraints for each low-carbon technology was introduced in a way to ensure the generation share of total low-carbon technology reaches at least 6% in 2030 and 11% in 2050.

CCS technology

Given that CCS technology is still not on the horizon in the 6th BPE as a large scale power generation technology, the first available year of CCS technology is assumed to be 2025. Also 10 thousand KRW/tCO_2 of transport and storage cost of captured CO_2 is introduced.

Backup capacity for variable renewable (varRE) technology

A greater share of varRE (e.g. solar and wind) will increase the variability and uncertainty in a power system. As penetration of varRE technology grows, measures will need to be taken to ensure continued reliable operation of the system. A measure was introduced to the model in a way that a generic backup technology (e.g. gas turbine plant) whose installed capacity corresponding to 30% of combined installed capacity of varRE technology is required at any point of time.

4.1.5 Carbon Mitigation Scenarios

Four alternative emission control paths are considered as possible future emission control policies. Four policy scenarios cover a wide range of emission pathways with different stabilization level by 2050 and peak level at different point of time as specified in Table 10 and illustrated in Figure 23.

The least stringent policy constraint is ‘mit0%’ where the GHG emissions level reaches its peak level at 30% more than in 2010 and stabilizes at present level by 2050. The most ambitious policy scenario is ‘mit50%’ which reduces power sector-wide emission by 2050 at 50% less than current level with peak emissions occurring as early as 2020. It should be noted that these policy scenarios do not reflect any policy goal discussed now in Korea. They have been chosen to provide the insight into the magnitude of reductions associated with various technology choices.

Table 10: Taxonomy of four alternative mitigation policy scenarios

Mitigation policy scenario	GHG emissions level in 2050 (% change relative to 2010)	Peak emissions level (% change relative to 2010) and year
mit0%	228 MtCO$_2$e (0%)	295 MtCO$_2$e (+30%) in 2035
mit20%	180 MtCO$_2$e (-20%)	272 MtCO$_2$e (+20%) in 2030
mit35%	150 MtCO$_2$e (-35%)	250 MtCO$_2$e (+10%) in 2025
mit50%	114 MtCO$_2$e (-50%)	238 MtCO$_2$e (+ 3%) in 2020

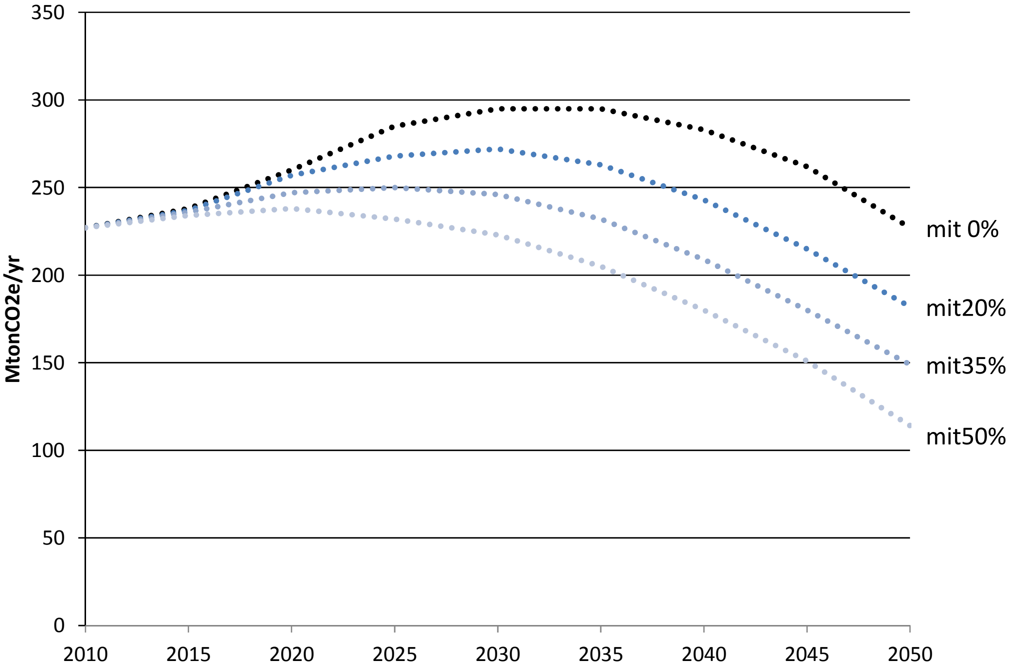

Figure 23: Emissions pathway of four alternative carbon mitigation scenarios. 2010-2050

4.1.6 Scenario Matrix

A two-dimensional scenario matrix is explored. Along one dimension of the matrix, alternative policy constraints on GHG emissions pathway are considered. Along the other dimension, alternative technology advances for given suites of technology options are considered. The policy dimension includes a case with no carbon emission constraint, labeled a reference scenario. The analysis considers four emission pathways representative of possible future emission policies as specified in Table 10. Three alternative technology advance cases are considered. The first case ('no advance') assumes the cost and performance of suite of technologies options are frozen at current level. The second case ('modest advance) is designed to represent modest improvement in performance and costs for a range of supply technologies on power system. The third case ('optimistic advance) is designed to represent more extensive technology improvement as described in previous chapter.

Table 11: Scenario Matrix: A combination of carbon mitigation pathways and technology advance cases

Mitigation scenarios (no.=5)		Technology advance (no.=3)
Reference mit 0% mit 20% mit 35% mit 50%	X	no advance modest advance optimistic advance

4.2 Key Scenario Results

This section summarizes the main scenario results with respect to mitigation portfolio, cost implication, electricity system transformation, and deployment of low carbon technology and corresponding investment. In particular the scenario result will be presented from two different angles, one is how the stringency of mitigation goal affects low carbon energy system transformation, and the other is the role of technological advancement in such transformation.

4.2.1 Reference Scenario

The reference scenario is a scenario without any carbon mitigation policy implemented. Given electricity demand schedule and a set of scenario assumptions and calibration described in the previous sections, the model finds the least-cost electricity system transformation over time as presented in Figure 24.

The total electricity generation increases from 470 TWh in 2010 to 980 TWh in 2050 (100% increase). The generation mix by energy source gradually evolves over time from 32% of nuclear, 42% coal, 22% of natural gas and less than 2% of renewable source in 2010, to 36% of nuclear, 46% of coal, 8% of natural gas, and 11% of renewable sources in 2050. GHG emissions also increase over time from the current level of 227 to 360 $MtCO_2e$ (60% increase from 2010 level) in 2050, but its growth rate is much slower than the past decades due to slower growth of electricity demand and gradual increase of electricity generation from non GHG-emitting renewable sources. The reference scenario serves as a reference against which any mitigation scenarios and associated system transformation is evaluated.

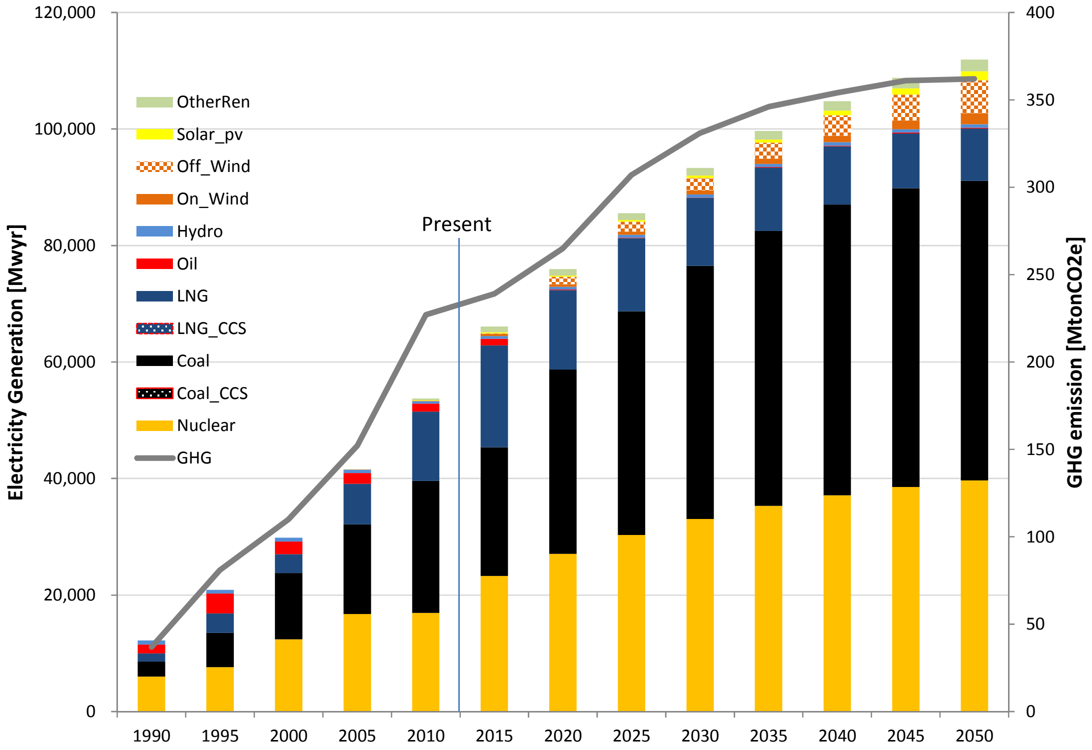

Figure 24: Electricity generation by technology and GHG emission in the reference scenario

4.2.2 Mitigation Wedge

The abatement of GHG emissions can be achieved through a wide portfolio of measures. The competitiveness of each mitigation option and its relative contribution are mainly determined by the development of cost and performance as well as deployment potential while the model finds the least cost combination of mitigation measures needed to meet the predefined emission pathways.

It is important to note that deployment of a diverse set of new and existing technologies is necessary and none of which will provide the majority of potential reduction. Consequently, if one or more of these mitigation options are not available, even more contribution from the remaining options (i.e. mitigation technology substitution) would be required and a given emission target would be achieved at higher cost than otherwise.

Figure 25 illustrates contribution of each mitigation options over time across 4 scenarios. All against the reference scenario, the upper left panel shows the result for the least stringent emission pathway under ‘no advance’ case (‘mit0%_N’) and the upper right panel for the same mitigation policy scenario under ‘optimistic advance’ case. The lower panels illustrate the result for the most stringent policy constraint. The horizontal comparisons in the figure will provide the effects of technology advance under identical mitigation policy scenario while the vertical comparisons provide the insight into the effects of policy stringency under the same technology advance scenario.

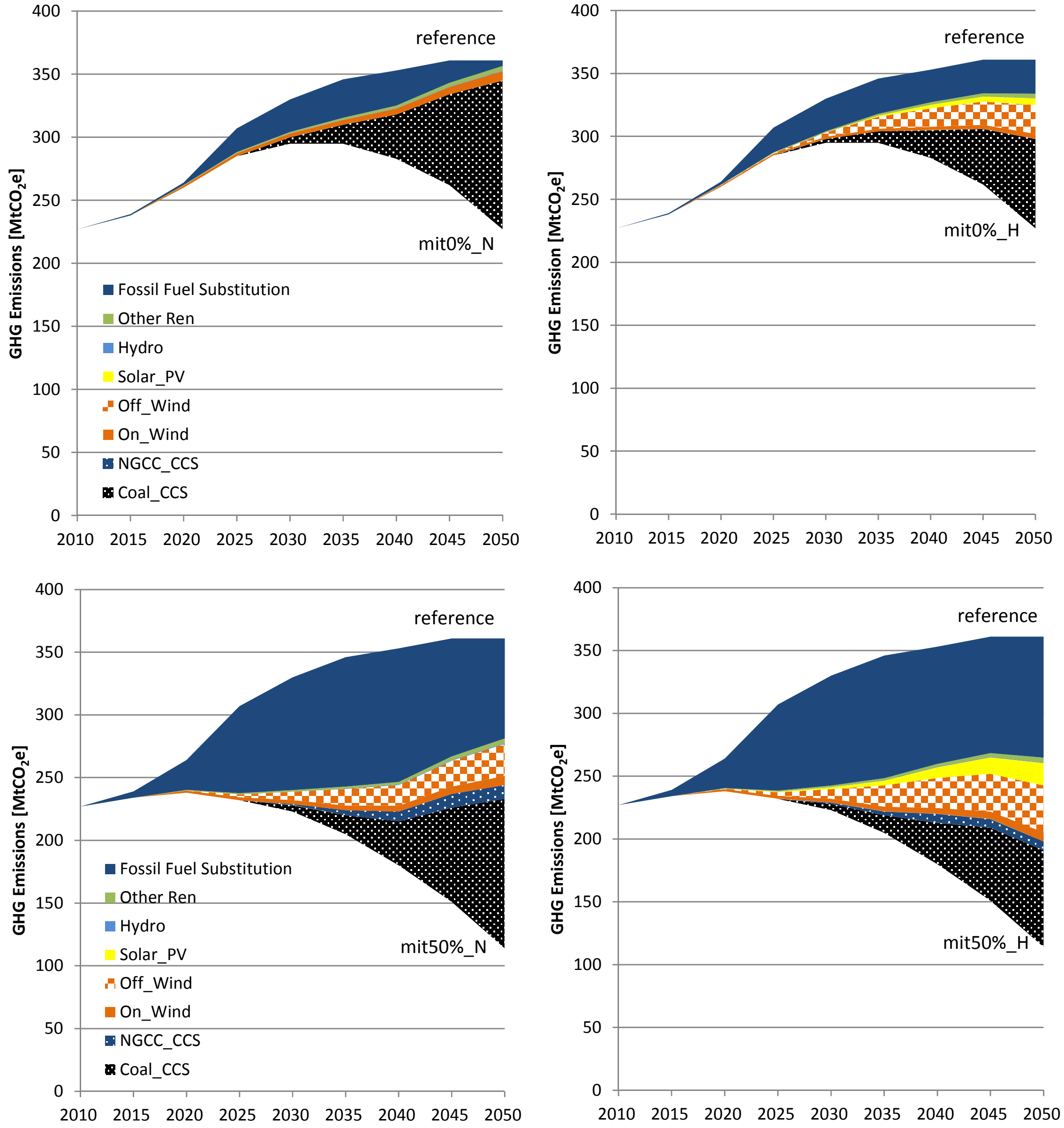

Figure 25: Contribution to emission abatement over time

(Note: Upper panels for ‘mit0%’ with ‘no advance (No)’ in left and ‘optimistic advance (H)’ in right. Lower panels for ‘mit50% with ‘no advance’ in left and ‘optimistic advance’ in right)

It should be noted that early GHG abatement until 2020, regardless of long-term stringency of mitigation target, is only possible through a switch to a relative clean natural gas. Given the short-term inertia of the system and fixed short-term capacity plan, the only remaining option for short-term abatement from the supply side[17] is to increase the utilization rate of relatively clean energy sources, i.e., natural gas. Currently electricity from gas-fired power plants, mostly natural gas combined cycle (NGCC), mainly satisfies an intermediate and peak demand with about 60% capacity factor due to relative expensive fuel cost. However, natural gas needs to substitute for oil and coal if any early emission reduction is necessary.

The contribution of fossil fuel substitution into natural gas is not limited only in the early abatement. The cumulative amount of GHG abatement by fuel substitution into natural gas is proportionally increased as the mitigation target gets stringent regardless of technological advancement as shown in Figure 26.

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[17] In reality GHG emission abatement can also be achieved by utilizing a demand side management (DSM) such as energy conservation and efficiency improvement. However, given the scope of this thesis which focuses on supply-side technology options, the potential of DSM for GHG abatement is not considered. The Chapter 5 will revisit this issue.

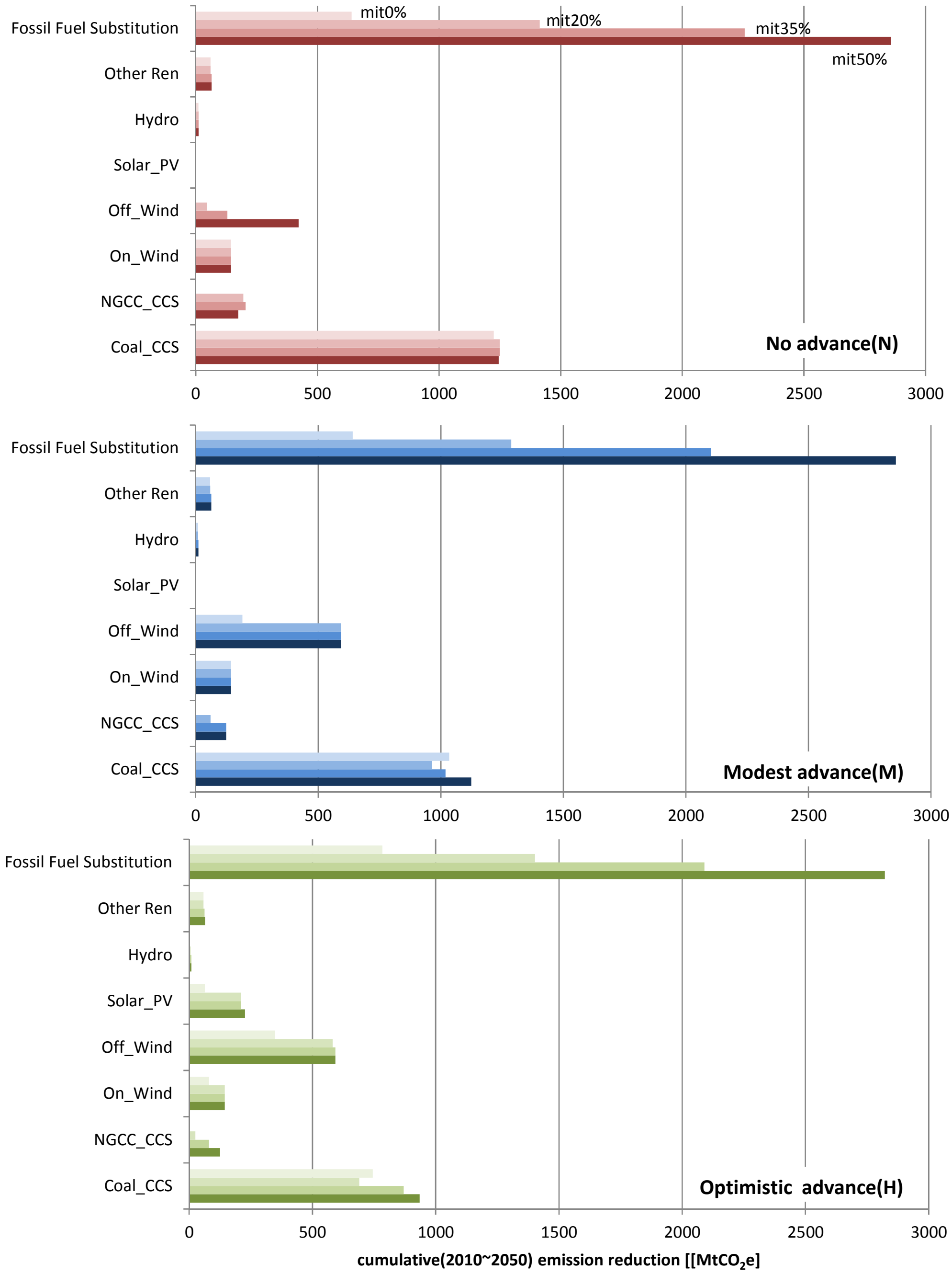

Figure 26: Cumulative contribution to emissions reduction by technology option.

What this result implies is that the switch to natural gas is the most economically attractive and no-regret supply-side mitigation option under the uncertainty of carbon policy mitigation stringency and technological advancement. There is no technical barrier which prevents natural gas power plants from working as a base load technology. Under a carbon constrained world, natural gas technology becomes more economically sound and competitive.

CCS technology plays a steady role regardless of mitigation stringency. Unlike the fuel substitution, the contribution of CCS is less affected by the level of mitigation. Even late entry into the system, assumed first available as early as 2025, CCS contributes to a deep cut of emissions in later period. However, the contribution of CCS is lessened in the optimistic advance case. The reason is that the slower rate of advance for CCS technology compared with other options drives reshuffling of optimal mitigation portfolio. It sounds counter-intuitive, but makes economic sense. The nature of MESSAGE, inter-temporal optimization with perfect foresight makes it possible to reorganize the least-cost combination of technologies with updated information. In other words, the change in economic merit order within a suite of technology options rearranges the relative contribution in carbon abatement. This model behavior can be said to more closely reflect the decision making mechanism (e.g. sequential decision making over time) in reality.

The robust role of natural gas and CCS in carbon mitigation observed in this thesis contrasts with the current policy direction. According to the 6th BPE, the share of natural gas in total installed capacity will be down to 20% (32GW of capacity) in 2027 from 26.3% (20GW of capacity) in 2010, and CCS is not on the horizon of generation mix until 2027.

The beneficiary technologies from future advance are solar photovoltaic and offshore wind power. While contribution of these technologies in the mitigation portfolio is not significant under the frozen technology case, their roles increase significantly with future advancement. Especially, if there is no technology advance, solar photovoltaic doesn't play any additional role in GHG abatement even under the most stringent emissions abatement. What it implies is that pricing carbon alone (i.e. carbon mitigation policy implicitly imposes a price on carbon in the model) doesn't necessarily guarantee the level playing ground for some currently expensive low-carbon technology. Thus, pricing carbon, in other words carbon control, on top of extensive technological advance is required for some renewable technologies to be economically competitive with other GHG emitting technologies. Weak economic competitiveness of these zero carbon-emitting renewable technologies even under the optimistic advance case can be explained from system integration perspective. The intermittent nature of these renewables requires additional backup or a storage system for the reliable operation of any power system in reality. This requirement imposes an implicit cost and weakens the economic competitiveness of these varRE technologies.

4.2.3 Mitigation Costs

How costly it would be to reduce GHG emissions is one of the main questions in an economic analysis of climate change. Future technological change in terms of its rate and direction, and availability of technology portfolio is a key driver of mitigation cost. Estimate of carbon mitigation cost can even serve as a key policy decision criterion at a country-level on how much to reduce or at what level the domestic emissions level to stabilize and by when.

A significant system-wide cost savings is expected from future technology advancement as highlighted in Figure 27. A range from 6% to 12% of cumulative electricity system cost, or 4 to 8 trillion KRW per year[18] over the next four decades, can be saved by assumed technology advance regardless of the stringency of mitigation target. The magnitude of the savings can be interpreted as a value of technology advance. However, it should be cautious that the savings is not a net value of technology advancement. The value is a pure benefit or value of technological advancement without consideration of any associated cost of technological development and/or deployment policy such as public and private R&D investment or tax credit for RD&D, any subsidy for technology deployment etc.

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[18] Put this estimate in another perspective, total expenditure on energy import is 120 billion USD (132 trillion KRW) in 2010 (KEEI and MKE, 2012) in Korea. The share of primary energy which goes to the energy transformation sector (town gas, heat, electricity, refining) is 25.2% in 2009. Thus approximately 20~25 trillion KRW/year is a fuel cost in electricity sector. Also the total revenue from electricity sale is 32 trillion KRW in 2010 (KPX, 2011)

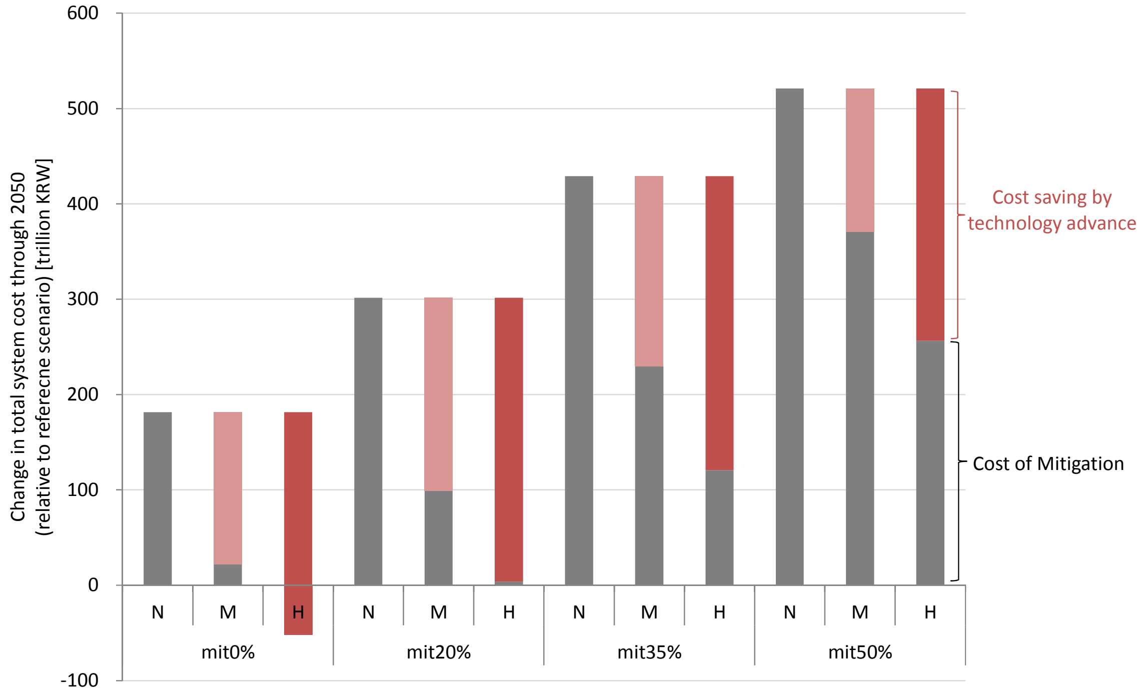

Figure 27: Cost of carbon mitigation and values of technology advance

Figure 28 translates the implication of both mitigation and technology advance effect in terms of unit GHG abatement cost[19]. The general pattern of marginal cost increase is observed in all technology advance cases. With current level of technology development frozen over time (i.e. no advance case) the unit abatement cost increases from 87 thousand KRW/tCO_2e in ‘mit0%’ scenario up to 106 thousand KRW/tCO_2e in ‘mit50%’ scenario. However, the same

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[19] The unit GHG abatement cost, average over time, is calculated by following simple calculation;

$$\text{unit cost}(i) = \frac{\sum_t syscost_t(i) - syscost_t(ref)}{\sum_t emission_t(ref) - emission_t(i)}$$

where, i = scenario, ref = reference scenario, syscost = total system cost, and emission = GHG emission level of GHG emission abatement can be achieved with less unit abatement cost depending on the rate of technology advance. With optimistic advance, the unit cost decrease as much as 50% compared with no advance case in the most stringent mitigation scenario.

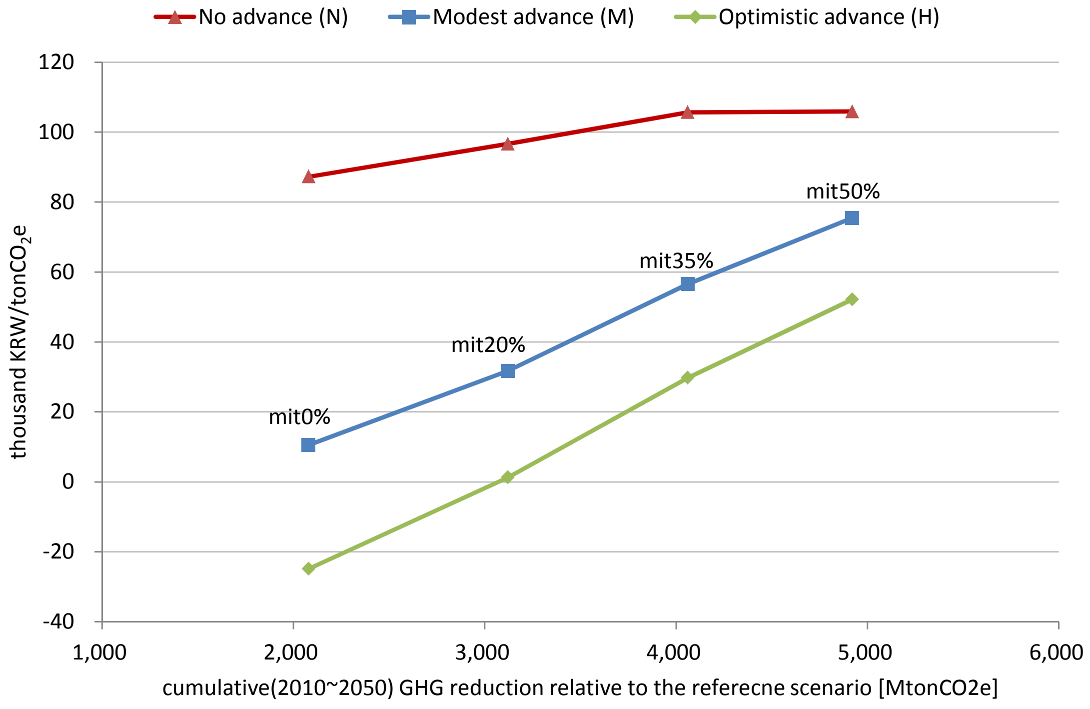

Figure 28: Unit GHG mitigation cost across all mitigation scenarios

Investment on electricity generating facility is a key component of total system cost because electricity supply system utilizes capital-intensive facilities in a large scale. Achieving a carbon mitigation pathway under growing electricity demand will require a new set of technology mix in electricity supply system. The resulting technology portfolio is the outcome of investment decision on what technology, how much, and when.

Figure 29 illustrates the effects of carbon mitigation and technology advancement on new investment in electricity generation technology. The system-wide cumulative new investment of 612 trillion KRW is required to achieve the emissions pathway specified in 'mit50%' scenario. This mitigation effect (ME) amounts to 40% (i.e., 176 trillion KRW) increase of new investment compared with that in the reference scenario. The increase of total investment is driven by reallocation of capital into a new low-carbon technology portfolio.

However, technological advances, with different technology portfolio, make it possible to achieve the identical emissions pathway with less investment. For example, the modest advance has a potential to reduce the new investment by 57 trillion KRW and the optimistic advance can alleviate the total investment as much as by 96 trillion KRW. If translated in annual term, these technology advancement effects (TE) amount to 1.4 trillion KRW savings per year and 2.4 trillion KRW savings per year, respectively.

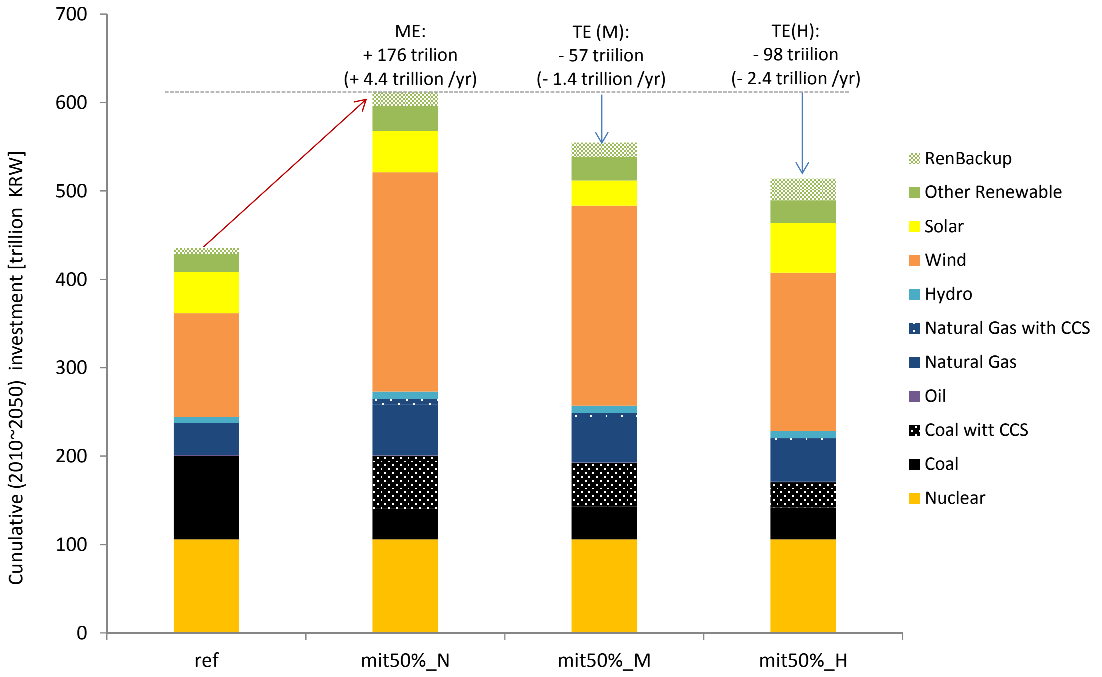

Figure 29: Cumulative investment on new electricity capacity by technology type

4.2.4 Deployment of Low Carbon Technologies

Figure 30 shows electricity generation mix by technology in two discrete periods of time across the reference and all mitigation scenarios. The extent of system transformation into less carbon dependent one is modest by 2030, but more drastic change is required by 2050. The share of electricity output from low carbon technology[20] is around 8% to 11% in 2030 across all mitigation scenarios, modest change from 6% in the reference scenario in 2030 while low

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[20] Low carbon technology here includes hydro, wind, solar, other renewable, and CCS.

carbon share needs to reach around 29% to 41% in 2050 which is a significant transformation from 11% in the reference scenario. This result is consistent with the finding in previous sections that major contributor of early mitigation is fuel switch to natural gas while more deep emissions cut in later period is achieved by more fundamental system transformation equipped with CCS and offshore wind.

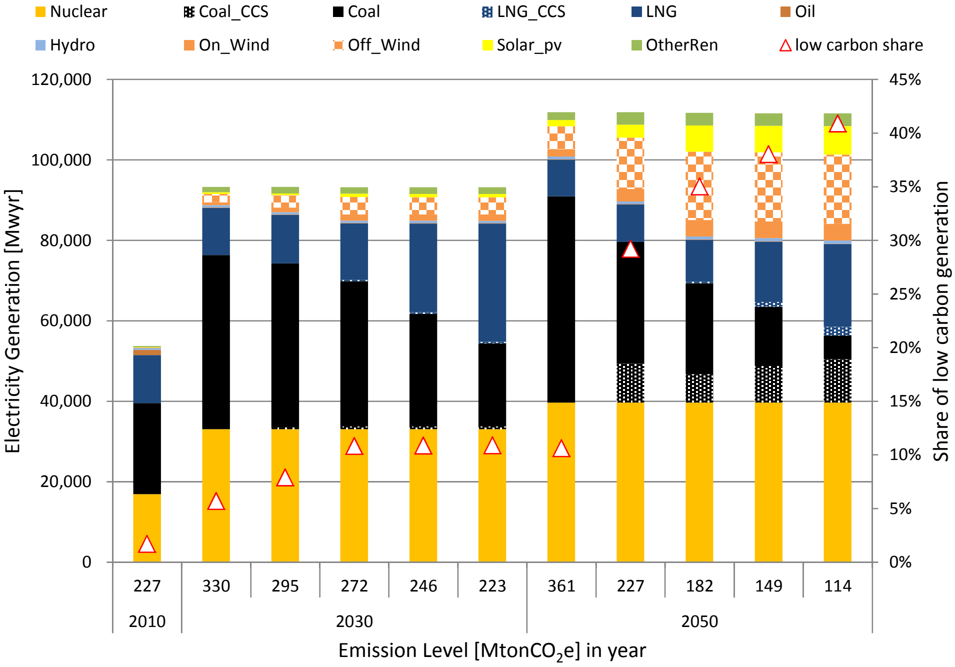

Figure 30: Generation technology portfolio and low carbon share in optimistic advance case in reference and four mitigation scenario.

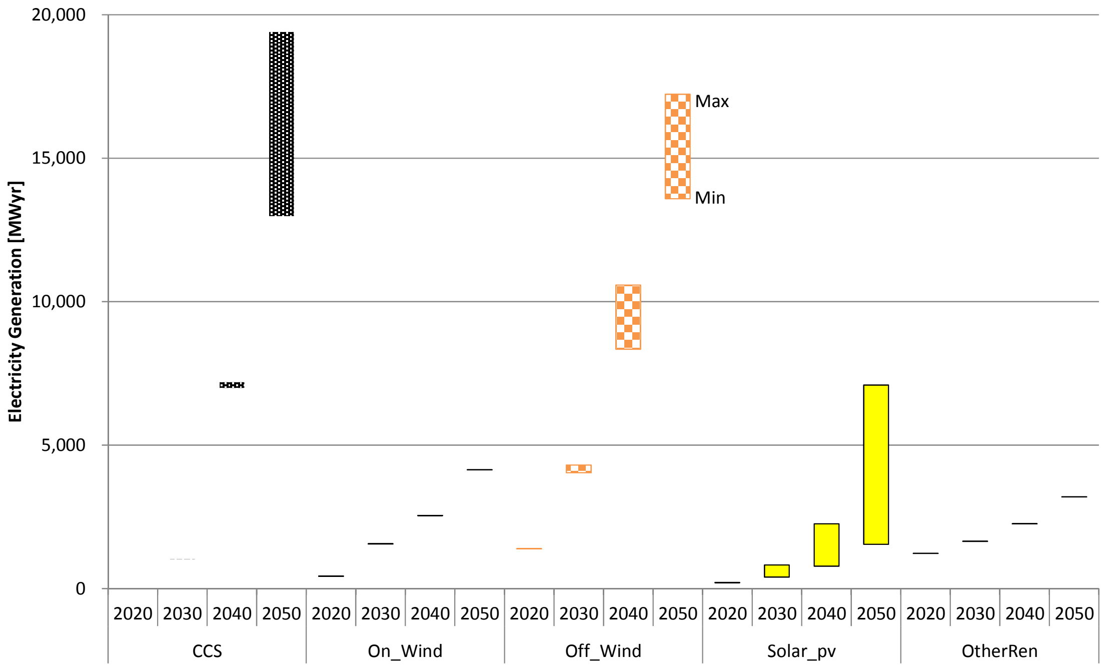

Figure 31: Technology advance effect on electricity generation across low-carbon technologies in ‘mit50%’ scenarios

(Note: Upper and lower end of bars indicates maximum and minimum generation respectively from three variants of technology advance)

Figure 31 demonstrates the effect of technology advance on the electricity generation from low carbon technology in ‘mit50%’ scenario. Under an ambitious decarbonized world (i.e., ‘mit50%’ scenario), the improvement in cost and performance makes a group of low-carbon technologies (offshore wind and solar photovoltaic) more cost-competitive and to contribute more to the generation mix while other technologies are barely affected by technology advance. One interesting technology is CCS whose total electricity generation is reversed by technology advance for the reason explained in Chapter 4.2.2.

The power system transformation into a less carbon-dependent one requires a corresponding capacity expansion which is required to replace retired aging capacities as well as to add new generating capacity to meet a growing energy demand. Figure 32 presents the amount of new generation capacity by technology over time which is required to achieve the most stringent mitigation scenario (i.e. ‘mit50%’) and contrasts with current (until 2019) policy outlined in the 6th BPE. While current policy tends to add majority of new capacity from fossil fuel-based, this trend needs to immediately change to meet the emissions pathway of ‘mit50%’ scenario. New coal-firing electricity generation capacity except CCS needs to be almost phased out as of 2020 while high-efficient natural gas combined cycle steadily need to be added in the technology portfolio to take over the role which coal-firing capacity do as base load technology. In later periods, the majority of new capacity should come from CCS and zero-carbon technology such as on- and off-shore wind and solar (especially in the optimistic advance case).

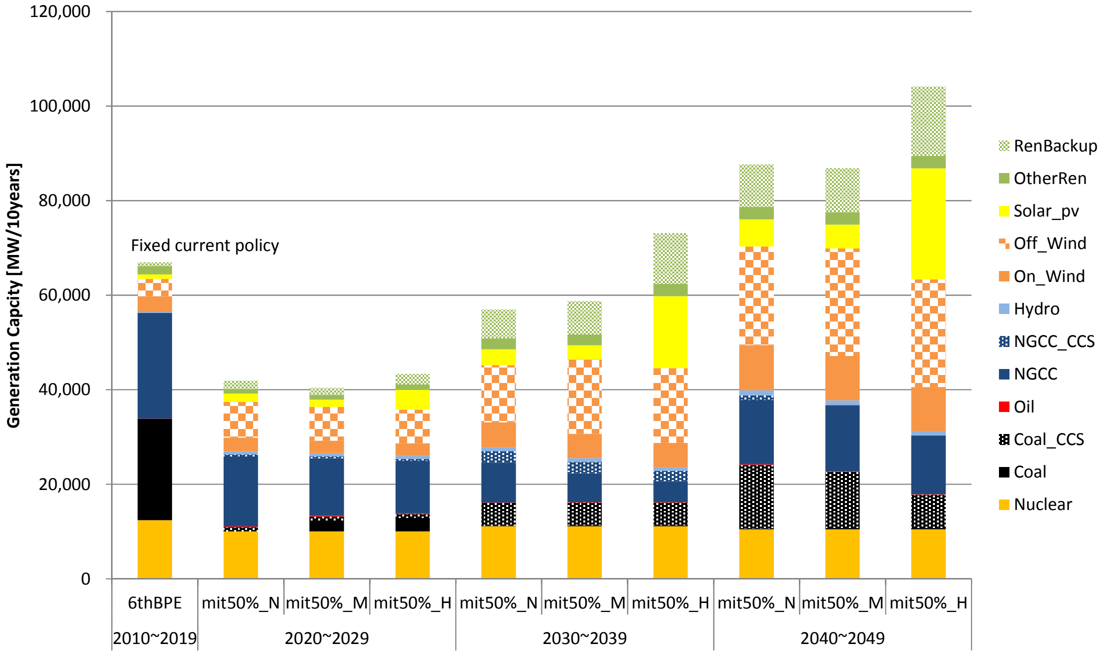

Figure 32: New capacity installation in 10 year period in 'mit50%' scenarios

While Figure 32 shows the new capacity installation schedule with technology advance effect to achieve the most stringent emissions pathway, Figure 33 illustrates the resulting total installed capacity profile under optimistic technology advance case with both generation and capacity share of low carbon technology. Total installed capacity and total generation of low carbon technology needs to be scaled up by 50-fold in the next 40 years, a steady annual growth of 10% over the next 40 years (from faster annual growth of 13% until 2030 to slower annual growth of 8% as of 2030). With this rate of deployment the share of low carbon technology in terms of electricity generation and capacity reaches at 41% and 61%, respectively, by 2050. In addition, a significant amount of backup capacity needs to be gradually connected into the systems to ensure the reliable operation of the power system as varRE technologies take a larger share in the generation mix.

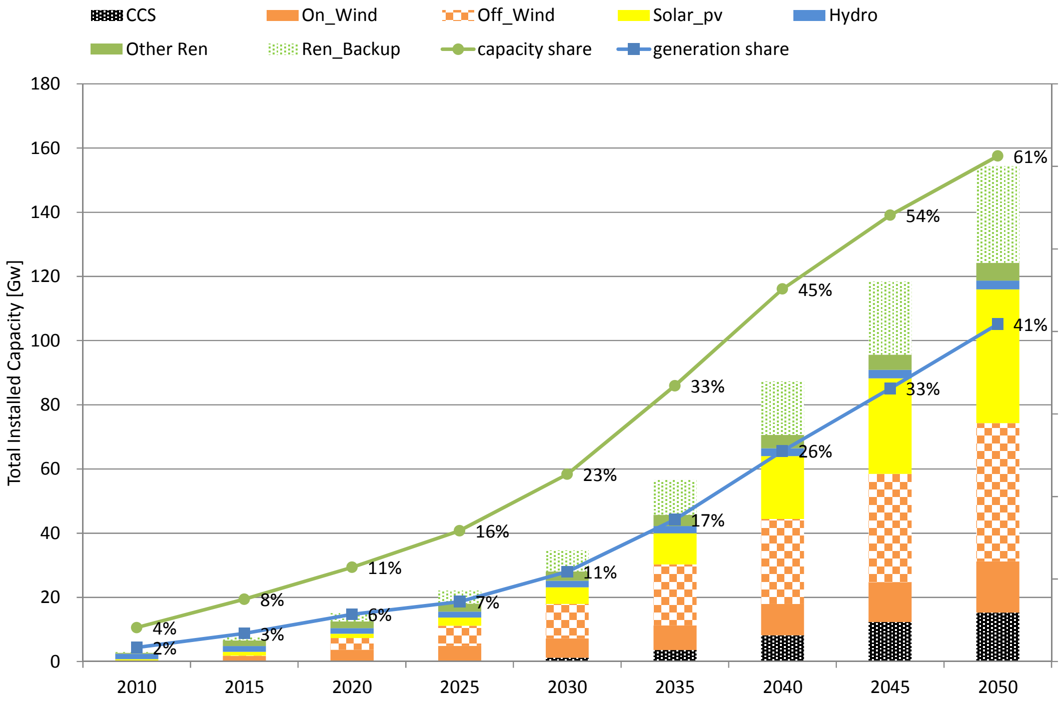

Figure 33: Deployment of low-carbon technology with their share in 'mit50%_H'

Figure 34 shows a comprehensive picture for the development of low carbon share in total electricity generation over time across all scenarios considered in this research. As addressed in previous chapters, technology advance alone without carbon constraints doesn't affect the extent of low carbon technology deployment. For example, the developments of low carbon share in total generation are identical in the reference scenarios regardless of technology advance (black dotted line). The effects of technological advancement on promoting greater deployment of low carbon technology are only observed in a carbon constrained world. However, the size of effect itself is modest (look into same-color lines with different types to see the effect of technology advancement on low carbon deployment under a carbon mitigation scenario). What this implies is that a significant challenge for a large scale deployment of low carbon technologies lies ahead regardless of technology advancement. For example, low carbon generation share needs to reach at 8% to 11% by 2030 and 28% to 41% by 2050, depending on the carbon control goals. Technology advance can only alleviates the cost incurring during these challenging transitions.

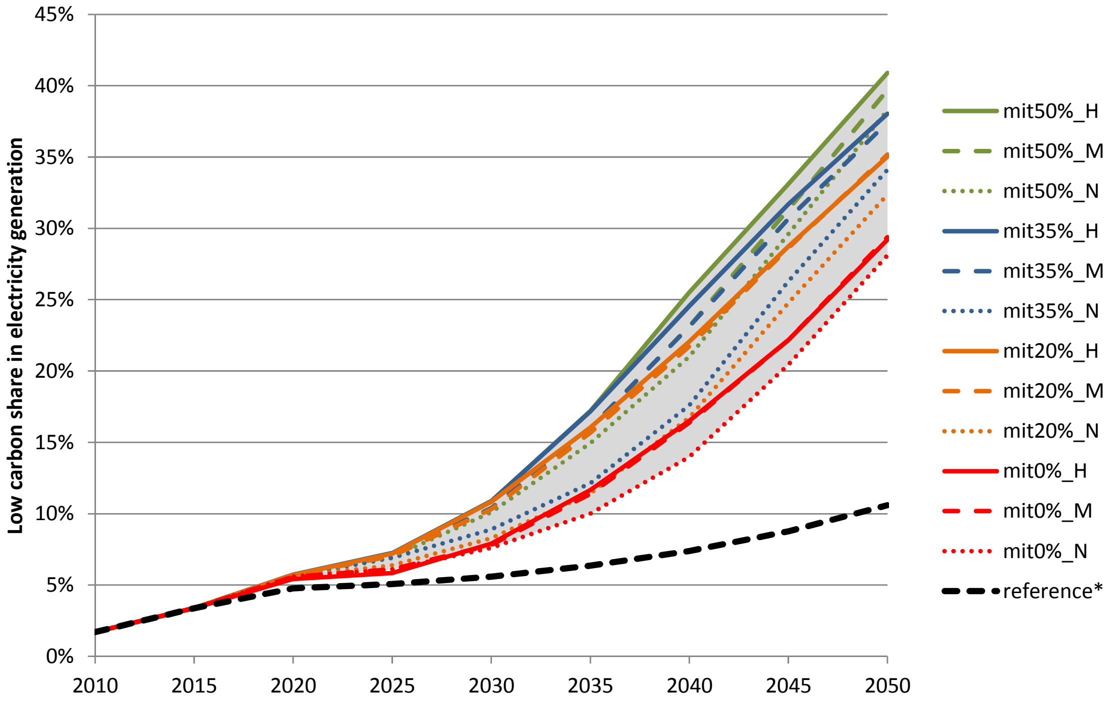

Figure 34: The development low carbon share in electricity generation over time across all scenarios

(* the development of low carbon share in total electricity generation is identical in the reference scenario across all three technology advance cases)

Chapter 5. Summary and Policy Implications

5.1 Summary of Key Findings

The overarching focus of climate change policies is to avert the threat of dangerous climate change through mitigation, i.e. the reduction of anthropogenic emissions of GHGs to the atmosphere. Costs of carbon abatement are at the center of policy debates, both at the domestic and international level, in the realm of discussion on how, how much, when, and where to abate. Costs seem inevitable in carbon mitigation since the use of energy, particularly fossil fuels that supply energy to virtually every activity in the economy, and for which there are currently no effective substitutes. However, many believe that technology doesn’t stand still and technological change will alleviate abatement costs. The specific objective of this thesis hinges on the role of technological change to determine carbon mitigation cost and its implications for cost-effective carbon mitigation portfolio, i.e. the question of how.

The objective is sought by conducting a scenario analysis in an energy system modeling framework for the Korean power sector. The combination of alternative carbon policy scenarios with three variants of technological advance, in terms of improvement in cost and performance, are examined in a bottom-up energy system optimization modeling framework, MESSAGE. The optimization feature of the MESSAGE serves to investigate technology-specific response strategies for achieving carbon mitigation policy constraints by solving for the cost-effective portfolio of electricity supply technologies and their deployment over time.

Several important points have been demonstrated.

First, the analysis identifies that carbon abatement costs can be reduced by 30% to 100% through technological advances. The range, dependent on the stringency of carbon mitigation and the extent of technology advancement, is equivalent to annual cost savings of 4 to 8 trillion KRW over the next 40 years compared with when technology advance is frozen at present level. Even a pure value of technology advancement, the magnitude of the savings is likely to be much greater than any costs associated with such technology advancement. This estimate can also serve as a reference for economic benefit of technology advances against which economic cost of policies is balanced when technology development or deployment policy is designed.

Second, cost-competitiveness of zero-emitting variable renewable (varRE) technologies is not ensured by technology advancement alone, but by the combination with aggressive decarbonization policy constraints. Although the economy of individual varRE technology can reach as low as so-called grid parity level, a complementary backup system which is required to ensure reliable operation of the overall power system, imposes an additional implicit cost on these technologies. Such implicit costs of varRE technologies can be offset by aggressive carbon policy constraints. Thus, the discrepancy in the economy of a technology between the stand-alone and system integration perspective should be carefully addressed in this type of analysis to avoid an overestimation of the role of varRE technologies.

Third, fuel substitution into natural gas utilized by advanced combined cycle technology is a robust carbon mitigation measure regardless of stringency of carbon constraint and the degree of technology advance. That is, the expansion of natural gas in the generation mix is a ‘no regret’ technology choice even under the combined uncertainty of technology advance and policy targets for carbon mitigation. This finding is supported in part by the reasoning addressed in the previous paragraph on the weakness of varRE technologies as carbon mitigation options. Relatively clean natural gas without any intermittent problem becomes more cost competitive under a carbon constrained world. CCS technology is also an attractive mitigation option if relative competitiveness among a broad range of low-carbon technologies is frozen at the current level. However, if the rate of advance for CCS is slower than that of other low carbon alternatives, as much of the technology scenario literature estimates, CCS technology would lose its competitive edge to other alternatives.

Finally, a significant challenge for a large scale deployment of low carbon technologies lie ahead regardless of technological advance. Depending on the carbon abatement policy goals, low carbon generation share needs to reach to 8% to 11% by 2030 and 28% to 41% by 2050, a fast increase from 1.7% in 2010. If the most ambitious decarbonization target (i.e. 50% reduction by 2050 from the current level as in ‘mit50%’) is pursued, an unprecedented deployment of low carbon technologies, a steady growth at the rate of 10% per year, is required over the next four decades. Technology advance will only alleviate the cost to achieve this transition. An effective policy response to such challenge is to make an immediate change in current policy direction for electricity supply portfolio. The later into the future this policy change is delayed, the greater the challenge and associated costs of carbon mitigation would be.

5.2 Policy Implications

Energy Technology RD&D (Demonstration) Expenditure

The policy implication that I want to draw first is whether the overall direction of current policy for technological development is consistent with key findings from this analysis. The first order indicator to technology development policy is a public energy technology research, development and demonstration (RD&D) expenditure. The public funding for energy-related activity and technology can serve as a proxy on how much public support is placed on which type of technology. Government expenditure on energy-related RD&D in Korea is among the highest in the OECD, 0.53% of GDP compared with 0.40% median of IEA member countries. Spending has increased significantly in the past decade and in 2010, government investment in energy-related RD&D was over KRW 600 billion (IEA, 2012b). Figure 35 compiles energy-related RD&D expenditure in Korea between 2002 and 2010 (IEA, 2012d). The total expenditure of KRW 3.6 trillion[21] (or KRW 0.4 trillion per year) in the past nine years, which is equivalent to USD 3.3 billion, has been spent on a wide array of energy-related RD&D activities.

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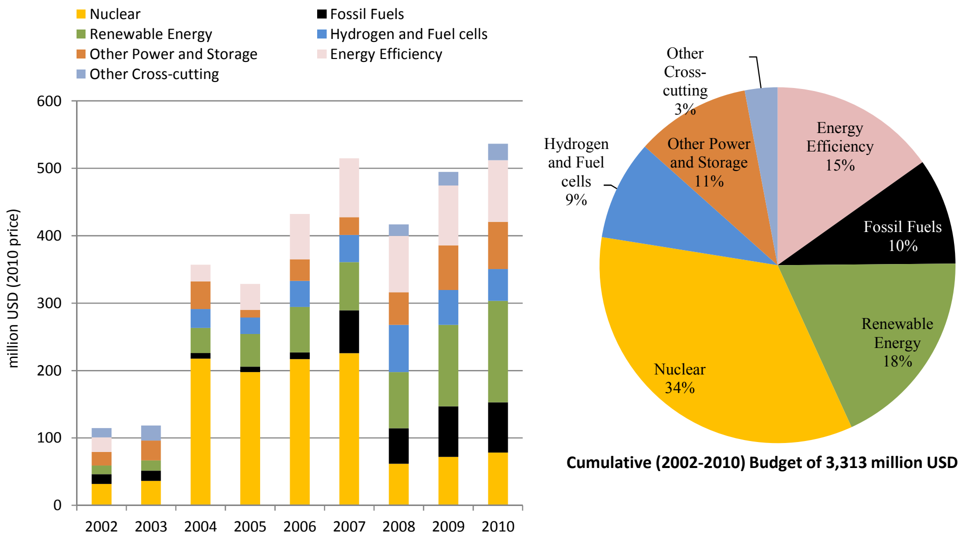
[21] Both KRW and USD is in 2010 price. For the currency conversion, 1USD = 1,100 KRW of exchange rate is applied



Cumulative (2002-2010) Budget of 3,313 million USD

Figure 35: Energy-related RD&D expenditure by category or technology in Korea, 2002-2010 (Note: Right panel for cumultative (2002-2010) spending with share (%) of each category. Source:IEA (2012d))

The rank, in terms of cumulative investment, of activity or technology is as follows; nuclear (34%), renewable (18%), energy efficiency (15%), other power and storage (11%), and fossil fuels including CCS (10%)[22]. The share of investment on decarbonization of supply system (i.e. renewable, CCS, hydrogen, other power and storage combined) rose from 29% in 2002 to 55% in 2010. More specifically, Figure 36 shows a high resolution profile of RD&D expenditure on renewable energy. Out of a 670 billion KRW (or 75 billion KRW per year) expenditure on renewable energy, solar (294 billion KRW, 44%) and wind (156 billion KRW, 23%) account for

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[22] For the guide to collecting and reporting 'IEA Energy RD&D Budget and Expenditure Statistics' (IEA, 2012d) and more detailed explanation of each category and sub-category, see IEA (2011).

two-thirds of the expenditure. Classified in the fossil fuel category, CCS attracted 77 billion KRW and gas combustion 48 billion KRW.

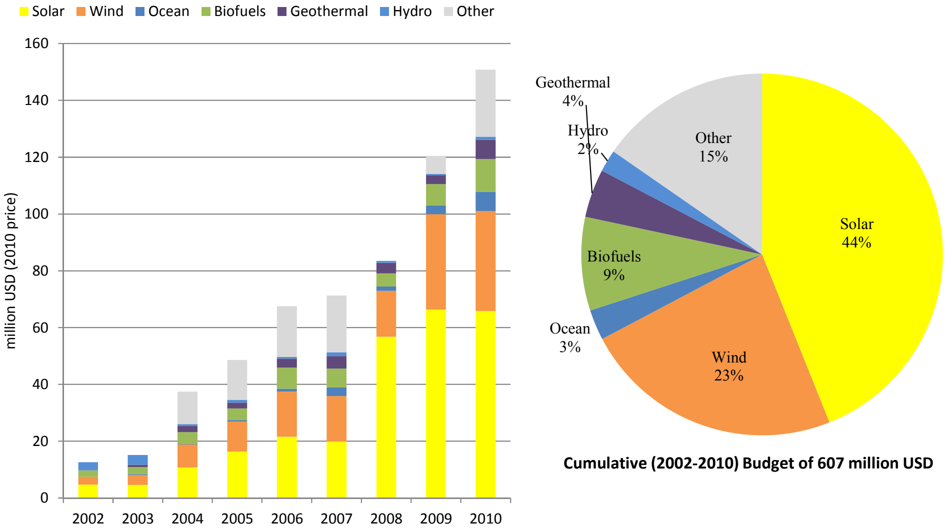

Figure 36: Renewable energy RD&D expenditure by technology, 2002-2010

(Note: Right panel is cumulative (2002-2010) spending with share (%) of each technology. Source:IEA (2012d))

The development of a public investment portfolio in energy-related RD&D, in general, seems to be well in line with what this research found. Growing public support with rising share of investment in climate-friendly technologies will increase the likelihood of technology advancement for currently less competitive low carbon technologies. Also the diversification of investment into a wide array of low carbon technologies is a reasonable risk hedge strategy under huge uncertainty over returns on energy-related technology RD&D.

A new policy encouraging natural gas

Natural gas employed by high-class combined cycle plant can play a robust role in carbon abatement. This is the case regardless the extent of technology advancement for low carbon technologies. That is, the increase of natural gas share in the generation mix is a kind of no-regret technology choice, unless carbon policy goal is to stabilize emission at near zero from the electricity sector. This finding is in line with what is currently happens in United States. The increased supply of natural gas, due to shale gas boom and price decrease, reduces carbon emissions in United States as coal-fired generation is replaced by natural gas generation (Burtraw and Woerman, 2012).

This finding, however, is contrary to current policy direction where the role of natural gas in the generation mix will be gradually shrinking over time according to the 6th BPE. One policy proposal which promotes the expansion of natural gas in the generation mix is the introduction of a clean energy standard (CES). Now proposed in the United States, a CES is a policy that imposes a national minimum level of electricity generation that comes from clean energy which includes even low CO_2-emitting technologies. A CES is similar to a renewable portfolio standard[23] (RPS), but it includes a broader range of non CO_2-emitting (e.g. nuclear) and even

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[23] In 2012, Korean government introduced a RPS by replacing feed-in-tariff (FIT) mechanism for the purpose of meeting its 10% target of new and renewable energy in electricity supply by 2022. The current RPS includes following sets of technologies with different weight on renewable energy certificate (REC) from each technology; solar, wind, hydro, biogas, land filled gas, biomass, fuel cell, tide, IGCC, Waste, and RDF. For detailed design and mechanism of RPS, see (MKE, 2013b)

low CO_2-emitting technologies such as generation from coal (or natural gas) with CCS or natural gas combined-cycle units. By giving partial credit to generation from relatively clean fossil fuel-based technology (most notably natural gas in current generation mix) the standard can encourage the role of natural gas at the same time reducing carbon emissions. This type of standard can also complement a RPS which tends to result in the displacement of new investment in natural gas with renewable. That is, the cannibalization of relatively clean natural gas by renewable in a RPS mechanism, due to the rank of marginal costs of generation, can be avoided and a switch from coal to gas is more encouraged than a switch from gas to renewable.

Integration of climate policy into energy policy

Although the energy-related RD&D budget allocation is well in line with key findings of this thesis, more specific policy direction with respect to the electricity supply and demand somewhat deviates from any carbon emission pathway considered in the thesis not to mention differs from the latest Korean government mitigation target (Government of Korea, 2011)[24]. That is, if generation mix and electricity demand were unfolded until the second half of the next decade as outlined in the 6th BPE, none of the carbon mitigation pathways explored in this research would be achieved. This finding reinforces the critiques by many researchers and commentators that electricity policy, the energy policy in general, and climate change policy is not well coordinated among policymakers. It should be noted that the energy system has inertia

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[24] GHGs emission cap for energy conversion sector (power, heat, and citygas supply sector) is 187.2 $MtCO_2e$ by 2020, i.e. 26.7% reduction from 255.4 $MtCO_2e$ in BAU scenario by 2020.

and rigidity because long-lived and capital-intensive assets are involved. Thus, a well-coordinated policy for energy and climate change is a prerequisite for smooth and cost-effective transition into a low carbon energy system.

5.3 Future Research

Comparison of carbon mitigation strategy between supply side and demand side

The focus of the thesis is on a supply-side technological solution to carbon mitigation in the Korean power sector. This study only considers cost-effective means to decarbonize electricity generated from supply system. However, in reality, carbon mitigation can be achieved from the demand side too. Energy demand is a driver of energy supply. Changes in demand affect supply. Reduction in overall energy demand through energy conservation and efficiency improvements is believed to be a promising area in carbon abatement. Thus, a comprehensive climate and energy policy package needs to be sought both on the supply and demand side, and socially optimal policy should balance response strategies on both sides in a way to achieve carbon mitigation policy goals in a cost-effective way.

The assessment of achievable electricity demand reduction potentials and its linkage to the supply system model developed in this study would provide implications for impacts of demand side management on the supply response strategy and GHG emissions abatement. For electricity, the potential of demand load management which shapes the load duration curve also need to be considered in addition to overall demand reduction since the entire supply system (i.e, generation technology mix, storage, transmission and distribution) should be designed in a way to reliably satisfy the instantaneous electricity demand. As the electricity system transforms to a low-carbon one with a greater share of varRE, the electricity load management become more important.

The assessment of demand side management potential, associated cost, and its impact on the supply system development and GHG emissions reduction will provide an insight into what strategies, i.e. supply-side decarbonization versus demand-side management, is more cost-effective to what extent, and/or what combination of both strategies would be a socially optimal way to control carbon emission.

Indigenous technological learning rate estimate

The study tries to estimate learning rates of a select electricity generation technologies based on indigenous data. Even though the learning rate estimates seem to be consistent with other literature, further data collection and more sophisticated analysis is needed. Especially cumulative experience data on relatively new technologies (e.g. solar photovoltaic, wind, and fuel cell) is very limited due to data availability and early stage of deployment. As more experience on these new technologies accumulates more reliable estimate will be possible. Future research on this empirical technology advancement will provide an insight into whether the theory of cross-country technology spillover can be empirically justified and what other indigenous factors affect in technology advancement, etc.

Policy costs of technology advancement

The thesis estimates the value of technology advancement in carbon mitigation, but technology advancement won't come from a vacuum. Many environmental and technology policies (e.g. renewable portfolio standard, feed-in-tariff, tax credits etc.) to promote low-carbon technologies are under implementation with associated costs. It would be a fruitful area of research to estimate the effects and costs of these policies and compare with the benefit (i.e. the value) of technology advancement on low-carbon technology in carbon mitigation. The outcomes of the research will serve to prioritize cost-effective policy instruments and to design a comprehensive energy, climate, and technology policy portfolio in a socially efficient way.

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Appendix A. Data for Experience Curve

This appendix provides detailed data on power plant specific construction cost in Korea. These data are used to construct the experience curve model and to estimate learning rate as presented in Chapter 2.4.2

Table A-1: Construction cost data for onshore wind power plant

Plant name	Construction Date		Construction Duration (years)	Capacity (MW)	Construction Cost		cum. cap (MW)
	Start	End			current KRW/kW	constant(2010) KRW/kW	
한경풍력#1	Jun-03	Feb-04	0.67	6	2,514,459	2,845,841	6
양양양수풍력	Jun-05	Jun-06	1.00	3	1,945,000	2,190,315	9
한경풍력#2	Nov-06	Dec-07	1.08	15	2,394,733	2,643,842	24
고리풍력	Aug-07	Jun-08	0.83	0.75	2,083,952	2,234,934	25
성산풍력#2	May-10	Sep-10	0.33	8	2,500,000	2,500,000	33
영흥 풍력	Oct-09	May-10	0.58	22	2,568,182	2,568,182	55

Table A-2: Construction cost data for fuelcell power plant

Plant name	Construction Date		Construction Duration (years)	Capacity (MW)	Construction Cost		cum. cap (MW)
	Start	End			current KRW/kW	constant(2010) KRW/kW	
분당연료전지	Feb-06	Oct-06	0.67	0.25	9,755,903	10,986,377	0.25
보령화력연료전지	Jun-08	Oct-08	0.33	0.3	6,753,189	7,242,457	0.55
일산연료전지	May-08	Sep-09	1.33	2.4	5,791,667	6,005,185	2.95
일산연료전지#2	Sep-10	Apr-11	0.58	2.8	5,500,000	5,500,000	5.75
엠피씨율촌연료전지 #2	Jul-11	Dec-11	0.42	5.6	5,714,285	5,714,285	11.35

Table A-3: Construction cost data for solar photovoltaic power plant

Plant name	Construction Date		Construction Duration (years)	Capacity (MW)	Construction Cost		cum. cap (MW)
	Start	End			current KRW/kW	constant(2010) KRW/kW	
영흥 태양광	May-06	Oct-06	0.42	1	8,082,492	9,101,905	1
동해태양광	Mar-06	Sep-06	0.50	1	6,290,000	7,083,333	2
삼랑진태양광	May-07	Sep-07	0.33	2	5,185,000	5,724,362	4
영광솔라파크 I,II	Jun-05	Jun-05	0.00	3	6,222,024	6,672,809	7
보령태양광#1	Oct-07	Apr-08	0.50	1	6,476,190	6,945,390	8
서천중부태양광#1	Jul-07	Jan-08	0.50	1	7,045,000	7,555,410	9
삼랑진태양광#2	Feb-08	Apr-08	0.17	1	5,250,000	5,630,362	10
하동화력태양광	Apr-08	Jul-08	0.25	1	7,377,995	7,912,530	11
삼천포 태양광	May-05	Apr-10	4.92	1	4,503,312	4,503,312	12
삼천포 화력 태양광	Jan-10	Apr-10	0.25	1	4,520,000	4,520,000	13
예천 양수 태양광	Jun-10	Oct-10	0.33	2	3,865,000	3,865,000	15
하동화력태양광#2,3	Jun-10	Dec-10	0.50	3	4,080,000	4,080,000	17
당진태양광	Jul-10	Sep-10	0.17	1	3,401,000	3,401,000	18
탕정태양광	Nov-10	Jun-11	0.58	1	3,823,773	3,823,773	20
서울태양광	Sep-10	Aug-11	0.92	1	4,384,615	4,384,615	21
수산정수사업소 태양광	Jun-11	Nov-11	0.42	1	3,851,703	3,851,703	22
울상화력태양광	Jan-11	Mar-11	0.17	1	3,760,000	3,760,000	22

Table A-4. Construction cost data for nuclear power plant

Plant name	Construction Date		Construction Duration (years)	Capacity (MW)	Construction Cost		cum. cap (MW)
	Start	End			current KRW/kW	constant(2010) KRW/kW	
고리 1	Sep-70	Apr-78	7.58	587	265,883	1,643,508	587
고리 2	May-77	Jul-83	6.17	650	862,914	2,773,652	1,237
월성 1	May-76	Apr-83	6.92	679	934,506	3,003,769	1,916
고리 3,4	Jan-78	Apr-86	8.25	1,900	783,697	2,220,804	3,816
영광 1,2	Mar-80	Jun-87	7.25	950	847,679	2,292,401	4,766
울진 1,2	Jan-81	Sep-89	8.67	1,900	1,050,000	2,513,298	6,666
영광 3,4	Jun-89	Dec-95	6.50	2,000	1,343,000	1,990,613	8,666
월성 2	Oct-91	Jun-97	5.67	700	2,052,558	2,788,802	9,366
월성 3,4	Aug-93	Oct-99	6.17	1,400	2,227,000	2,913,227	10,766
울진 3,4	May-92	Dec-99	7.58	2,000	1,790,125	2,341,733	12,766
영광 5,6	Sep-96	Dec-02	6.25	2,000	1,610,932	1,946,615	14,766
울진 5,6	Jan-99	Apr-05	6.25	2,000	1,884,000	2,119,500	16,766
신고리 1,2	Jan-05	Feb-11	6.08	2,000	2,697,732	2,697,732	18,766

Table A-5: Construction cost data for bituminous coal power plant

Plant name	Construction Date		Construction Duration (years)	Capacity (MW)	Construction Cost		cum.cap (MW)
	Start	End			current KRW/kW	constant(2010) KRW/kW	
호남#1,2	May-69	Oct-72	3.42	600	69,162	1,341,504	600
삼천포#1,2	Oct-78	Feb-84	5.33	1,120	391,684	1,203,947	1,720
보 령 #1,2	Dec-79	Sep-84	4.75	1,000	444,722	1,366,973	2,720
보 령 #3,4	May-89	Jun-93	4.08	1,000	764,584	1,311,215	3,720
삼천포#3,4	Oct-89	Mar-94	4.42	1,120	629,660	1,001,934	4,840
보 령 #5,6	Mar-90	Apr-94	4.08	1,000	690,824	1,099,260	5,840
태 안 #1,2	Mar-92	Dec-95	3.75	1,000	1,175,477	1,742,308	6,840
삼천포#5,6	Mar-94	Dec-97	3.75	1,000	818,230	1,111,726	7,840
태 안 #3,4	Jan-94	Aug-97	3.58	1,000	693,424	942,152	8,840
하 동 #1,2	Oct-93	Oct-97	4.00	1,000	991,424	1,347,043	9,840
하 동 #3,4	Feb-95	Mar-99	4.08	1,000	883,069	1,155,177	10,840
당 진 #1,2	Apr-95	Dec-99	4.67	1,000	1,646,894	2,154,367	11,840
하 동 #5,6	Dec-96	Jul-01	4.58	1,000	994,264	1,240,074	12,840
당 진 #3,4	Sep-96	Mar-01	4.50	1,000	1,139,396	1,421,087	13,840
태 안 #5,6	Nov-97	May-02	4.50	1,000	820,900	991,958	14,840
영 흥 #1,2	Mar-96	Dec-04	8.75	1,600	1,450,000	1,641,097	16,440

당 진 #5,6	Sep-02	Mar-06	3.50	1,000	940,867	1,059,535	17,440
태 안 #7,8	Nov-03	Aug-07	3.75	1,000	905,729	999,946	18,440
당 진 #7,8	Mar-04	Dec-07	3.75	1,000	836,200	923,184	19,440
영 흥 #3,4	May-04	Dec-08	4.58	1,740	895,196	960,053	21,180
보 령 #7,8	Mar-05	Dec-08	3.75	1,000	1,265,000	1,356,649	22,180
하 동 #7	Nov-05	Dec-08	3.08	500	1,130,857	1,212,788	22,680

Appendix B. Key Model Outputs

Table B - 1: LCOE estimation for ‘modest advance’ case

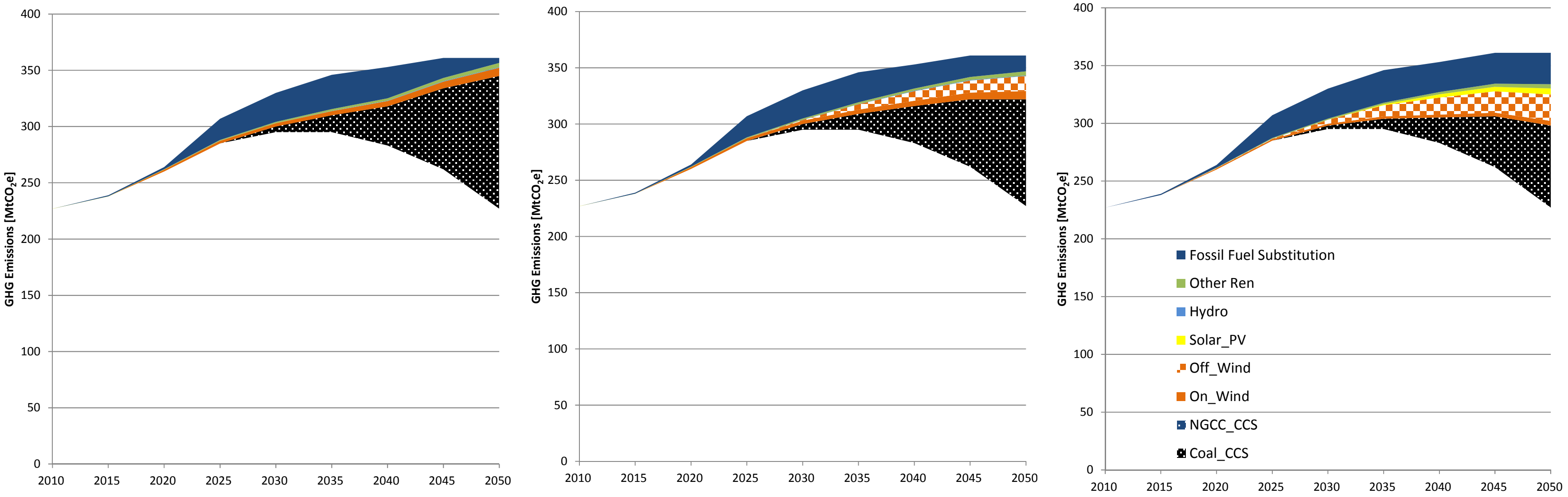
Year	Nuclear	Bcoal_adv	Bcoal_advCCS	IGCC	IGCC_CCS	NGCC_H	NGCC_CCS	On_Wind	Off_Wind	Solar_PV	Fuelcell	Tide	Geothermal
2010	33	49	n.a.	n.a.	n.a.	117	n.a.	102	147	256	210	174	37
2015	35	47	n.a.	n.a.	n.a.	113	n.a.	100	132	217	194	164	36
2020	36	46	n.a.	73	n.a.	107	n.a.	98	121	194	181	158	36
2025	38	46	76	71	106	103	129	96	114	169	171	153	35
2030	38	46	75	70	103	100	124	92	108	161	163	150	35
2035	38	46	75	70	101	97	120	91	106	147	155	148	35
2040	38	45	74	70	101	97	120	91	105	144	154	147	35
2045	38	45	74	69	100	97	120	90	104	143	154	146	35
2050	38	45	74	69	100	97	120	90	104	142	153	145	35

Table B - 2: LCOE estimation for ‘optimistic advance’ case

Year	Nuclear	Bcoal_adv	Bcoal_advCCS	IGCC	IGCC_CCS	NGCC_H	NGCC_CCS	On_Wind	Off_Wind	Solar_PV	Fuelcell	Tide	Geothermal
2010	33	49	n.a.	n.a.	n.a.	117	n.a.	102	147	256	210	174	37
2015	35	46	n.a.	n.a.	n.a.	113	n.a.	96	116	164	178	131	35
2020	36	45	n.a.	69	n.a.	107	n.a.	92	99	118	158	107	35
2025	38	44	72	66	99	103	127	90	88	89	144	94	34
2030	38	44	71	65	96	99	122	84	81	78	135	87	34
2035	38	43	71	65	93	96	118	83	78	69	127	83	33
2040	38	43	70	64	93	96	117	82	77	66	126	81	33
2045	38	43	70	64	92	96	117	82	76	65	125	80	33
2050	38	43	70	64	92	96	117	81	75	64	124	80	33

Figure B-1: Mitigation Wedge across all mitigation scenarios

(a) ‘mit0%’ scenarios

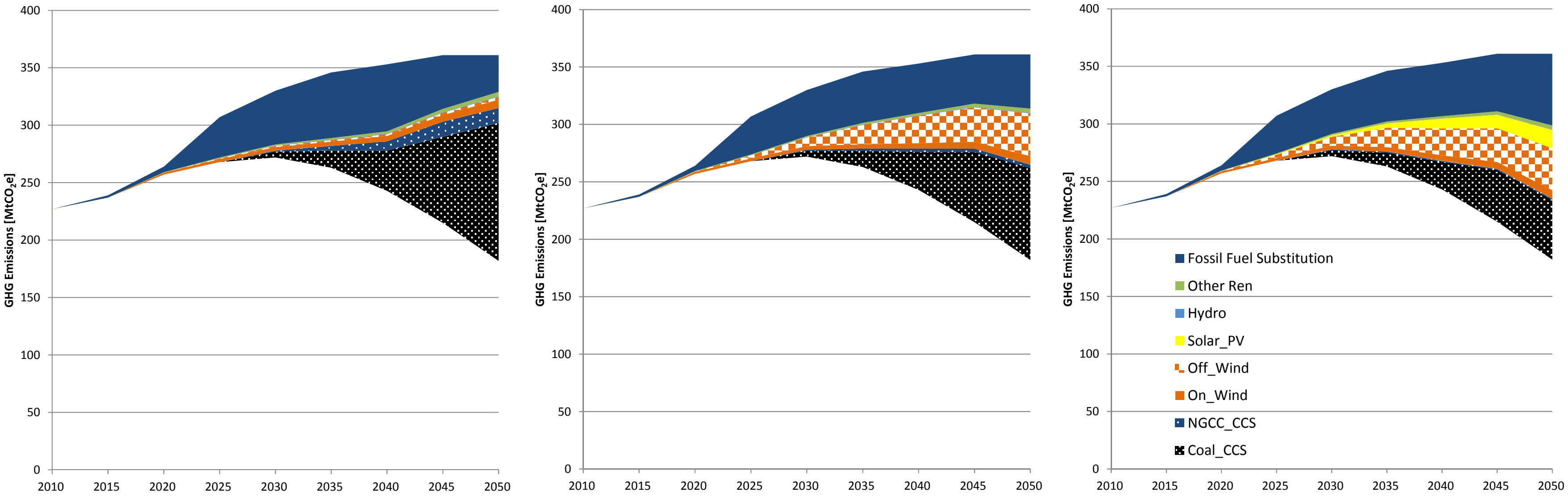


No advance

Modest advance

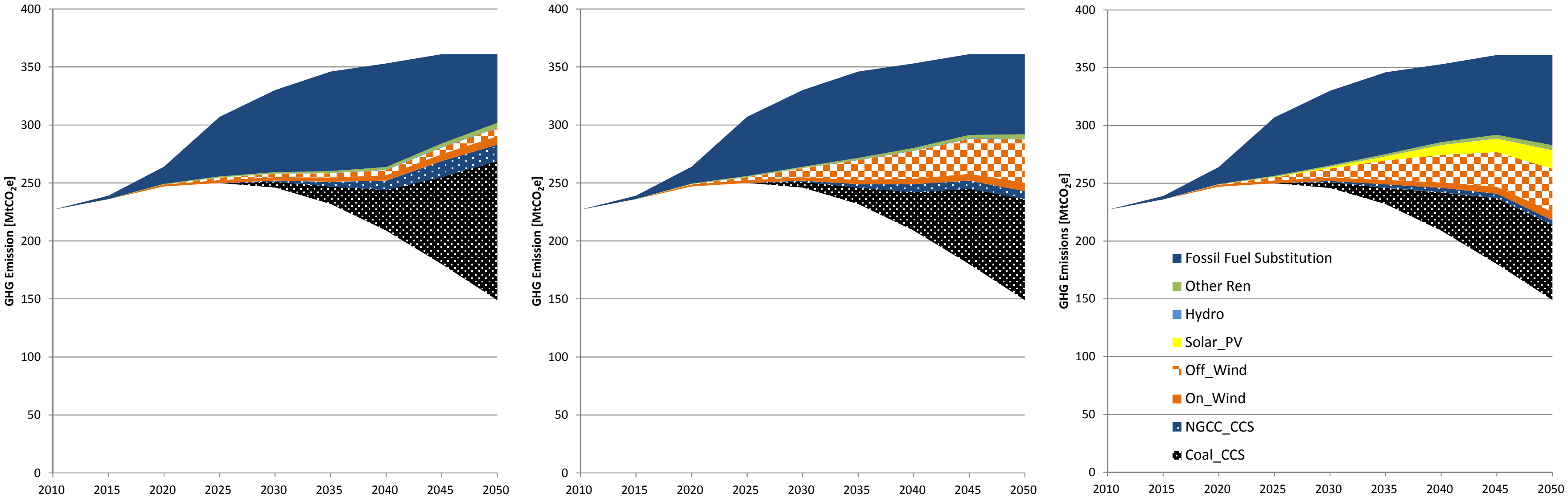
Optimistic advance

(b) ‘mit20%’ scenarios



No advance Modest advance Optimistic advance

(c) ‘mit35%’ scenarios

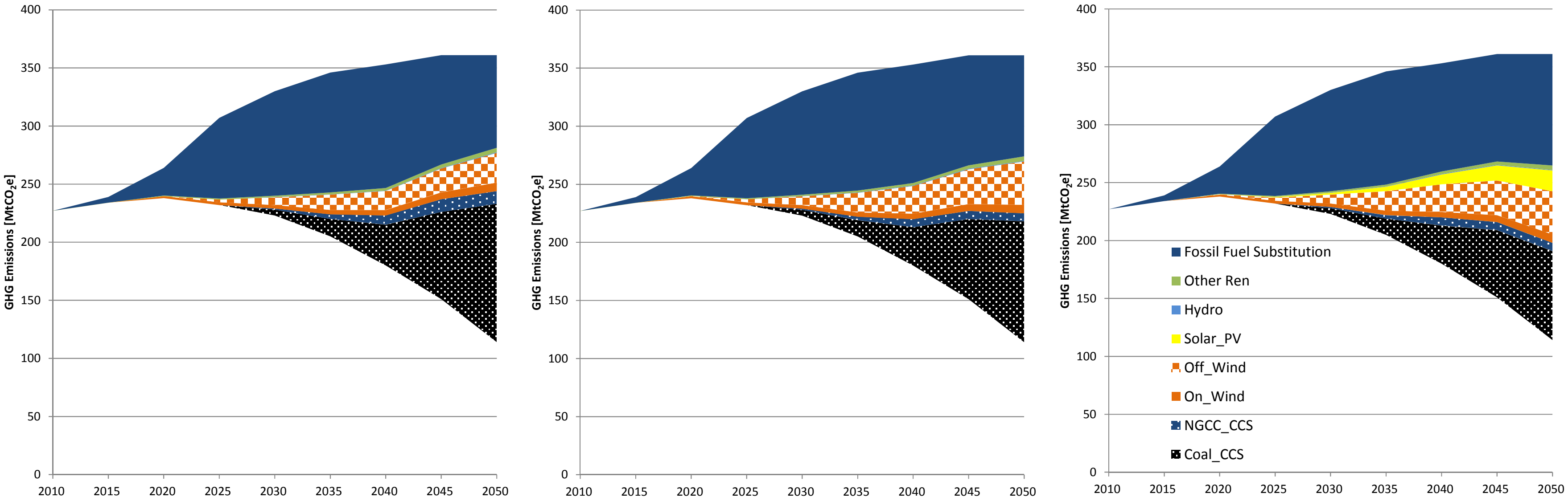


No advance

Modest advance

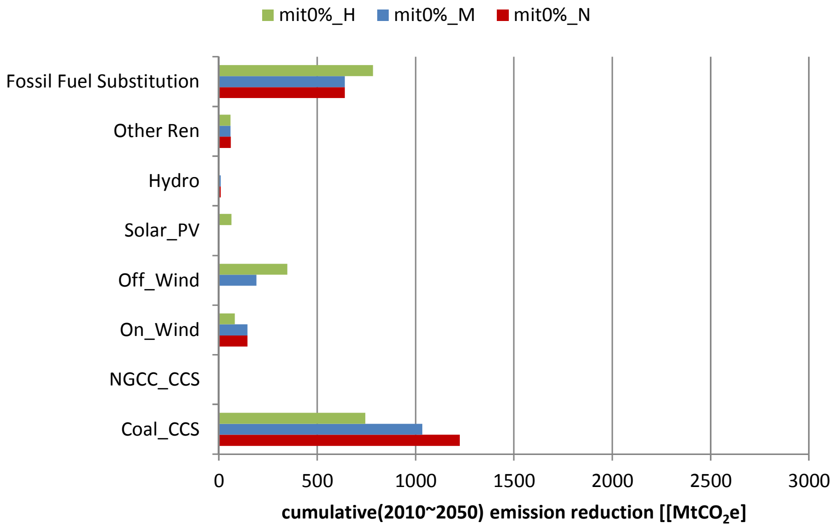
Optimistic advance

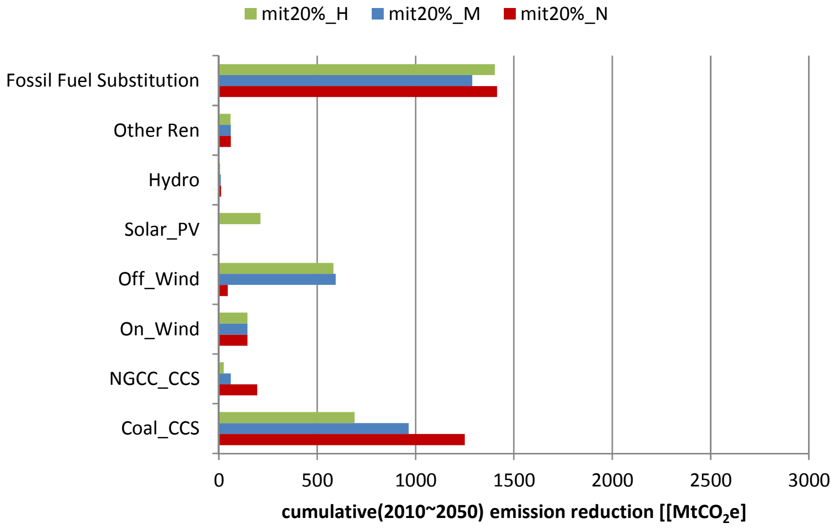
(d) ‘mit50%’ scenarios

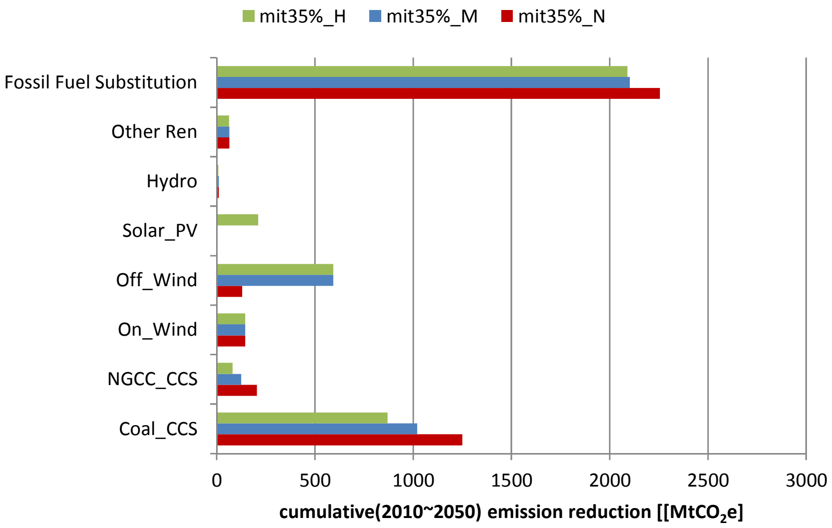


No advance Modest advance Optimistic advance

Figure B-2: Emission abatement by mitigation measures and effects of technology advancement






mit35%_H
mit35%_M
mit35%_N
Fossil Fuel Substitution
Other Ren
Hydro
Solar_PV
Off_Wind
On_Wind
NGCC_CCS
Coal_CCS
0
500
1000
1500
2000
2500
3000
cumulative(2010~2050) emission reduction [[MtCO2e]

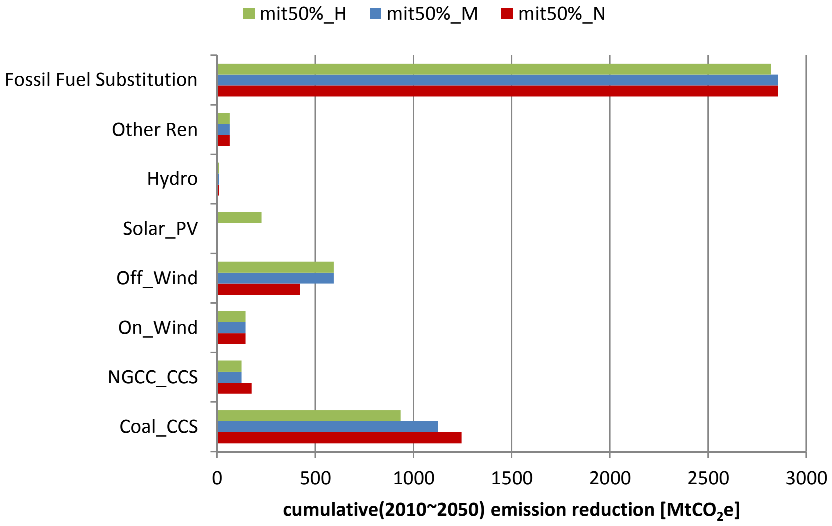
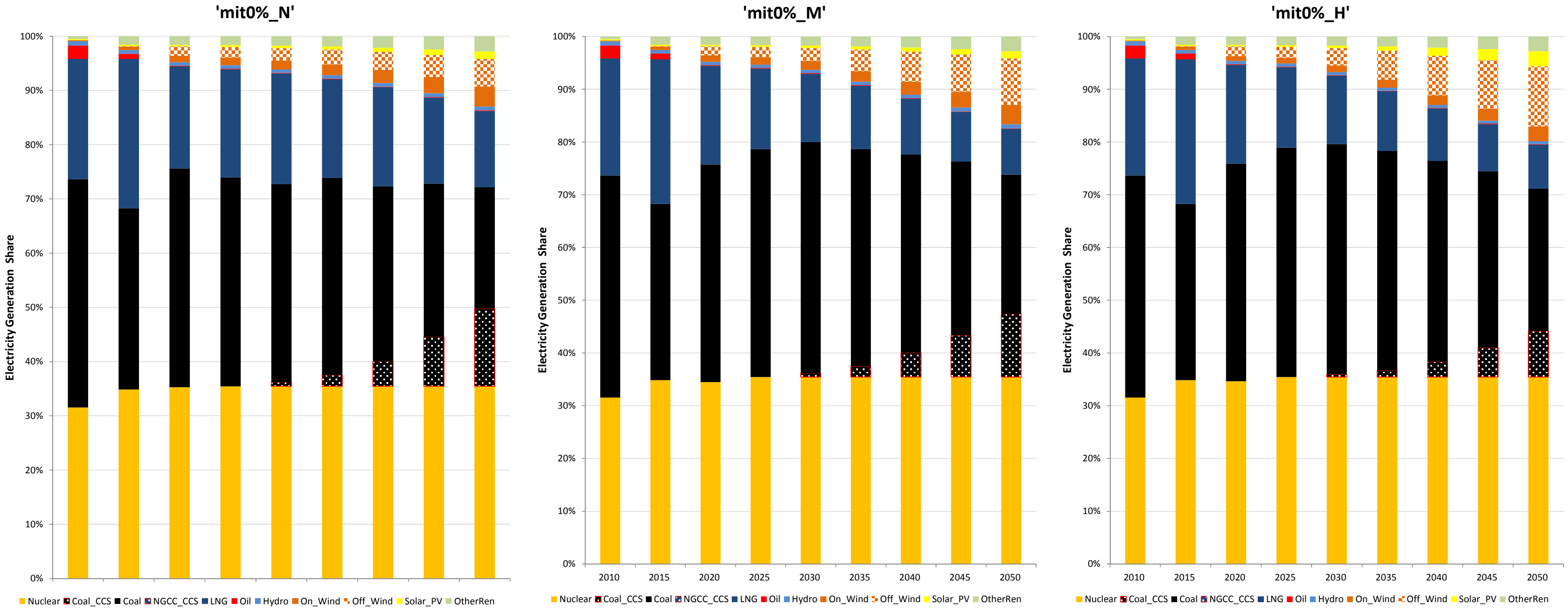
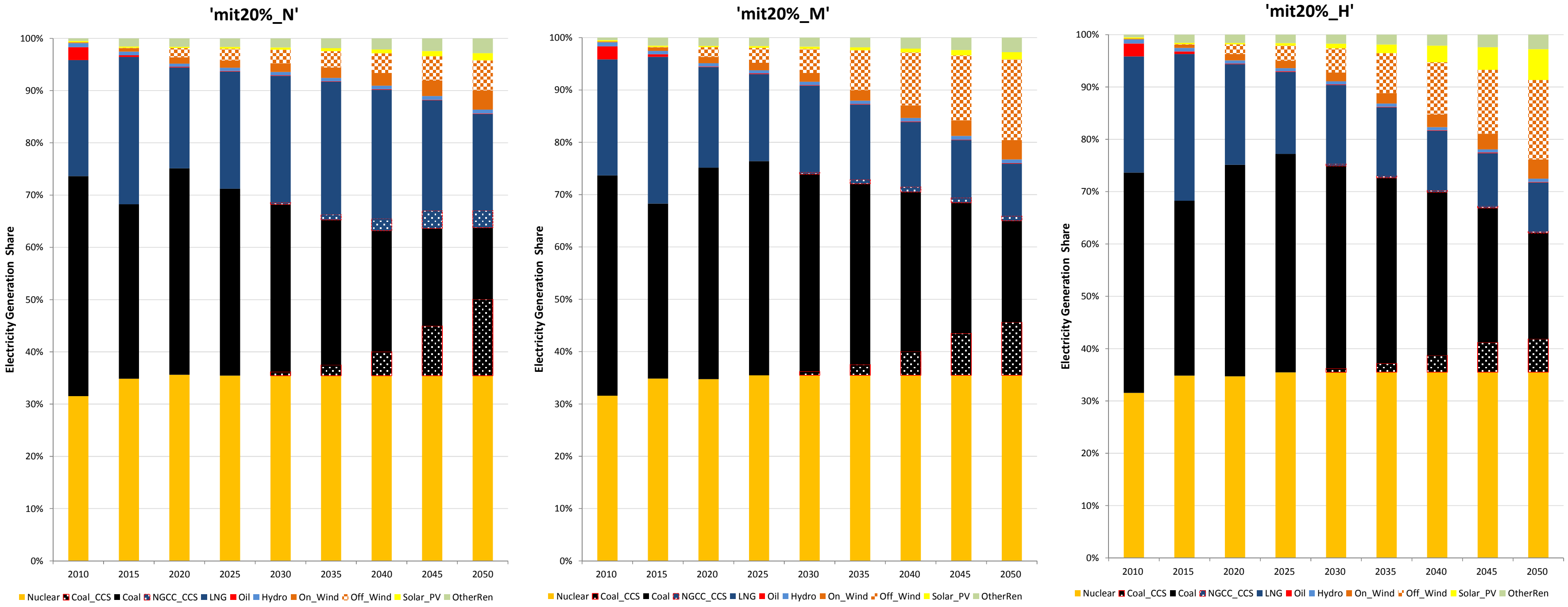

mit50%_H
mit50%_M
mit50%_N
Fossil Fuel Substitution
Other Ren
Hydro
Solar_PV
Off_Wind
On_Wind
NGCC_CCS
Coal_CCS
0
500
1000
1500
2000
2500
3000
cumulative(2010~2050) emission reduction [MtCO2e]

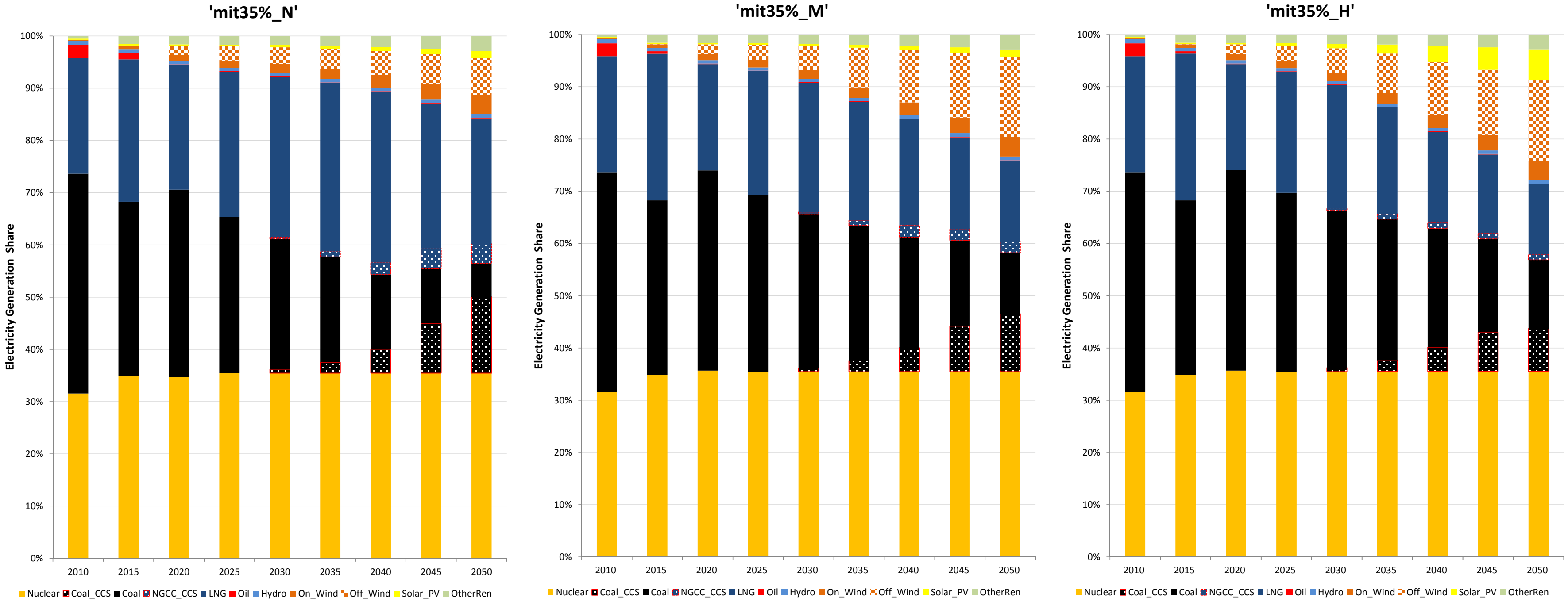
Figure B- 3: The development of electricity generation mix over time



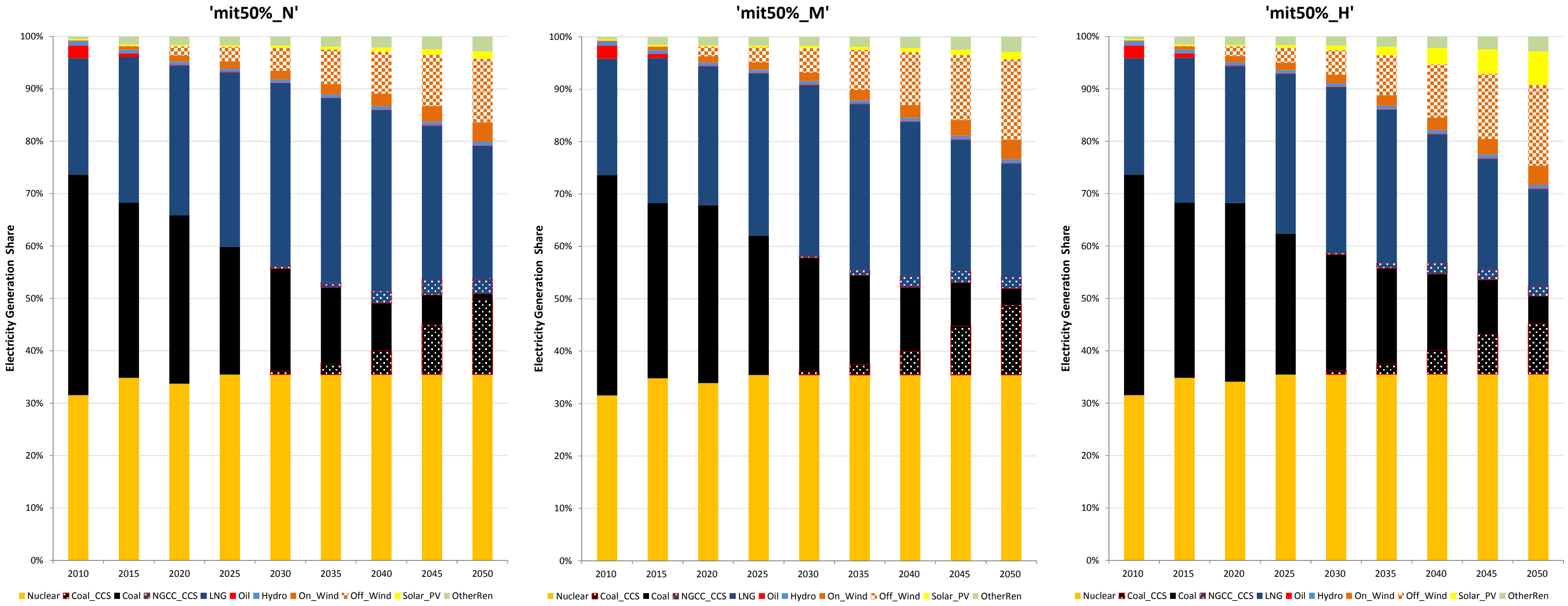
(a) ‘mit0%’ scenarios



(b) ‘mit20%’ scenarios



(c) ‘mit35%’ scenarios



(d) ‘mit50%’ scenarios

Table B-3: Total system costs (investment, OM, and fuel costs) over time

(a) Reference Scenarios

Reference_N [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.98	5.46	7.72	9.81	11.37	14.76	13.42	0.00	*435*
OM cost	35.23	8.78	9.50	9.98	10.35	10.26	10.34	10.44	10.42	*576*
Fuel	22.62	27.61	23.49	24.51	24.93	25.18	25.22	25.41	25.43	*1122*
sum	*67.42*	*51.36*	*38.44*	*42.21*	*45.09*	*46.81*	*50.32*	*49.27*	*35.85*	***2134***

Reference_M [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.43	4.83	6.82	8.59	9.65	12.35	10.55	0.00	*384*
OM cost	35.23	8.77	9.50	9.97	10.35	10.26	10.34	10.45	10.40	*576*
Fuel	22.62	27.60	23.29	24.27	24.58	24.73	24.66	24.84	24.86	*1107*
sum	*67.42*	*50.81*	*37.62*	*41.06*	*43.52*	*44.65*	*47.35*	*45.84*	*35.26*	***2068***

Reference_H [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	13.65	4.62	6.03	7.80	8.11	10.32	8.70	0.00	*344*
OM cost	35.23	8.76	9.48	9.96	10.32	10.26	10.33	10.46	10.41	*576*
Fuel	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	22.62	*1018*
sum	*67.42*	*45.03*	*36.72*	*38.61*	*40.74*	*40.99*	*43.27*	*41.78*	*33.03*	***1938***

(b) ‘mit0%’ Scenarios

mit0%_N [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.98	5.23	7.23	13.73	11.17	20.78	18.22	0.00	*504*
OM cost	35.23	8.80	9.52	9.98	10.33	10.23	10.33	10.38	10.37	*576*
Fuel	22.62	27.30	23.59	26.55	28.49	28.34	29.78	29.91	30.15	*1234*
Sum	*67.42*	*51.07*	*38.34*	*43.76*	*52.54*	*49.74*	*60.88*	*58.51*	*40.52*	***2314***

mit0%_M [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.43	7.47	9.18	10.67	11.52	16.71	15.99	0.00	*478*
OM cost	35.23	8.77	9.48	9.99	10.34	10.24	10.31	10.40	10.42	*576*
Fuel	22.62	27.34	23.49	23.84	23.92	24.43	24.55	24.91	25.20	*1101*
sum	*67.42*	*50.54*	*40.44*	*43.01*	*44.93*	*46.19*	*51.58*	*51.30*	*35.62*	***2155***

mit0%_H [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	13.65	6.96	8.11	10.24	9.91	14.24	13.68	0.00	*432*
OM cost	35.23	8.76	9.47	9.98	10.34	10.28	10.29	10.41	10.43	*576*
Fuel	22.62	27.34	23.50	23.84	23.84	23.73	23.60	23.75	23.70	*1080*
sum	*67.42*	*49.74*	*39.93*	*41.93*	*44.42*	*43.93*	*48.14*	*47.84*	*34.13*	***2087***

(c) ‘mit20%’ Scenarios

mit20%_N [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.98	7.83	6.91	11.04	11.88	21.94	18.99	0.00	*516*
OM cost	35.23	8.77	9.50	9.97	10.29	10.24	10.30	10.35	10.36	*575*
Fuel	22.62	27.03	23.74	27.30	30.22	32.57	34.69	35.30	35.08	*1343*
Sum	*67.42*	*50.77*	*41.08*	*44.19*	*51.56*	*54.69*	*66.93*	*64.64*	*45.43*	***2434***

mit20%_M [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.43	10.54	8.09	13.50	13.65	19.58	19.22	0.00	*543*
OM cost	35.23	8.78	9.47	10.00	10.30	10.24	10.32	10.42	10.43	*576*
Fuel	22.62	27.07	23.62	23.94	25.51	25.26	25.05	24.97	24.41	*1112*
sum	*67.42*	*50.28*	*43.63*	*42.03*	*49.32*	*49.15*	*54.95*	*54.61*	*34.83*	***2231***

mit20%_H [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	13.65	10.58	7.64	12.21	12.27	16.83	17.29	0.00	*500*
OM cost	35.23	8.77	9.46	9.97	10.28	10.27	10.29	10.44	10.46	*576*
Fuel	22.62	27.07	23.62	23.37	24.60	23.98	23.35	22.95	21.85	*1067*
sum	*67.42*	*49.48*	*43.66*	*40.98*	*47.09*	*46.52*	*50.46*	*50.68*	*32.31*	***2143***

(d) 'mit35%' Scenarios

mit35%_N [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.98	7.82	8.27	11.60	12.73	22.51	20.61	0.00	*540*
OM cost	35.23	8.78	9.51	9.99	10.31	10.25	10.32	10.39	10.36	*576*
Fuel	22.62	26.68	25.74	29.66	33.12	35.59	38.61	38.93	38.12	*1445*
Sum	*67.42*	*50.43*	*43.06*	*47.92*	*55.03*	*58.57*	*71.44*	*69.93*	*48.48*	***2561***

mit35%_M [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	14.43	8.90	8.73	14.32	14.09	20.56	19.19	0.00	*549*
OM cost	35.23	8.78	9.49	9.99	10.29	10.25	10.30	10.43	10.42	*576*
Fuel	22.62	26.79	23.91	27.25	29.43	29.43	30.07	29.45	28.43	*1237*
sum	*67.42*	*50.00*	*42.30*	*45.97*	*54.04*	*53.77*	*60.93*	*59.07*	*38.85*	***2362***

mit35%_H [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	13.65	8.62	8.09	13.32	13.75	17.35	17.30	0.00	*508*
OM cost	35.23	8.76	9.46	9.98	10.28	10.25	10.31	10.42	10.48	*576*
Fuel	22.62	26.79	23.90	26.95	28.77	27.96	27.06	26.30	24.80	*1176*
sum	*67.42*	*49.20*	*41.98*	*45.02*	*52.36*	*51.95*	*54.72*	*54.02*	*35.28*	***2260***

(e) 'mit50%' Scenarios

mit50%_N [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.568	14.98	8.29	10.95	15.73	14.53	24.63	23.69	0.00	*612*
OM cost	35.233	8.79	9.51	9.99	10.29	10.22	10.26	10.38	10.36	*575*
Fuel	22.619	26.43	27.80	32.12	34.75	36.25	38.61	37.88	36.60	*1465*
Sum	*67.42*	*50.20*	*45.60*	*53.05*	*60.77*	*61.00*	*73.50*	*71.94*	*46.96*	***2652***

mit50%_M [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.568	14.43	7.77	9.40	14.63	14.09	21.19	19.89	0.00	*555*
OM cost	35.233	8.77	9.49	9.96	10.29	10.24	10.29	10.40	10.41	*575*
Fuel	22.62	26.48	26.72	30.72	33.24	33.92	34.85	33.62	32.31	*1372*
sum	*67.42*	*49.68*	*43.98*	*50.09*	*58.16*	*58.25*	*66.32*	*63.91*	*42.71*	***2503***

mit50%_H [trillion KRW/year]	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum. (2010~2050) [trillion KRW]
investment	9.57	13.65	7.50	8.75	13.58	14.06	17.68	18.04	0.00	*514*
OM cost	35.23	8.75	9.48	9.96	10.28	10.24	10.30	10.43	10.47	*576*
Fuel	22.62	26.48	26.53	30.46	32.61	32.42	31.52	30.13	28.38	*1306*
sum	*67.42*	*48.87*	*43.52*	*49.17*	*56.48*	*56.72*	*59.49*	*58.61*	*38.85*	***2396***

국문초록

기술진보가 발전부문의 최적 탄소감축 조합에 미치는 영향

– 상향식 에너지 모형을 이용한 시나리오 연구 –

조철흥

지구환경과학과

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기술은 에너지–환경–경제 시스템의 상호작용을 규정하는 중요한 요소의 하나로 널리 인식된다. 대부분의 환경적 오염 문제들은 인간의 필요를 충족하기 위한 경제적 활동의 과정에서 현존하는 기술들의 사용에 따르는 부산물인 반면, 새로운 기술들은 같은 필요를 충족하기 위한 경제활동에 대안적인 수단을 제공함으로써 환경적 문제들을 해결할 수 있는 해법을 제시하기도 한다. 기후변화와 같이 장기적인 환경문제의 해법을 모색해야 하는 경우에 기술진보의 중요성은 더욱 두드러진다. 미래의 기술진보는 비용 경쟁력을 갖춘 기술적 대안의 부족에서 야기되는 경제활동과 환경적 목표의 달성 사이의 단기적 갈등을 완화하는데 중요한 역할을 할 수 있기

때문이다. 기술진보의 역할에 대한 이와 같은 긍정적 관점은 기후변화에 대한 궁극적이고 장기적인 해법은 기술변화에 의해 이루어질 것이라는 공감대를 널리 형성하게 한다.

본 논문의 가장 우선적인 목적은 기술진보가 탄소감축과 그에 따르는 저탄소 에너지 시스템으로의 전환을 달성하는데 어떠한 역할을 하는 지를 한국의 발전부문에 적용을 통해 탐구해 보는 것이다. 다양한 저탄소 기술 옵션들의 기술진보 잠재성에 대한 종합적인 평가, 그러한 기술진보가 탄소감축기술과 수단의 최적의 조합과 탄소감축 비용에 미치는 역할 등에 대한 평가는 저탄소 에너지 시스템으로의 전환을 위한 정책방향 설정에 중요한 시사점을 제공해줄 것이다. 또한 본 연구의 결과는 기후친화적인 기술의 연구개발 자원의 효과적인 분배, 기술의 확산 및 보급을 위한 공공정책 (에너지 및 기술정책, 기술개발 로드맵 등)을 수립하고 디자인하는 데 활용될 수 있을 것이다.

2010 년 현재 세계 7 번째 온실가스 다배출 국가인 한국에서 발전부문은 최종에너지의 20% (475 TWh)를 공급하고, 연료연소에 의한 국가 총 배출량의 41% (235 $MtCO_2e$)를 차지하는, 에너지 공급과 온실가스 배출 양 측면에서 모두 중요한 역할을 하는 에너지 부문이다. 사회전반의 급격한 전기화로 전력소비가 지속적으로 증가할 것으로 예상되는 상황에서 발전부문은 향후 예상되는 국내외적인 탄소감축 요구에 가장 크게 영향을 받는 부문이 될 것이다.

본 연구는 MESSAGE(Model for Energy Supply System Alternatives and their General Environmental impacts) 모형을 분석의 틀로 사용하여 한국의 전력부문을 모형화하였다. MESSAGE 모형은 풍부한 기술적 묘사가 가능한 상향식, 에너지 시스템 최적화 모형으로 중장기 에너지 계획 수립, 에너지 정책 분석, 에너지와 환경문제의 상호작용을 분석하는 각종 시나리오 개발 등에 활용되고 있다. 모형은 주어진 환경적 목표를 최소 비용으로 달성할 수 있는 에너지 공급기술의 포트폴리오를 제시하고, 각 기술 별 보급 및 환경문제에 대한 대응 전략을 시계열적으로 제공해 준다. 한국의 전력부문 MESSAGE 모형은 전력설비의 오랜 내구연한과 자본 집약성에서 기인하는 전력 공급시스템의 단기 경직성을 고려하기 위해 현존 전력 설비의 연식 구조와 단기 설비 확장 계획 등을 반영하여 구축되었다. 최적화라는 모형의 특징과 실증 데이터에 근거한 모형의 교정(calibration)은 좀더 현실적인 시나리오의 결과들을 제공할 것이고, 이는 장기적 환경 목표 달성을 위한 비용효과적인 저탄소 에너지 시스템의 전환과 그 과정에서 기술진보의 역할을 모색해 보고자 하는 본 연구의 목적에 부합하는 중요한 특징이다

본 연구에서 기술진보를 반영하는 방법은 저탄소 기술의 비용과 성능의 미래변화에 대한 다양한 전망을 시나리오를 통해 반영하는 것이다. 본 연구에서 반영된 저탄소 기술은 이미 기술개발의 실증단계를 넘어섰고, 국제 시장에서 이미 상업적으로 사용되고 있으며, 한국정부의 장기(~25 년) 전력계획에 이미 포함되어 있는 기술들만을 포함하였다. 기술의 비용과 성능에 대한 전망은 장기 온실가스 배출 및

감축시나리오를 연구하는 국외의 문헌들의 전망을 한국의 실증 데이터에 기반하여 보정하였다. 미래의 기술진보와 탄소감축의 정책적 목표에 대한 불확실성을 반영하기 위해 다양한 탄소감축 경로와 기술진보(속도와 정도)의 조합을 대안적 시나리오를 통해 반영하였다.

시나리오 분석 결과 다음과 같은 몇 가지 중요한 시사점이 도출되었다.

첫째, 기술의 진보를 통해 탄소 감축비용을 30%에서 100%까지 줄일 수 있다는 점이다. 탄소감축의 정도와 기술진보의 수준에 따라 차이가 있지만, 이는 기술진보의 수준이 현재 상태에서 답보한다는 시나리오 대비, 향후 40년의 기간 동안 연간 평균 최소 4조원에서 최대 8조원에 해당하는 액수이다. 이와 같은 기술진보의 경제적 편익 또는 경제적 가치에 대한 분석은 향후 기술 개발과 보급 정책의 비용편익 분석에 기준으로 활용될 수 있을 것이다.

둘째, 시스템 전반의 비용효과성의 관점에서 보면 기술의 진보 자체만으로 탄소배출이 없는 간헐적인 재생에너지(태양광 및 해양풍력 등)의 확산을 보장할 수 없다는 점이다. 즉 엄격한 수준의 탄소감축 목표와 상당한 수준의 기술진보의 조합 하에서만 간헐적 재생에너지의 비용 경쟁력이 확보된다는 점이다. 비록 기술진보에 의해 간헐적 재생에너지의 경제성이 화석연료에 기반한 발전기술의 경제성 수준에 도달한다 하더라고, 시스템통합의 관점에서 재생에너지의 간헐성의 한계를 극복하기 위한 백업 및 전력저장 설비의 필요는 간헐적 재생에너지에 기술진보를 상쇄하는 추가적인 내재적 비용으로 작용하기 때문이다. 개별 기술과 전력공급시스템의 통합

관점에서 발생하는 간헐적 재생에너지 발전기술 경제성의 차이는 향후 관련 연구에서 좀더 심도 깊게 다루어져야 할 주제이다.

셋째, 천연가스로의 연료대체는 탄소감축 목표와 저탄소 기술진보의 정도와 무관하게 비용 효과적인 감축 수단이다. 즉, 천연가스에 의한 발전 비중을 확대하는 것은 탄소감축 목표와 기술진보의 불확실성 하에서도 후회 없는 기술적 선택이라는 것이다. 상대적으로 청정하고, 재생에너지와 같은 간헐성의 문제가 없는 천연가스 발전은 탄소배출이 제한된 세상에서는 다른 여타의 기술에 비해 비용 경쟁력을 확보하게 되는 것이다. 탄소포집 및 저장 기술 또한 경제적으로 매력적인 감축의 수단이다. 하지만, 탄소포집 및 저장 기술은 다른 저탄소 발전기술에 비해 기술진보의 속도가 더딜 것으로 전망되며, 이러한 경우에는 탄소포집 및 저장기술의 상대적 비용 경제력은 약화되며, 탄소감축 기여도는 낮아질 것으로 평가된다.

넷째, 기술수준의 정도와 무관하게 상당한 수준의 저탄소 기술보급이 달성되어야 한다는 점이다. 탄소감축 목표의 정도에 따라 차이가 있지만, 저탄소 발전 비중은 2030년까지 8% 에서 11%, 2050년까지는 28%에서 41%까지 도달해야 한다. 이는 2010년 현재 1.7%인 상황과 비교해보면 상당히 도전적인 목표이다. 특히, 가장 엄격한 수준의 탈탄소화의 목표(2050년까지 현재 대비 50% 감축 시나리오)를 달성하기 위해서는 향후 40년간 지속적으로 연평균 10%의 저탄소 발전설비의 증가라는 상당히 도전적인 목표가 달성되어야 한다. 이와 같은 엄격한 수준의 목표는 향후 예상되는 기후변화 국제협약의 결과에 따라 가시화 될 것이다. 기술의 진보는

이러한 전환에 필요한 사회적 비용을 줄이는 역할을 하지만, 탈탄소화의 목표 달성을 위해서 저탄소 기술의 보급 자체는 불가피하다. 이러한 도전적인 목표달성을 위해서는 전력공급 기술 포트폴리오에 대한 현재의 정책 방향에 대한 즉각적인 변화가 필요하며, 그러한 변화가 미래로 미루어 질수록, 탄소감축에 수반하는 도전과 관련 사회적 비용은 더욱 증가할 것이다.

주제어: 기술의 진보, 발전부문, 탄소감축, 상향식 최적화 에너지 모형, 저탄소 기술, 에너지/기술 정책