Ph. D. Dissertation in Economics

A Study on Optimal Allocation of Energy Sources for Sustainable Development

: Focus on Electricity Industry

지속 가능한 발전을 위한 에너지 자원의 최적 배분에 대한 연구

: 전력산업을 중심으로

February 2013

Graduate School of Seoul National University

Technology Management, Economics, and Policy Program

Joongha Ahn

A Study on Optimal Allocation of Energy Sources for Sustainable Development

: Focus on Electricity Industry

지도교수 이종수

이 논문을 경제학박사학위 논문으로 제출함
2013 년 2 월

서울대학교 대학원
협동과정 기술경영경제정책 전공
안 중 하

안중하의 경제학박사학위 논문을 인준함
2013 년 2 월

위 원 장 ______________________(인)

부위원장 ______________________(인)

위 원 ______________________(인)

위 원 ______________________(인)

위 원 ______________________(인)

Abstract

A Study on Optimal Allocation of Energy Sources for Sustainable Development

: Focus on Electricity Industry

Joongha Ahn
Technology Management, Economics and Policy Program
College of Engineering
Seoul National University

Human beings cannot live an ordinary life without energy. Energy is an essential factor for human life. Especially, after the Industrial Revolution, the increase in consumption and production of energy has become necessary for economic growth. Supplying enough energy at a reasonably price is essential for stable economic growth and peaceful life. But, human societies throughout the past have kept policies for cheap, abundant energy as the increase in consumption and production was considered a standard of advanced civilization. As a result, mankind is now faced with many environmental problems and energy depletion. Conflicts between social classes, countries have become important issues.

If people continue to rely on fossil fuel as the main source of energy, the welfare of mankind will reach a crisis. The production and consumption of fossil fuel leads to air and water pollution. Furthermore, conflicts between nations may arise due to competition in investments for stable energy supplies. The statement about greenhouse gases pushing human civilization towards the edge of a disaster is currently coming true. The issue regarding energy is no longer a domestic matter but a topic worth international discussion. If we fail to act properly, we will be faced with 3 major disasters regarding pollution, energy and economic development.

As a result, many policies regarding climate change are in the works at home and abroad. People are finally recognizing the seriousness of worldwide climate changes from global warming. Advanced countries are funding new policies and research/development projects related to New Renewable Energy. South Korea has also declared to promote green, low carbon development in 2008 and is continuing to introduce green technology as the driving force of future developments

Also, after 1987 report of World Commission on Environment and Development (WCED), attentions and efforts about sustainable development were diffused world widely and these have been considered as 21 century's value that human being need to pursue and new development paradigm. The cores of sustainable development are wise use of natural resources and sustainable economic growth. Therefore, energy usage should be within nature's ability to support, that is to say social and environmental effects by energy usage should be minimized. Moreover, energy demand should be satisfied by stable energy supply. To solve an assignment like sustainable development, we need to figure out whether current energy system is appropriate for sustainable development or not and what kind of work should be done for sustainable development under current energy policy. Thus, this research has been carried out using two points of view. First, a portfolio for the supply of electricity under minimum cost was created. This is the analysis under perspective of minimizing social and environmental effects for sustainable development mentioned above. By observing the energy sources that can be composed for the minimum cost of energy production under physical, political limitations, a political measure for optimal energy supply and a target supply amount of new renewable energy have been set out. Second, a cost-risk analysis for the optimal composition of electricity supply has been carried out. This is the analysis under perspective of stable energy supply for sustainable development. The former research regarding the minimum cost cannot show the relations between energy sources because the risks of the costs of fuel, management, and carbon were not considered. However, a cost-risk analysis takes into account the relative influences of the cost factors of each energy source, and has allowed a new portfolio to be created which can efficiently show the energy source that requires minimum cost at a given risk level. Furthermore, this research has carried out a cost-risk analysis on the initial minimal cost analysis, analyzing its cost and risk level. Existing researches would only separately carry out each analysis. But, the significance of this research lies in that it has also done a cross analysis of two different points of view.

This research has been carried out among the major energy sources: three

conventional energy sources (coal, gas, nuclear energy) and four non-conventional energy sources (hydro, wind, photovoltaic, biomass) under three scenarios regarding the total cost of power production (a basic scenario considering only the social cost of nuclear energy, a scenario considering the social cost of nuclear energy and external costs per source of energy, and a scenario considering the social cost of nuclear energy and the costs of air pollution per source of energy).

The quantitative results drawn from this research are expected to be utilized as important core data for the process of attaining the strategic main determinant. Also, they can be strategically used in Emissions Trading for reaching the goal of reduction and minimization of costs. Furthermore, by analyzing the management strategies and studying cases of CERs exchange in main countries and electric power companies, we can review the feasibility of taking part in foreign CERs exchanges, analyze the profitability, and plan participation strategies. From the results of this research, the influences of the obligatory reduction of the electric power industry on the electricity market and the counterstrategy have been laid out. Finally, a counterstrategy suitable to South Korea’s situation has been suggested from the results of this research. The significance of the systemic strategy research process introduced by this research is high, because it can be utilized in electricity industry and other new energy-related businesses as well.

주요어 : 지속 가능한 발전, 전력 믹스, 외부 비용, 최소 비용 모형, 비용-위험 최적 모형

학 번 : 2007-23110

Keywords: Sustainable development, Electricity mix, External costs, Least-cost optimization model, Cost-risk optimization model

Student Number: 2007-23110

Contents

List of Tables

List of Figures

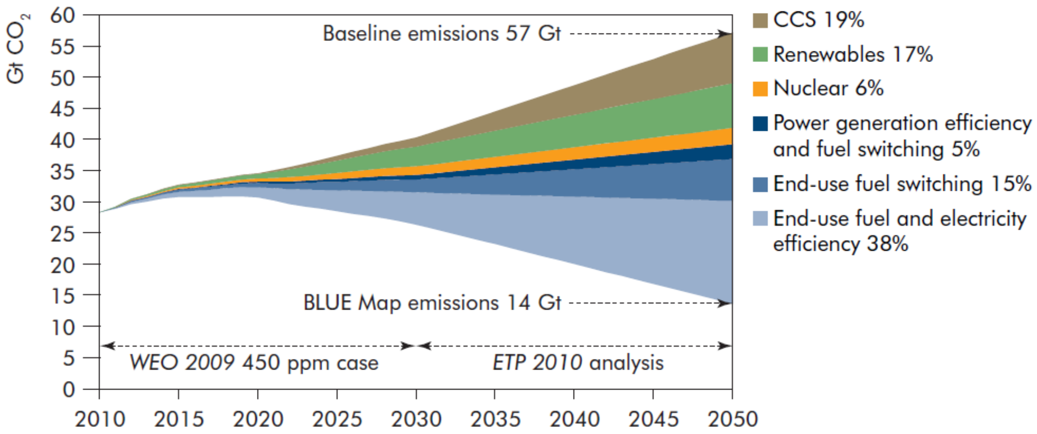
Chapter 1. Introduction of Dissertation

1.1 Research Background

Mankind was able to develop safely by producing and using many different types of energy. Most of this energy is produced from fossil fuels such as oil, coal, and natural gases. There is a fixed amount of fossil fuel stored in the Earth, which means that we have a finite supply of this type of energy. Considering the estimated reserve divided by the yearly amount of production (reserve/production ratio: RP ratio), we have 42 more years of oil left, 60 of natural gases, and 133 of coal. Apart from coal, we don't even have enough amounts of fossil fuel to last for two generations (Petroleum, 2008).

If people continue to rely on fossil fuel as the main source of energy, the welfare of mankind will reach a crisis. The production and consumption of fossil fuel leads to air and water pollution. Furthermore, conflicts between nations may arise due to competition in investments for stable energy supplies. The assertion that greenhouse gases are pushing human civilization to the edge of a disaster is currently coming true. The issue regarding energy is no longer a domestic matter but a topic worth international discussion. If we fail to act properly, we will be faced with three major disasters related to pollution, lack of energy, and the halting of economic development. Thus, we have to act now.

According to the scientific evidence, the average temperature of the Earth has risen by 0.74℃ in the past 100 years, and if a global action is not taken, the emission of greenhouse gases will rise continually, and the average temperature of Earth will have increased by 6.4℃ in 2100 since 1990. In addition, according to the International Energy Outlook, published in 2010, the amount of CO2 emitted in 2007, 29Gt, will rise to 40Gt by 2030 and, according to the Energy Technology Perspective 2010, will reach almost 57Gt in 2050.

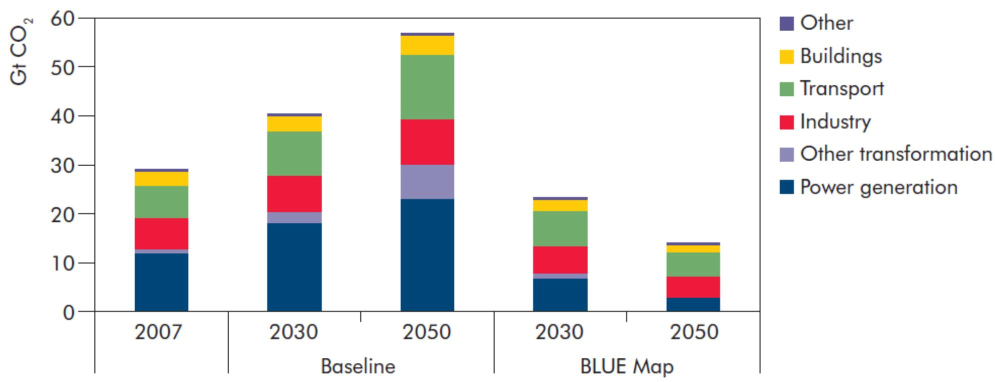


Source: IEA (2010)

Figure 1. Key technologies for reducing CO2 emissions under the BLUE Map scenario

Under such circumstances, the climate change as a result of greenhouse gases and its effect lead to a rise in economic/uneconomic costs. If the rate of climate change continues as it is now, the annual average temperature of South Korea in 2100 will be 15.71℃, 4℃ higher than the current average, and precipitation will have increased by 21% to 1,465mm. The estimated monetary damage from this will be up to 280 billion Won between 2008 and 2100 (KEI, 2011). Also, the cost for instantaneous response to climate change is about 1% of the total global GDP. However, if this problem is neglected, the cost of the damage of climate change will reach from 5% to 20% of the global expenditure per capita (Stern's Report, 2007). In addition, many reports of the past 10 years or so indicate that climate change due to global warming is a serious problem.

The BLUE Map scenario, based on technological advances and improvements in government policies, shows that we can reduce CO2 emissions by 2050 to a striking 12Gt. To achieve this, a world-class innovation in technology is required. The diagram below suggests that an increase in energy efficiency, improvements in conversion rates, CCS, and renewable energy can help to achieve this.



Source: IEA (2010)

Figure 2. Global CO2 Emissions in the Baseline and BLUE Map Scenarios

As a result, many policies regarding climate change are in the works at home and abroad. People are finally recognizing the seriousness of worldwide climate change from global warming. Advanced countries are funding new policies and research/development projects related to New Renewable Energy. South Korea has also declared the promotion of green, low carbon development in 2008 and is continuing to introduce green technology as the driving force of future developments.

South Korea’s new renewable energy industry is in its beginning stages right now, but South Korea, one of the top 10 countries in high energy consumption, has great potential to expand the supply of new renewable energy and is expected to show strong demands in terms of new renewable energy in the future. Also, the South Korean government is pushing policies to support the New Renewable Energy industry as a measure to counteract climate changes. Therefore, accurate estimation and evaluation, of the changes in the New Renewable Energy industries home and abroad by various environmental policies, has a great significance in terms of economy, society, and national development.

However, even though the environmental policies related to climate change and New Renewable Energy is considered important, existing research have limitations. They are restricted only in introducing the field, analyzing nearby countries’ policies, and concluding that there are “lessons to be learned.” Also, there are close to no concrete research providing strategies in the field of new renewable energy based on quantitative, graded analysis. Few researches have estimated the optimal proportion of new renewable energy in the industry and suggested strategies for management and policies. However, considering the fact that there are many types of new renewable energy such as solar energy, wind power, geothermal energy, and bio-energy and that they have different characteristics in terms of technology and economics, a study must be conducted that provides strategies against climate change based on portfolios of each energy source. Therefore, this research has carried out a study, on account of South Korea's reality, on the efficient redistribution of energy resources for sustainable development. It focuses especially on the electricity power industry, researching the composition of the portfolio of energy sources for optimal electricity supply under physical, political limitations. Also, in order to find out the external effect of each energy source, an analysis of the external costs and environmental costs of each energy source was carried out. Within this analysis, the effects of each energy source on the environment were analyzed quantitatively.

1.2 Objectives of Dissertation

This research aims to carry out a study on the efficient distribution of energy resources for sustainable development considering South Korea's reality. It focuses especially on the electricity power industry, researching the composition of the portfolio of energy sources for optimal electricity supply under physical, political limitations. This research has been carried out based on two points of view. First, a portfolio for the supply of electricity under minimum cost was created. By observing the energy sources that can be composed for the minimum cost of energy production under physical, political limitations, a political measure for optimal energy supply and a target supply amount of new renewable energy have been set out. Second, a cost-risk analysis for the optimal composition of electricity supply has been carried out. Former research regarding the minimum cost cannot show the relationship between energy sources because the risks of the costs of fuel, management, and carbon were not considered. However, a cost-risk analysis takes into account the relative influences of the cost factors of each energy source and has allowed a new portfolio to be created which can efficiently show the energy source that requires minimum cost at a given risk level. The details of each method of analysis are provided as follows:

1.2.1 Least-Cost Optimization for Optimal Portfolio

First, in order to put together a powerful portfolio for minimizing the cost of development, evaluation on the policies for greenhouse gas reduction and new renewable energy, based on research on the policies regarding climate change in main countries, was carried out. The interrelationship between South Korean environmental policies was also examined.

Firstly, this research has considered current environmental policies and regulations of South Korea as constraint conditions in order to calculate the amount of production that minimizes the production cost to reduce CO2 emission, for each energy source. South Korea currently has obligatory quotas in new renewable energy and restrictions in greenhouse gases and excessive energy use. To take these policies into account, the following were reflected in the research as constraint conditions: 1) the total obligatory supply of new renewable energy from the quota, 2) the total obligatory supply of sunlight,

3) the total obligatory supply of light from non-solar sources, and 4) the target amount of CO_2 reduction.

In addition, this research also includes 5) an estimation of the physical supply reserve of New Renewable Energy, including nuclear energy, based on professional opinions. This shows the limits of South Korea's development of new renewable energy, making the research more realistic. The realizable potential of energy supply is the maximum amount of energy that can be produced as time flows under the condition that all principal agents of new renewable energy developments have done their best and that there are no political restraints on the development. The realizable potential increases as time flows and reaches the technical potential[1].

To estimate the amount of production of energy to minimize the production cost for each source, a factor that takes into account the uncertainty of fuel/carbon price was also added. The basic concept of learning is cost reduction as a result of learning by doing. This means that the performance improves as capacity or a product expands (Kobos et al., 2006). Learning can also be regarded as the cost-reducing effect in each energy system that might be used in economics to describe improvement in productivity (Soderholm and Sundqvist, 2007). Many studies assert that cost reduction is dependent on industry, region, and time. Especially for renewable system, empirical studies show that learning is influenced by cumulative capacity.

---

[1]Technical Potential: The total amount of energy that can be technically produced considering South Korea's geological characteristics. As technology advances, the technical potential may increase slightly as well.

Fuel prices, carbon cost, and learning rates are treated as uncertain variables. They are generated by the Monte Carlo sampling.

1.2.2 Cost-Risk Optimization for Optimal Portfolio

Cost-risk optimization is a methodology that first started from the Mean-Variance Portfolio Theory, a modern finance theory. It is an approach that targets optimization in a cost-risk level by considering the uncertainty of costs and minimizing the costs from an initial plan or design. The relative sizes of the risks are lowered when price fluctuations of each asset in different magnitudes are gathered as a portfolio. As more various assets are gathered in a portfolio, the portfolio effect is amplified. Cost-risk optimization reveals the most efficient portfolio by considering both the cost of development and risks and evading irrelevant risks and minimizing the cost of development.

By putting together an efficient portfolio using the least cost optimization mentioned earlier, one can make the mistake of neglecting the advantages of new renewable energy technology and putting oneself at the risk of fossil fuels. Therefore, cost-risk optimization may produce totally different outcomes as compared to the least cost optimization. This is a sign that new renewable energy, previously omitted in consideration due to high O&M costs, is now being considered as a feasible alternative. New renewable energy such as solar energy and wind power has high costs of investment compared to fossil fuel energy but has almost no cost in terms of fuel. This is a great advantage when considering the risks in terms of uncertainty of fuel prices. This suggests that a proper analysis of risks in new renewable energy can show that it may be an alternative approach to fulfill the least cost.

Technology for renewable energy development has fuel-less, O&M-cost, low-risk, passive, investment-intensive characteristics and therefore presents low risk. On the other hand, fossil fuel power supply presents a higher risk because of the flexible price of fuel. Also, the prices of fossil fuels are linked to each other, which means that the composition of energy sources mainly consists of fossil fuels, which are very risky. New renewable energy technologies use different energy sources and thus are less risky. A realistic analysis can be achieved by taking these factors into account.

This research has carried out a cost-risk analysis on the initial minimal cost analysis, analyzing its cost and risk level. Existing research would only separately carry out each analysis, but the significance of this research lies in that it has also done a cross analysis of two different points of view.

This research has been carried out under three scenarios regarding the total cost of power production: a basic scenario considering only the social cost of nuclear energy, a scenario considering the social cost of nuclear energy and external costs per source of energy, and a scenario considering the social cost of nuclear energy and the costs of air pollution per source of energy. By analyzing the total cost of production after taking into account the many scenarios, a quantitative examination of the external effects of each energy source per different situation can be achieved.

1.3 Outline of Dissertation

This research is largely composed as follows. In Chapter 2, an investigation of existing research related to the topic was carried out. First, the two approaches that this research has utilized for analysis is introduced: the least cost optimization and the cost-risk optimization. Next, an investigation on the social costs was carried out. Here, the social cost signifies external costs and environmental costs. A basic study of the ranges of social costs in existing documents was carried out. Then, an investigation on environmental policies was carried out. Finally, in the research of the management of electric power supply, a study of different methods to produce different power and electricity compositions was carried out. Chapter 4 explains the methods and structure of this research. Chapter 4 defines the general form, explained in 2.1, and explains in detail the factors used in the model. Then, 4.3 provides the sources of information used in the analysis and the figures themselves. In Chapter 5, the analysis of the results of each model is shown. Chapter 5 is the analysis of future energy portfolio policies based on the comparison of the results from the least cost optimization model and the cost-risk optimization model. Based on the results of Chapter 5, Chapter 6 suggests thoughts on policies and an analysis of South Korea's future energy policies for sustainable development. Chapter 6 summarizes the whole research and attempts to show how this research can assist in future energy policies for sustainable development in South Korea. Finally, the limitations of this research and the suggested direction of future research that should follow are reviewed.

The conceptual scheme of this research is as follows:

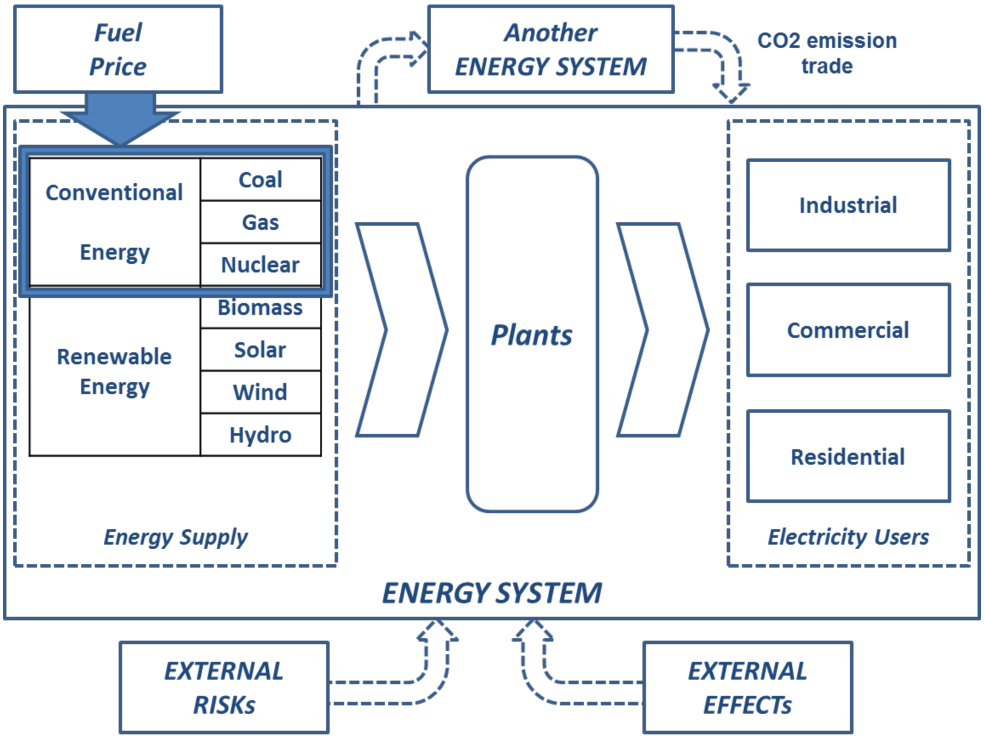


Figure 3. Structure of Proposed Model

Chapter 2. Previous Literature

In this chapter, we reviewed policy researches regarding GHG reduction and renewable energy. Through previous researches and policies, we can consider various ways to reduce GHG as well as suggest limitation. Recently, because of fluctuations of fuel price and climate change, we have become concerned with the importance of the electricity generation proportion. Therefore, first, we reviewed methodologies for optimal portfolio from least-cost and risk-cost perspectives.

2.1 Methodology

2.1.1 Least-Cost Optimization Model

Linear programming refers to the problem of determining the optimal value of a linear function subject to linear constraints. Hitchcock (1941) carried out the first recognized discussion of the methodology for solving the transportation problem. Realizing the need for a feasible method for solving linear programming problems, Dantzig (1949) developed what is now known as the Simplex method. Among the various techniques available to date, the Simplex method has been chosen for solving the proposed problem. It is the primary tools used today to solve linear optimization problems like the one in this study, and it is useful in that it can handle even the exceptional cases in which, for example, it is required to determine whether or not the problem has any feasible solutions. Before applying the Simplex method to the modeled problem, it is necessary to change its form into what is called the standard form of linear programming that looks like the following:

Clearly, this is not the form in which the problem has been modeled due to the presence of inequalities in the constraints. Fortunately, it can be overcome by adopting slack variables that equal in number as large as there are inequalities. On the other hand, the nature of the proposed problem being maximization and not a minimization can be dealt by multiplying -1 to the objective function and changing it into a minimization

Spinney & Warkins (1996) explore the use of MCS techniques. They use it as an method of the electric utility integrated resource planning and assert that MCS and related techniques are capable of addressing many of the limitations of decision analysis. MCS computes outcomes as functions of multiple uncertain inputs, each expressed as a probability distribution. Such distributions can take various different functional forms that provide a much richer description of possible outcomes for an input variable than the small number of discrete, point probabilities used in decision analysis.

They introduce steps in MCS as follows[2]:

(1) Identification of key uncertain model input variables relating to resource options and their operational environment; (2) Statistical description of the risk for these key inputs by assignment of probability distributions; (3) Identification and statistical description of any relationships (covariance) among key inputs; (4) Multiple iteration, where sets of input assumptions are drawn from each specified variable’s probability

[2] MCS steps are reorganized by citing Spinney & Warkins (1996)

distributions; and (5) Description of key model outputs by probability distributions.

These researchers finally address that this is an improvement over the more ad hoc judgments required by methods such as scenario, sensitivity, and decision analyses, and the analytical approach they developed can be used to capture the value associated with resource plan attributes such as fuel diversity, modularity (the ability of a resource type to be added in relatively small increments), and the covariance between demand and resource outputs (Spinney & Warkins, 1996).

Vithayasrichareon et al. (2009) propose a stochastic method based on the MCS. They explain various uncertainties by using MCS, which can determine the overall generation cost of electricity generation portfolio. This approach widens old methods to solve the optimal generation mix and solves the probability distribution of the expected generation costs of various generation technology portfolios. They apply this model to a case study of electricity generation portfolios consisting of three different generation technologies: coal, ccgt[3], and ocgt[4] and consider the uncertainty of fuel and carbon prices. The case study presents the ability of proposed model in approaching the impact of uncertainty on the cost and risk across different possible electricity generation portfolios. Therefore, proposed model help to make decision for generation investment to identify what generation technology and/or the generation technology portfolio mixes are appropriate for achieving the objectives regarding expected costs, risks, and CO2 emissions (Vithayasrichareon et al., 2009).

---

[3] Ccgt: combined cycle gas turbine
[4] Ocgt: open cycle gas turbine

Kim et al. (2012) study optimization plans of conventional and prospective renewable energy systems with respect to production cost which include investment, O&M, variable, and external costs. For this purpose, they propose least cost linear programming method for evaluating costs of energy systems including CO2 trading and apply to the Korean energy situation. The proposed method presented the optimization, considering the uncertainties in the learning rates and external factors such as fuel and CO2 prices. To handle uncertainties, MCS was performed.

2.1.2 Mean-Variance Portfolio Optimization Model

The core of this alternative is to optimize cost-risk criteria considering not only cost but also uncertainty or risk of long-term cost flow which goes further than the concept of minimizing cost in the electricity generation plan. This alternative is based on the Cost Risk efficient portfolio model, which is modified from the efficient diversification model or mean-variance efficient portfolio model proposed by Markowitz (1952), which is widely used in the financial area as an asset allocation method.

This model has a long history in economics. Markowitz (1952) associated risk with the variance in the value of a portfolio. He derived the optimizing portfolio and behavior from the avoidance of risk. The portfolio selection models provide a positive explanation and normative rules for the diversification of risky assets, but the degree of diversification can reduce risk according to the correlations among returns (Levy & Sarnat, 1970). After the initial development by Markowitz (1952), the mean-variance optimization model has been developed through studies and applications (Sharpe, 1964; Feldstein, 1969; Lintner 1965; Levy & Markowitz, 1979). Sharpe (1964) and Lintner (1965) developed the theory which is called Capital Asset Pricing Model (CAPM) − when all investors follow the same objectives with the same information − and showed that there is a natural relationship between expected returns and variance (Engle, 2004). This model played a central role in financial theory. Merton (1973) also developed a model that is consistent with the CAPM to evaluate the pricing of options.

The assumption of the mean-variance optimization model has received inspection. Since the utility implied increasing absolute risk aversion, the quadratic utility justification was not very appealing (Pratt 1964; Arrow, 1971). Then, they instead considered restrictions on the distribution of the random returns. Tobin (1958) showed that a sufficient condition for the mean-variance model is that the random returns have a multivariate normal distribution. However, Samuelson (1967) pointed out that any two-parameter family of distributions would not, as did Borch (1969) and Feldstein (1969). Cass & Stiglitz (1970) argued only that the normal distribution was sufficient. However, Agnew (1971) suggested a counterexample. Porter & Gaumnitz (1972) and Fishburn (1977) showed the results of several empirical studies of the similarities and differences between mean-variance and stochastic dominance efficiency to solve the question of whether the application of stochastic dominance rules to portfolio choice yields results that differ significantly from the results that would be obtained using mean-variance analysis. These two models were used for comparing uncertain prospects. Then these researchers showed where risk aversion is strong, as second- and third-degree stochastic dominance rules are more consistent with the maximization of expected utility than is the mean-variance rule (Porter & Gaumnitz, 1972).

As mentioned above, the portfolio approach method means that if the price fluctuation of several assets which are moving to different widths and to different directions comes together as a portfolio, the relative risk of the total portfolio will be decreased. In practice, the greater the variety of characteristics of constituted assets becomes, the bigger the portfolio effect gets. Even though the rate of return does not increase, the variability of the rate of return rapidly decreases. Also, the most efficient portfolio which gets the highest earning rate in a certain risk level could be composed (Yun, 2009). Consistent with these research results, Awerbuch introduced research about constituting electricity generation mix with the portfolio method in the operational side. Awerbuch (1993, 2002) and Awerbuch & Berger (2003a) are textbook studies about introducing the portfolio method and application cases of this method.

In this paragraph, basic explanations of the portfolio method and the possibility of constituting low cost-efficient electricity generation plans with financial theories are presented. Moreover, if an electricity generation plan is formulated based upon the portfolio method, the resulting relative high O&M cost enables new electricity sources that had not been included in the preexisting least cost-focused electricity generation to be considered (Awerbuch, 1995a, 1995b, 2000a, 2000b; Bolinger et al., 2002; Bolinger & Wiser, 2005; Awerbuch & Yang, 2007). This means that new forms of energy like solar energy or wind energy require more investment costs than fossil fuel, but that they are still profitable from the perspective of risk, because they hardly require any fuel expenses. Thus, if these risk factors are correctly assessed, they can reap results that are different from those of the electricity generation that is based on least cost. In Korea, there seems to be close to no research regarding the use of the portfolio method in the areas of fuel mix or electricity generation.

The mean-variance approach considers the expected value of individual investors and risk, thereby defining the most efficient investment amount for each investor. The cost-risk optimization, on the other hand, considers a given budget and the cost and risk of each alternative. It then tries to find the alternative that most effectively combines cost and risk. In order to understand the cost-risk efficiency portfolio method, it is necessary to understand the concept of a portfolio's expected value of cost and risk. The expected value $E(c_p)$ in a portfolio composed of various investment properties can be defined as follows.

$$E(c_p) = \sum_{i=1}^{n} w_i E(c_i)$$

Here w_i is the proportion of the investment property i in the portfolio, and $E(c_i)$ is the expected value of investment property i's cost. The variance of the portfolio can be calculated as follows.

$$Var\left(c_p\right)=\sigma_p^2$$

$$=\left[w_1,w_2,\cdots,w_n\right]\begin{bmatrix}\sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1n}\\ \sigma_{21} & \sigma_2^2 & \cdots & \sigma_{2n}\\ \cdots & \cdots & \ddots & \vdots\\ \sigma_{n1} & \sigma_{n2} & \cdots & \sigma_n^2\end{bmatrix}\begin{bmatrix}w_1\\ w_2\\ \vdots\\ w_n\end{bmatrix}$$

σ_{ij} is the covariance between investment property i and j. A portfolio's risk can be represented by the portfolio's standard deviation in order to express its risk and cost on the same level. The standard deviation of portfolio is calculated by logarithm differences between a variable's value of a previous and current period and calculating the standard deviation of the resulting rate of change. Alternatively, it is also possible to simply calculate the difference between a previous and current period and to use the standard deviation of those differences. Based upon these two equations, the investor can choose the most efficient portfolio by adding an appropriate weight based upon his preference concerning cost and risk. In other words, he will choose the portfolio that has the same expected value of cost while having the least variance, or he will choose the portfolio that has the smallest expected value of cost from among portfolios with the same variance. The selected portfolio is called the cost-risk efficient portfolio. If one alters the expected value of the wanted cost and marks the portfolios with the least variance on a graph, this will create the cost-risk efficient frontier. Conclusively, according to the cost-risk criteria, the investor will choose a portfolio located on the cost-risk efficient frontier. The establishment of the cost-risk efficient frontier can be summarized by the following object function and constraints.

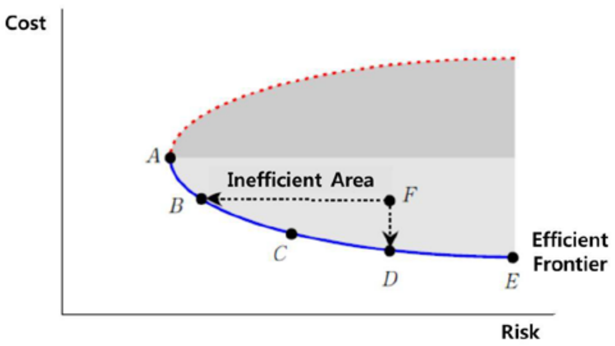
Object function: $\underset{w}{Min}\ w'\sum w$

Constraint (1): $\sum_{i=1}^{n} w_i = 1$

Constraint (2): $\sum_{i=1}^{n} w_i E(c_i) = E(c_p)$

Constraint (3): $0 \le w_i \le 1$

Here $w_i = [w_1 \quad w_2 \quad \cdots \quad w_n]$ stands for the vector of individual investment property i 's investment rate and $\sum$ is the variance-covariance matrix that is composed of the covariance□ σ_{ij} between property i and property j. The first constraint requires that the sum of investment rates must be 1. The second constraint requires that the expected value of the portfolios' cost is equal to the expected value of each investment property's cost multiplied by the investment rate. The third constraint assumes that an investor's investment rate will be restricted from 0% to 100% and that short sale is therefore not possible. The result, including the third constraint, can be called the limited most efficient rate by alternative. On the other hand, if the third constraint is removed and there is no limitation to the investment rate, this can be called the unlimited most efficient rate per each alternative. In the end, creating the cost-risk efficient frontier is equal to creating the smallest portfolio variance of the object function while applying the three constraints. The selected variable in this case is each investor's investment rate w_i. $E(c_i)$ and $\sum$ are usually compiled through the use of past results. In practical use, $E(c_i)$ is set down as a specific value and the value of w_i that creates the smallest object function is defined. This process is repeated as $E(c_i)$ is altered to another value and each appropriate w_i is further calculated.



Source: Yun (2009)

Figure 4. Cost-Risk Efficient Frontier

Figure 4 represents the cost-risk-efficient frontier. All points located on frontier AE are efficient portfolios regarding cost and risk. The area below the frontier is the inefficiency sector, and alternatives in this area are inferior with regard to cost and risk when compared to those on the frontier. For example, portfolio alternative F is less efficient than portfolio alternative B, because it holds more risks at the same cost. Equally, portfolio alternative F is less efficient than portfolio alternative D, because it is more expensive at the same risk. In order to reduce the cost of the portfolio alternatives on the efficient frontier, the risk must be increased, while in order to reduce the risk, the cost needs to be increased. But in the case of the portfolio alternatives that are located in the inefficiency sector, this is not necessary. Portfolio alternative A is a high cost–low risk portfolio alternative and usually reflects the most balanced allocation among investors. Portfolio alternative B is a same cost–lesser risk alternative to portfolio alternative D. Portfolio alternative D is a lesser cost–same risk alternative to portfolio alternative F. Portfolio alternative E is a low cost–high risk portfolio alternative and normally creates the greatest focus of allocation on specific investors. From the cost-risk perspective, the portfolio effect takes place when it is possible to reduce risk without further cost or to reduce cost without adding any risk. The most opportune condition for this portfolio effect to happen is to have the least amount of correlation among the investors. If there is a correlation of +1 among investors, there is no portfolio effect. But if their correlation is -1, then the risk can be removed with the same cost (Yun, 2009). The many portfolio alternatives located on the cost-risk efficient frontier are indiscriminate with regard to the cost-risk standard. In order for the investors to choose the most preferable portfolio from among these indiscriminate portfolio alternatives, investors have to decide the exchange rate of the cost at which they will ascribe to one set of risks. In other words, they need to consider the interrelation between cost and risk as seen in the following formula. Through assessment of an appropriate weight for a portfolio’s cost and risk through formula which mentioned above, investors are able to find the portfolio that considers risk with the least cost.

$$\text{Total amount of cost taking risk into account} = E\left(c_p\right) + \alpha \cdot Var\left(c_p\right) \quad (7)$$

For example, if the weight for cost and risk are 30 : 70, then (70/30) = 2.33, and if the weight is 70 : 30, it follows that (30/70) = 0.43. The next table includes examples of the definitions of cost and risk and the weight that leading American power plants used. (Bolinger & Wiser, 2005).

Table 1. Applications of Major U.S. Power Company

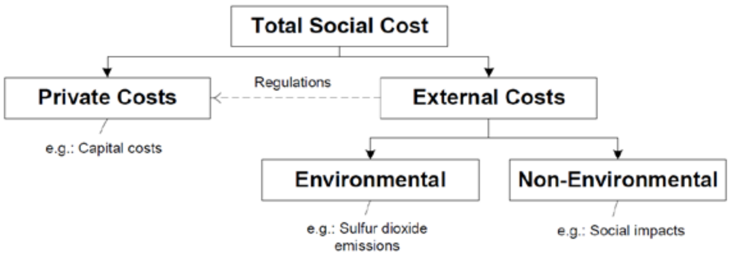
Company	Cost definition	Risk definition	cost-risk weight
Avista	Average electricity supply cost based upon the Monte Carlo simulation	coefficient of variation of cost	50% / 50%
North-Western	Yearly average cost based upon the Monte-Carlo simulation	95% Percentile	70% / 30%
Pacific-Corp	present value average internal rate of return based upon the Monte-Carlo simulation	5% and 95% Percentile	qualitative judgment
PGE	present value of internal rate of return based upon applying the Monte-Carlo simulation 100 times	variability index of the yield to average	qualitative judgment

PSE 2003	average present value of expected customer charge based upon the Monte-Carlo simulation	coefficient of variation of cost	qualitative judgment

Source: Bolinger & Wiser (2005)

2.2 Social Costs Research

IEA (1995) classified total social costs as represented in the figure below. Total social cost is classified into private costs and external costs, and external costs are divided into environmental costs and non-environmental costs.



Source: IEA (1995)

Figure 5. Total Costs to Society of a Productive Activity

When current generating costs are calculated, social costs by carbon dioxide are internalized in external costs of generating costs, but social costs by air pollutant and green-house gas emission except carbon dioxide don't feed into generating costs. Therefore, this chapter will look into external costs and environmental costs among total social costs and the way that those are fed into generating costs. Furthermore, energy security costs among non-environmental costs are examined. Generating mix is estimated by total generating least cost and mean-variance portfolio approach considering the contents this chapter explores.

2.2.1 External Costs Research of ExternE

The main way to estimate external costs of electricity generation are the damage cost approach and control cost approach. Moreover, in order to decide the value of a specific issue, there is a way to develop relative weights for environment issues according to the votes of experts or consumers, and then multiply weight by total damage costs (Hohmeyer et al., 1997).

Damage cost approach is mainly used for analyzing air pollution substances influences regarding not only harmful effects for the human body (heart or respiratory disease, death rate), but also harmful effects for crops and tangible property. This is a consumer-oriented approach to track down various environmental damaged effects which are caused by pollutant emission during the electricity generation process. However, this approach basically has the following problems. First, estimating the direct physical effects of environmental pollution (e.g., air pollution, water pollution) could be very complicated and include uncertainty. Seconds, evaluating and monetizing environmental damage is difficult, and arguments break out as a result (Hohmeyer et al., 1997). A damage cost approach could be divided into a top-down and bottom-up approach; a top-down approach is a way to estimate nations or specific region-based total pollutants and their total effects. Upon estimating the damage of pollution sources (%) all over the country divided by the total pollution cumulative quantity, the quantity of pollution according to generation activity is estimated based on national unit. However, this approach cannot handle a specific regional effect and has limitations on considering the difference of effects according to various steps of the fuel cycle. A bottom-up approach is a way to track down and quantify the effect of single pollution sources. This approach uses technology-specific data and could make use of the disperse model, dose-response function. However, this model presents difficulty in applying the effect of factors whose data does not exist and considering synergy effects between sources of pollution and other environmental factors (Sundqvist, 2004).

The control cost approach is another approach for estimating social costs, which presents the advantage that it is easy to implement, but it has disadvantages in that it underestimates social costs because it has private costs concepts for reducing pollutants on the producers' side. In the case of a control cost approach, it is useful to use marginal reduction cost, but usually the average control costs are used temporarily because of the difficulty in estimating marginal reduction cost (Sundqvist, 2004).

About 40 previous studies analyzing the 1980s and 1990s social costs with a damage cost approach and control cost approach are organized and presented in Appendix 1. The social costs of each generation source based on research material of Appendix 1 are organized below.

Table 2. Descriptive Statistics of Externality Costs

[US cents/kWh]	Coal	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Mean	14.87	5.02	8.63	3.84	0.29	0.69	5.20
SD	16.89	4.73	18.62	8.40	0.20	0.57	6.11

Source: Data was reorganized by using Sundqvist (2004)

The research material by Sundqvist (2004) is organized above with results of research mainly about developed countries. The above research results are mainly based on the ExternE project (1999), which uses a bottom-up damage cost approach, because many follow-up researches based on ExternE project are conducted. To compare the external costs of each generating source, the scope of costs based on various results of previous researches should be considered. Therefore, this research will apply the results of previously analyzed social costs as a factor that influences total generation costs.

2.2.2 Environmental Costs Research for Air Pollution

Environmental costs analyze not only the effects of air pollution and human body harm, but also the damage to crops and tangible property caused by pollutants from generation sources. Environmental costs could be expressed as multiplying social marginal costs of air pollution of each pollutant by air pollutant emissions. However, Korea does not have a reliable estimation result of environmental costs which could be socially agreed upon, so foreign estimation results which have public confidence are used in this study.

Previous works about the social costs of air pollution are as follows:

EC (1999) estimated the social marginal costs of air pollution caused by energy consumption for each country and for each kind of air pollutant through a project spanning several years of research called ExternE (Externality of energy). Total damage costs such as human body harm costs, crop reduction costs, and construction corrosion costs were considered as social costs, but global warming damage costs were excluded. Only SO2, NOx, and dust were considered as research target pollutants. This research result has been highly cited recently and has generated lots of researchers' confidence. However, it presents three limitations. First, the estimated target pollutants are limited only in the case of SO2, NOx, and dust. Second, the estimated target countries are limited only in the case of 15 European countries. Finally, social costs are estimated only in each country and are not estimated in each region like towns or countries within countries.

Markandya (1998) estimated the social costs of air pollution of each pollutant considering the economic power of each country to apply each country's purchasing power parity based on ExternE or U.S. existing estimation. This research includes Korea as one of the estimation target countries, but its estimation method is not significantly different from ExternE, so it has all of the limitations that the ExternE project had.

Holland & Warkiss (2002) estimated social costs per air pollution unit; they re-estimated social costs per air pollutant unit by using the ExternE project method. The target pollutants were decided to be SO2, NOx, VOCx, and PM. The results of dust and SO2 are drawn by adding values of the country side to consider the effects of both emitted values from the urban area and secondary pollutant simultaneously. In the case of the effects of VOC and NOx emission, after these are emitted, they need time to form ozone and nitrate, so they used the same value with country sides. This research presents two differences from that of ExternE. First, VOCs are added as estimation target pollutants in addition to SO2, NOx, and dust. Second, this research estimated the social costs of air pollution to divide one country into towns and country and to sort the urban side into population size.

In Korea, KAIST carried out a survey targeting experts and proposed air damage index of five kinds of pollutants: SO2 1, NOx 0.97, fine-dust 1.21, CO 0.74, and HC 0.86. The research results of KAIST as the first proposed air damage index for five kinds of pollutants in Korea is of great significance, but it has limitations in that it was drawn from experts' survey rather than from a systematic process.

2.3 Environmental Policy Research relating with GHG

2.3.1 Carbon Emissions Policy Research

Along with the world trend about climate change, Korea also takes low carbon green growth as a main agenda and promotes various policies on this subject. Especially, Korea voluntarily announced the greenhouse gas reduction plan, showing interest in climate-change-related environmental policies. Furthermore, Korea decided to implement the Renewable Portfolio Standard (RPS) from 2012. According to Korea's environmental policies related to climate change, attention to the reconstitution of electric power sector is growing.

Elliott (2000) is a main researcher regarding the implementation of renewable energy in the electric power sector related to climate change or environmental policies. He asserts that renewable energy is the only solution to solve environmental problems, and a social institutional system should be set to promote the generation of renewable energy. Showalter et al. (2010) conducted similar research that claims that renewable energy and advanced energy efficiency technology will help reduce greenhouse gas emissions, and these technologies would have large effects on the total cost of meeting the total carbon emissions target. In particular, this research forecasts a portfolio of electricity generation, based on various scenarios about the improvement of renewable energy and advanced energy-efficiency technologies.

Beard et al. (2010) recognize an important issue between world climate change and the electricity industry focusing on the U.S. The research introduces a carbon emissions target, carbon trade policies, carbon tax policies, electricity demand reduction policies, RPS policies (which could be used to cope with world climate change), and their issues related to the electricity industry. There are similar works of research to provide a wide range of contents regarding this issue, such as De Vita et al. (2009), who organized the U.S. and EU's climate-change-related policies, Bird et al. (2007), Finkenrath (2011), and EPRI (2000).

Carbon emissions are a main factor causing climate change. Kirat & Ahamada (2011) analyzed whether the Emission Trading Scheme (ETS), which is a carbon emissions trade system implemented in EU, gives proper economic incentives to electric power companies in France and Germany. Kara et al. (2008) examined the economical effects of the EU carbon emission trade system on Northern Europe's electric market using simulation. These researchers conducted a quantitative analysis on the effects of EU policies on the electricity industry. Green (2006) described an optimal electricity generation portfolio, which an electric power company can choose by setting two different situations: the introduction of carbon taxes and a carbon emission trade system in the U.K. In addition, other works of research, such as the one by Newcomer et al. (2008), estimated the correlation and elasticity between the price of electricity and the carbon price of three different electric power companies in the U.S. Mondal et al. (2011) also carried out research analyzing Bangladesh's electricity generation portfolio regarding a carbon emission restriction policy.

Sims (2004) asserts that the Earth's climate has changed as a result of human activities, and this climate change will affect renewable energy supply, outcome, and technology conversion. This research pays attention to the response strategy of the world's renewable energy industry to the carbon emission reduction plan. The research compared the cost of renewable energy sources and the cost of fossil fuel energy and analyzed how carbon emission influences the conversion of energy sources. Sims (2004) insists that the era of decarbonization will not only have climate change under control, but also provide opportunities regarding a new type of business field.

Asif & Muneer (2007) described the current state of energy market in China, India, Russia, the UK, and the U.S. and the status of generating renewable energy sources. Moreover, they emphasized the necessity of renewable energy to give a reason for the reduction of potential fossil fuel energy, the continuation of global warming, the insecurity of energy supply, and the rise in oil prices.

Yoon (2002) asserts that Korea’s 21st energy policy should be changed for sustainable development and suggests 7 different reasons regarding this issue. She claims that the modification of energy system is inevitable due to the consciousness of crisis surrounding climate change caused by the excessive use of fossil fuel, and that energy systems should be modified into the sustainable energy system, since fossil fuels and uranium are on the brink of exhaustion, implying unstable supply and financial weakness. Moreover, she asserts that energy policies should be altered in a more desirable direction, as nuclear waste presents difficulty in handling, expanding citizen participation in the decision process of energy policies, and the newly rising trend of renewable energy.

Cao (2010) proposed a direction of carbon reduction obligation assignment method in each country and a direction of climate policies. He particularly brought up the issue of the time shortage in the climate settlement and the importance of agreement on carbon reduction target, assignment methods, financial mechanism, technology transfer, failure in duty penalty, and the connection between climate change and trade, on which he finally proposed a solution. Cao (2010) pointed out the difficulty of burden sharing of obligatory reduction and suggested expanding the number of participants for a fair assignment. That is, he suggested that at least major greenhouse gas emission countries need to participate in the greenhouse gas reduction plan, regardless of the degree of development of one country, and then the connection between fairness and economic development is important for promoting participation of developed countries.

The United Nations Environment Program (UNEP) published a report in 2010 about feasibility to meet the long-term greenhouse gas reduction target based on the greenhouse gas reduction plan. This report suggests that greenhouse gas levels should be under 44GtCO2e in the atmosphere in 2020 to meet the long-term carbon reduction target, and it forecasts that the 2020 greenhouse gas levels will be 56GtCO2e if the current trend is followed. In the expectation that the meeting of the long-term goal might be difficult due to the excessive emission of greenhouse gas, which will be about the amount of 12GtCO2e based on the current tendency, the report analyzed whether the countries involved could reduce the gap between the goal and the expected emissions with their efforts. The analysis drew the conclusion that, even though the countries involved will be able to attain the goal of reduction that they presented, only the reduction of the amount of 7GtCO2e would be achieved, which makes it impossible to meet the long-term goal, with the amount of 5GtCO2e of greenhouse gas exceeding the goal still being generated. UNEP (2010) emphasized that, in order to reduce or remove the gap of emissions among the countries involved, they should make efforts to attain their goals, taking action to domestically reduce emissions and make strict accounting rules as long as they suggested themselves conditional targets for reduction of gas emissions. UNEP also suggests that the countries involved set 2020 targets for reduction in a stricter way and that they play a more active role in reducing emissions after 2020.

2.3.2 Renewable Energy Policy Research

The following are the works of research performed regarding the classic renewable energy development policies, which are Feed in Tariff (FIT) and RPS.

Wiser et al. (2002) collected both policies by country, conducted a comparative analysis of FIT and RPS policies used as renewable energy promoting policies in the U.S. and European countries, and suggested energy policies suitable for China. In addition, Ragwitz & Huber (2005) compared and analyzed renewable energy promoting policies of Spain and Germany, and Conture & Gagnon (2010) performed similar research by dividing FIT policies under the supporting methods. In addition, Bird et al. (2010) researched the estimation of the renewable energy demand under the scenarios based on various factors (e.g., the price of renewable energy and consumers' interests) under the RPS circumstances. This research implies a lot for South Korea, which will implement RPS after 2012.

Despite the great necessity for renewable energy, its development presents several limitations. Painuly (2001) maintains that renewable energy might cause issues related to market failure, market distortion, economic and financial matters, technological matters, and sociocultural matters, in spite of its high importance. Therefore, to eliminate these obstacles, he suggests diverse political measures that could solve those problems, such as relaxation of the energy market, guarantee of the market, economic and financial compensation, government investment, and setup of regulation and standards. As mentioned above, when considering limitations of renewable energy, rigidity of energy market, and renewable energy technologies, it is hard to leave the introduction of renewable energy to the market and expect it to naturally grow. Painuly (2001) offered the prospect that the renewable energy market would take over 90% of the overall energy market in 2020 unless there exist renewable energy-promoting policies. This supports the fact that renewable energy still faces a lot of difficulties in its development. In fact, renewable energy faces several reasons for its inability to develop itself, such as economic feasibility, limitary environmental conditions, and deactivation of the market. Due to these limitations, the countries that have developed renewable energy are currently implementing various policies for the promotion of the development of renewable energy.

Helby (1998) carried out an analysis on the process of the Swedish government's promotion of renewable energy to replace nuclear energy. Between the two options as an alternative form of energy, one of which was natural gas and the other the improvement of energy efficiency with boosting the renewable energy supply, the latter was adopted due to the amount of carbon emissions expected from natural gas. The Swedish government was able to promote the supply of renewable energy through government subsidies, programs that support taxes, and the finance system.

Ragwitz & Huber (2005) compared the renewable energy promotion system of Spain and Germany, which are considered advanced countries in terms of their supportive renewable energy policies. While both countries have similarities in the system in that they attract innovation of technologies on renewable energy and active investment, there are also major differences in terms of the price of FIT, the supporting period, and ways to lower the basis price.

Couture & Gagnon (2010) propose that FIT be considered the most successful policy among many renewable energy promoting policies and that this policy is divided under the supporting method. While fixed-price policy lowers the risk of investment, being independent from the electricity price, premium price policy can be an attracting factor for producers to lower the price. The research above revealed that FIT can become different policies depending on its composition and that each has its pros and cons.

South Korea, one of the ten countries that consume the most energy in the world, is yet considered to be a country with a low renewable energy distribution rate among OECD countries. In particular, there is unsteady development in the field of renewable energy, as it mostly relies on water and bio-energy. Park & Park (2009) performed a comparative study on the introduction of renewable energy on the domestic level and examined the problems and improvements of renewable energy resources which have not been distributed yet in the country. The report says that, as a result, South Korea has faced an imbalanced growth of renewable energy; the largest amount of electricity generated by renewable energy comes from water energy, and the imbalanced growth is caused by the absence of technologies with high dependence on imports, lack of national supporting policies, and shortage of fostering specialists. It claims that, to solve these problems, we need to develop ocean energy which utilizes the domestic geographical conditions, waste energy which is greatly supported by the nation, and fuel cells that make use of advantages as an IT-advanced country.

The National Energy Committee of Korea (2008) explains the reasons why the distribution of renewable energy in South Korea is somewhat poor in terms of two aspects: political and environmental. What was seen as a political reason is that the budget for developing renewable energy was absolutely short, that the government focused on developing sunlight generation and hydrogen fuel cells which had low distribution effects, and that due to the increase of government's financial burden there were certain limitations in performing distribution policies.

Due to the above reasons, the groundwork formation for the renewable energy industry in South Korea is insufficient, which makes renewable energy policy promotion highly important. Lee et al. (2007) asserts that the existing policies for expanding the distribution of renewable energy, such as FIT and RPS, focus on expanding the supply amount, paying little attention to the electricity consumers. To compensate for this situation, he estimated the potential of eco-friendly consumption in the electricity sector and examined the plans for introducing green price, which is a typical demand policy measure that sells green electricity at a high price. As a consumer survey shows that the level of awareness of renewable energy is higher, people's willingness to buy and pay is higher, and he concluded that advertising renewable energy is necessary. However, the above research presents the limitation that it did not apply heat production, based only on the electricity from renewable energy.

Kim et al. (2006) analyzed whether renewable energy can compete with the existing fossil fuel energy with the help of FIT in Korea using a system dynamics model through the change of market price and the supply of renewable energy and on how much wind power, small hydro power, and biomass energy can satisfy the government's distribution objective. They show that, even if as much sunlight generation could be distributed as the government wants, it would only satisfy two thirds of the government's goal amount, and wind power would satisfy 10%. Even though small hydro power, which has relatively low generating cost, was expected to exceed the aimed supply amount, conditions under which a power plant can be constructed would make it hard to meet the aimed supply amount of the government. The above research reveals that the activation of renewable energy simply with price policies might jeopardize government policies. However, the research holds the limitation that it only considered the generating cost as a factor when calculating a market share of renewable energy and assumed that other energy resources would use the same price policy in the process of deciding the model.

Lee (2009) compared and analyzed FIT and RPS, which are the typical renewable energy policies focusing on sunlight generation energy. He examined the cases of developed countries that had implemented the renewable energy policies for a relatively long period and claimed that we pay attention to the rising trend of either enhancing each policy or combining two policies due to the drawbacks of each policy. Indeed, in the U.S., a representative country using RPS, many states are trying to introduce FIT, and Japan, an example of failure of sunlight generation, is recently planning to revive FIT. However, he also notes that we need to take notice of Italy's case, in which RPS was employed at the same time due to the financial burden from introducing FIT, and Germany's case, which tried to complement FIT to lower a financial burden. He asserts that, in the sunlight generation market of South Korea, the existing FIT needs to be kept for a certain period, with the gradual introduction of RPS. In other words, he argues that it is more effective to introduce FIT to activate the market in the beginning stage of distribution of renewable energy and to introduce RPS and keep FIT for a certain period after the expansion of renewable energy supply and market stabilization. He also proposes a plan to implement FIT to the small-scale generation businesses and combine FIT with RPS to businesses over a certain size. He asserts that, in the case of FIT, which implies a big financial burden, we need to consider Germany's case, which relieves the burden as the consumers partially pay the difference, and especially for the sunlight generation business, which demonstrates economic weakness. With the government and people's burden sharing, a social consensus might be formed regarding reducing greenhouse gas and fostering sunlight generation business.

Kim & Cho (2002) maintain that, even though renewable energy has its perks, such as substitutability of fossil fuel, eco-friendliness for reducing greenhouse gas, and security of supply in case of exhaustion of fossil fuel, it cannot be treated as separate from the existing fossil fuel generation in the electricity market. They asserts that, if renewable energy causes market failure in the process of entry into the market, it would only be grounds for government involvement. The above research progressed with questions regarding the necessity of government involvement and regulation in the free competitive market, the correlation between renewable energy and fossil fuel generation, and the more effective choice between subsidy package and tax policy. According to the survey and analysis of fuel demand function estimation, renewable energy causes market failure, and policy variables such as setting a standard price, compensating the gap between the standard price and market price, and RPS were discussed to solve this problem. The result also revealed that renewable energy is still a complement to fossil fuel energy, not a replacement. It also shows that, since a subsidy package greatly increases the supply of renewable energy, lowering its price, it would bring about positive effects, which expand the distribution of renewable energy and raise the business's competitiveness along with stabilization of prices. However, while the policy that induces the development of renewable energy by reinforcing tax on the existing energy would have effects of reducing the overall consumption of energy, tax policy forces the energy price up and weakens the competitive position of the business along with price increases.

2.4 Electricity Supply Management Research

2.4.1 Electricity Mix Policy Research

Jegarl et al. (2009) present four kinds of scenarios according to the master plan of the national electricity of South Korea and simulated the country's future development portfolio to analyze and predict it. The research reveals the introduction of technologies for carbon reduction related to fossil fuel, such as IGCC and CCS as one scenario and considers the introduction of carbon tax and restriction policy on carbon emission as the remaining scenarios. However, since this was published before South Korea decided to implement RPS, it has its drawbacks in that the circumstances of implementing RPS were not reflected in the simulation. This research finds that South Korea's future electricity generation rate by renewable energy would be extremely low, much lower than the obligatory rate of electricity generation expected in the RPS policies. Accordingly, a follow-up study that simulates an electricity generation portfolio in consideration of RPS situations and suggests the optimal portfolio is necessary. The report by Korea Energy Economics Institute (2004) entitled "A study of influences that reconstruction of electricity business have on choosing electricity generating fuel" offers similar points as Jegarl et al. (2009) does, in that it simulated an electricity generation portfolio supposing a carbon tax situation. However, it has its limitations; it is a relatively old study, it does not consider the implementation of RPS, and it has a weak link to climate change and environmental policies.

Hart et al. (2011) introduced a new Monte Carlo-based grid integration model. The model has been described as capable of planning and providing analyses of systems with large penetrations of variable renewables combined with conventional generators that meet a time-dependent load with a specified reliability. The California ISO operating area applied this model to identify a portfolio which is capable of providing 99.8% of the 2005-2006 generation with non-carbon-based technologies, including wind, solar thermal, photovoltaic, geothermal, and hydropower methods. Through this system, an 81%

reduction in electric power sector carbon emissions is expected to be achieved from 2005 levels. A comparison of the model results presents that the analyses may overestimate the attainable carbon emissions reductions by approximately 33%. In this study, the low-carbon systems are described as requiring large capacities of dispatchable generation with very low-capacity factors. As a consequence of the low capacity factor fleets required by these systems, expanded capacity-based markets will help to achieve high penetration variable renewables. But these systems will also require investments, because the infrastructure needs to be transmitted and distributed. This work suggests that the use of high penetration variable renewables will cause a reduction of emissions to rely on new technologies that can replace the capacity-based role provided by natural gas in these simulations.

Muis et al. (2010) developed a Mixed Integer Linear Programming (MILP) model for the optimal planning of electricity generation, meeting a specified CO2 emission target. According to this model, investment cost and the availability of RE sources are the main driving forces of this lection type of RE power plant. In the case of the 5% RE mix, palm oil shell and fibre were found to be the most favorable, because they are common and cheap. Solar energy is also recommended because it is a free renewable source that is low cost. Grid electricity demand of 9% RE generation mix can be achieved by selecting 96.4% RE from palm oil residues. Another 1.8% should come from municipal solid waste (MSW) and the remaining 1.8% from other types of RE. Biomass, IGCC, NGCC, and the nuclear power station are new technologies that should help reduce CO2 emission.

Biomass plants such as landfill gas and palm oil residue tend to become competitive at the 50% CO2 reduction target. However, municipal waste, rice husk, and wood residues are not appropriate because they are too costly. Solar power plants also present high investment costs and low efficiency. In the end, the hydroelectric and natural gas power station was recommended due to the emission -free technology and low operating cost.

Xie et al. (2010) developed an interval fixed-mix stochastic programming (IFSP) model for planning GHG-emission management and energy systems under uncertainty. Integrating interval-parameter programming (IPP), fixed-mix stochastic programming (FSP), and 0e1 integer programming techniques, the model incorporated uncertainties into a general optimization framework. IFSP also addresses capacity expansion issues and emission-reduction scenarios related to different levels of economic implications. Under a series of fixed levels through the introduction of FSP, probabilistic distributions of electricity demand can be integrated into the optimization process, which has advantages in reflecting uncertainties for large-scale problems with a long planning period. The results of the study suggest that the methodology is applicable to the reflection of complexities of large-scale energy management systems and addressing of the GHG emissions reduction issue with a long planning period. It could help energy managers identify desired management policies under various environmental and economic considerations. However, there is still great room for improvement. Compared with other approaches, especially two-stage stochastic programming (TSP) methods, FSP can reflect the dynamic variations of system conditions and simplify a large amount of the design scenarios that will normally lead to the problem of “dimension disaster.” This study attempted to integrate FSP and IPP methods into a general framework and apply the IFSP for GHG-emission management under uncertainty. The optimization algorithm is further applicable to many other environmental problems where complex uncertainties exist in a long planning period. It is also possible that other programming techniques (such as fuzzy programming and dynamic programming) can be integrated with FSP for handling more complicated cases.

Arnesano et al. (2012) provided a mathematical tool for energy planning decision making through the description of a new calculation model. Awerbuch’s approach has been improved based on territorial characteristics of the possible contribution that renewable sources can give. The results encourage investment in more technologies based on renewable sources. This can help to reduce the total generation cost at the same level of risk. When nuclear energy is included in the Italian mix, the portfolio composition changes. The energy mix would be characterized by a cost of 9.42 cent V/kW h with 6.07% of risk if one assumes 10% of energy produced by nuclear plants; moreover, 52% of CO2 emissions would be avoided. Nuclear energy would cover 36% of energy production, while renewable energy would be increased (for example, wind should cover 15% of the total production); as a consequence, 66% of fossil plants would be uninstalled. In conclusion, the preventive evaluation of the criticalities deriving from the territory will reduce the negative impacts on the environment or on the community. Pursuing reality and the interests of the local communities is suitable for the potentialities and the constraints of the territorial contest. Geographic Information Systems and cartography will allow elaboration, control, and analysis of the interested areas and evaluation of the characteristics and planning of the energy strategies.

Kim et al. (2012) suggests a model to evaluate the costs of energy systems, including CO2 trading, and applies it to the Korean energy situation. It took into consideration the uncertainties in the learning rates and external factors such as fuel and CO2 prices by performing an MCS. Kim's method can be evaluated as a useful method to estimate unpredictable variables instead of complicated analysis. A "learning effect" concept was introduced to provide cost reduction of the investment cost of the energy systems. Fuel price and CO2 emission cost and the possibility of CO2 trading were considered external factors for the future. With regard to robustness, three scenarios in energy growth rate were adopted, and randomly sampled learning rates, fuel price, and CO2 emission cost were applied. The results of Kim's case study provide several directions for Korean energy planning. They imply that renewable energy systems, especially solar and biomass energy, are essential for satisfying the increasing energy demand in the future. Because Kim's results reflect the realistic Korean energy situation and satisfy the official target of the renewable energy system, it can be of value to decision makers who are planning energy systems. Based on Kim's method, a decision maker can improve the model through supplementary information and more realistic data.

2.4.2 Energy Mix Methodologies Research

There are many methodologies to analyze the economic effects on greenhouse gas reduction and energy sources. Representative methodologies are as follows. Many methodologies and schemes for energy planning have been studied and proposed for optimal energy planning. Most notably, schemes have been introduced by the time-stepped energy system optimization model (TESOM), market allocation model (MARKAL), energy flow optimization model (EFOM), and the inexact community-scale energy model (ICS-EM).

Kydes and Rabinowitz (1981) provide a descriptive overview of the TESOM for energy system analysis, developed at the National Center for Analysis of Energy Systems (NCAES) at Brookhaven National Laboratory (BNL). TESOM is a single-region energy system model, incorporating a sequentially solved series of linear programs (LP). It was developed to quantitatively evaluate national energy technologies and policies within a dynamic system's framework. Examining the interfuel substitution in the context of time-dependent constraints on the availability of competing resources and technologies and their associated costs is one of its goals. TESOM is structured around the Reference Energy System (RES), a specialized format for representing the detailed technological structure of the energy system along with resource consumption and associated environmental emissions. The model satisfies a set of energy service demands as it optimally allocates energy resources and products and selects the optimal mix of fuels and conversion and end-use demand technologies according to user-specified energy, environmental, or economic criteria (usually least cost).

Fishbone & Abilock (1981) introduces a demand-driven, multi-period, linear-programming (LP) model for a national energy systems analysis, the MARKAL model. The technical structure of the model defines the functions determined when satisfying the model's relationships and the parameters that must be supplied to give the model content. Furthermore, MARKAL verifiably does what is intended and provides a valid description of the energy sector of the economy.

MARKAL helps to illuminate the behavior of possible future national energy systems and energy resources in satisfying plausible future demands for useful energy. The introduction of and investment costs for new technologies and resources and the decline of existing resources was discussed. Other factors included were the sensitivity of future energy systems to different goal choices and ordering, with system cost, the amount of imported petroleum and the relative contributions of nuclear, renewable, and fossil resources. Moreover, MARKAL demonstrates the distinguishing modeling features of powerful capabilities for multi-objective analyses, a flexible formulation and streamlined problem size, an improved representation of plant shut-down (both scheduled and unscheduled), an improved fuel-processing representation, with period-to-period fuel-flow lags, and stockpiling of all fuels. Also noteworthy are the detailed modeling of the coupled production of electricity and heat, an automated data-management system for input to MARKAL, and improved hydroelectric and hydroelectric and pumped-storage modeling, with seasonal variations in availability and up to 16 time periods.

According to Hill et al. (1981), many new energy technologies offer the potential of moderating the rising costs of energy while reducing dependence on imported oil. To conduct their evaluation, they used MARKAL. The MARKAL model used in this research is strictly an energy-sector model. Its links to the rest of a nation's economy are primarily through the exogenous specification of energy service demands; there is no model connection to the economy through such techniques as input-output analysis. Energy resources and technology in particular do not depend on demand levels through the model, but simply compete against one another. Moreover, MARKAL is very flexible, optimizing a network representation with respect to several possible criteria. Hill et al. (1981) conclude that the most promising technologies include the light-water reactor, residential and commercial conservation, enhanced oil recovery, shaleqil recovery, industrial cogeneration, the heat pump, and coal liquefaction. Furthermore, this usage yields a decline in oil imports to about half of the present levels.

Chapter 3. Consideration for Energy Planning

In this chapter, we reviewed methodologies for energy planning from an energy economy perspective. The objective of this research is to find an energy portfolio in the electricity industry considering the stability of energy supply and consumption regarding the minimization of social/environmental effects, so the least cost optimization model and mean-variance portfolio model are used among many energy-planning methodologies for this research. This chapter examines how these methodologies—the least-cost optimization model and mean-variance portfolio model—are applied in the energy economics area and limitation of previous methodologies. Furthermore, the model this study proposes which can overcome limitations of previous models will be reviewed, and the way to use this model for optimal energy planning will be determined.

3.1 Models for Energy Planning

Energy is an essential input for economic development of country. With increasing production activities, the demand for energy is also increasing. Although many countries have strived to decrease energy consumption, world consumption of fossil fuels in generating energy has continuously been increasing (Lior, 2010). This increase has caused the depletion of natural resources and the emissions of greenhouse gases, which has resulted in environmental problems (Baños et al., 2011). To solve this problem, many kinds of methodologies are used for national energy planning. Policy makers and researchers have used different optimizing models to make an appropriate energy allocation. When setting long-term energy supply strategy and energy generation mix, sufficient diversification of energy sources is preferred (Delarue et al., 2011). One of the ways to quantitatively determine diversification is the least cost optimization model, a kind of linear programming. During the last decades, energy planning has focused on satisfying energy demand at lower total production costs. However, global warming has become a problem in energy planning, and it is presenting more complex tasks, with many issues to be considered. The only way to reduce greenhouse effects is to make investments in renewable energy systems (e.g., hydro, wind, solar, and biomass). Under this circumstance, the least-cost optimization model is used for minimizing CO2 emission and electricity generation cost. The objective of this model is to minimize social/environmental costs through energy consumption. By reflecting this, the social/environmental effects could be reflected in objective function or constraints. Moreover, if various renewable energies are added, then their effects could be detected. The other method for determining diversification quantitatively is portfolio theory, a mean-variance model. This methodology forms energy mix considering the risk-cost relationship among energy sources from a perspective of stable energy supply. Different electricity generation technologies and fuels are characterized by a certain cost, with a standard deviation on that cost. Correlations between different types of costs can be determined. Accordingly, it is possible to define optimal portfolios, with minimum cost and/or risk levels.

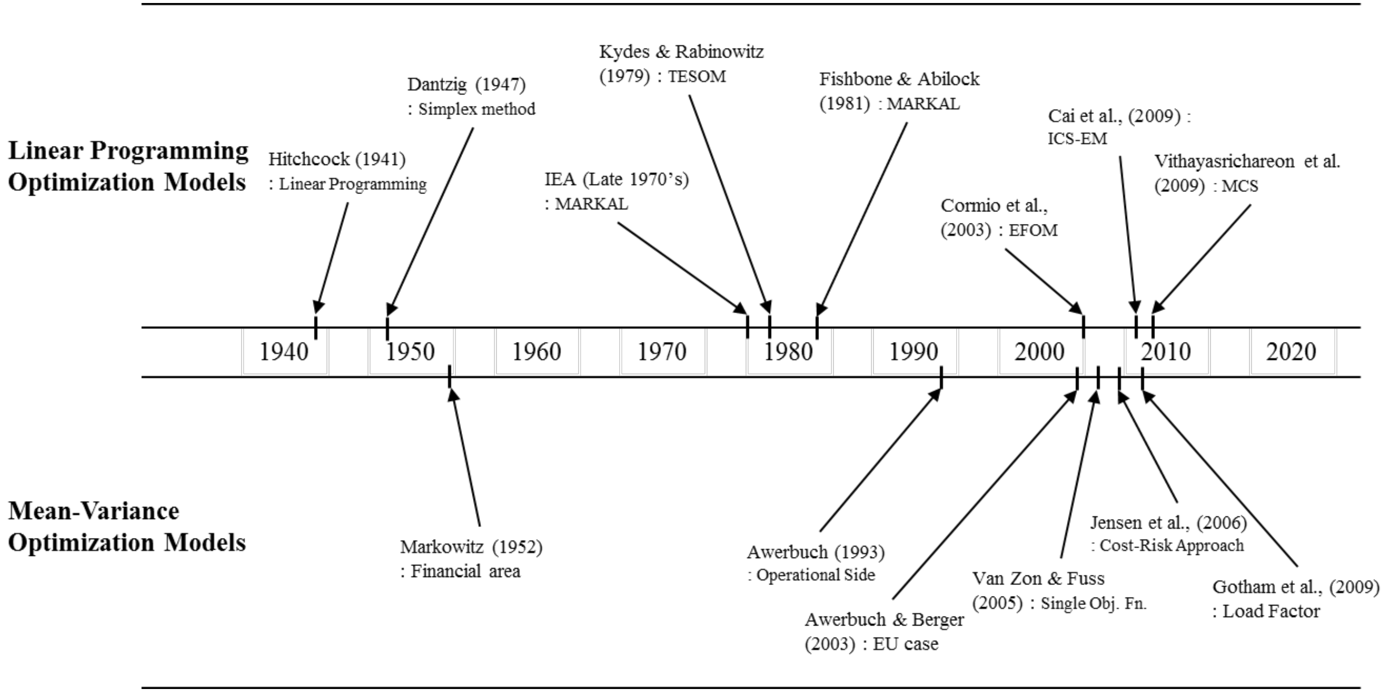


Figure 6. Chronicle of the Linear Programming and the Mean-Variance Optimization Model

Then, classic examples and applications of the two methodologies for energy planning—the least cost model and mean-variance model—will be examined. These models and representative examples of these methodologies for energy planning are presented as follows in Fig.6.

First of all, the least cost optimization model starts with linear programming. This model refers to the problem of determining the optimal value of a linear function subject to linear constraints. Hitchcock (1941) is the first researcher who used this model to solve a problem, and he solved the transportation problem with this model. Since then, Dantzig (1949) recognized the need of the feasible method for solving linear programming problems, and he developed the Simplex method. Other models have applied linear programming to energy planning like MARKAL, TESOM, EFOM, ICS-EM, and so on. MARKAL is the model developed for evaluating technology about energy system with the Energy Technology System Analysis Program (ETSAP) of IEA in the late 1970s. The MARKAL model is an energy supply model, and it is specified to energy supply, conversion, and demand technology as opposed to other energy technology evaluation models. Some models have applied MARKAL to energy planning, like Fishbone & Abilock (1981), Hill et al. (1981), and Kanudia & Loulou (1998). Fishbone & Abilock (1981) described the technical structure of the model, defining the functions determined when satisfying the model's relationships and the parameters that must be supplied to give the model content. Hill et al. (1981) evaluate each technologies, and their study is complex and requires analysis of competition in the marketplace among new and existing technologies over the long term. Kanudia & Loulou (1998) describe a multi-stage stochastic programming approach to formulate a flexible energy plan. They suggest multiple future scenarios and provide corrections depending upon the future uncertainties (Kanudia & Loulou, 1998). Kydes & Rabinowitz (1979) provide an overview of TESOM, used at Brookhaven National Laboratory for energy systems analysis. They highlighted special control theoretic features which include a new-market penetration algorithm. The EFOM model is a dynamic linear programming model which minimizes total supply costs of an energy system under given technology, environment, and economic conditions and optimizes energy supply, energy technology, and energy mix to satisfy given total energy or energy demand simultaneously. Cormio et al. (2003) assert that the modeling framework is improved to modify the model to the characteristics and requirements of the region under investigation in order to support planning policies for promoting the use of renewable energy sources. In particular, they incorporated an exhaustive description of the industrial cogeneration system, which proves to be the more efficient and increasingly spread (Cormio et al., 2003). Cai et al. (2009) develop the ICS-EM for planning REM systems under uncertainty. The develop method has then been applied to a case of long-term REM planning for three communities. They generate useful solutions for the planning of energy management systems and obtain interval solutions associated with different risk levels of constraint violations (Cai et al., 2009).

Furthermore, MCS is used for the linear programming optimization model to reflect the uncertainty of energy. Spinney & Warkins (1996) explore the use of MCS techniques.

They use it as an approach of the electric utility integrated resource planning and assert that MCS and related techniques are capable of addressing many of the limitations of decision analysis. Vithayasrichareon et al. (2009) propose a stochastic method based on the MCS. They explain various uncertainties by using MCS, which can determine the overall generation cost of electricity generation. This method widens old methods to solve the optimal generation mix and solves the probability distribution of the expected generation costs of various generation technology portfolios. The linear programming optimization model explained above reflects the characteristics and optimization methods of each model. Moreover, according to the objective of research on the energy, technology, or environment side, various analyses could be operated by various models. In other words, information about climate change countermeasures like reduction costs, investment size, and R&D investment size for greenhouse gas reduction could be provided.

Next, the mean-variance optimization model is examined as follows. The mean-variance optimization model optimizes not only cost, but also uncertainty or risk of long-term cost flow. This alternative is based on the cost risk efficient portfolio model, which is modified from the efficient diversification model or mean-variance efficient portfolio model by Markowitz (1952), which is widely used in the financial area as an asset allocation method. Bar-Lev & Katz (1976) applied this theory to the electricity sector, and Awerbuch & Berger (2003b) follow this portfolio approach to reflect an optimal generation mix for the EU. In this research, they use a certain expected rate of return

[MWh/€] (inverse of cost) and a certain standard deviation, risk [MWh/€]. Then they test various scenarios with assuming a total amount of installed capacity. The following costs are included in their model: investment costs, fuel costs, and O&M and variable O&M costs (Awerbuch & Berger, 2003b). Other examples that follow this approach are presented in Awerbuch (2006) and Krey & Zweifel (2006).

A second model formulation is proposed by Jansen et al. (2006). The major difference between their approach and that mentioned above lies in the fact that cost and cost risk are both addressed instead of return and return risk. Furthermore, energy produced over a particular period instead of installed power is used, this approach explain some extent for the limited availability of renewable energy sources. Another example that follows this cost based approach is presented in DeLaquil et al. (2005).

Van Zon & Fuss (2005) suggest the development of a classic portfolio method using a single objective function. The total cost consisting of a weighted sum of the overall cost and the corresponding variance is minimized. They also make difference between capacities and generated electric energies on a long-term scale. Huang & Wu (2008) describe this approach in a more detailed way, also using a risk weighted generation cost. They use a load duration curve to define different demand blocks. Gotham et al. (2009) also present a portfolio approach, with divided different load, which have different load factors. This approach explains the effects of different technologies operating in different classes with equivalent load factors. Doherty et al. (2006) present a load duration-based investment model with focus on wind power penetration. They calculate the risk of different portfolios obtained with this model. However, they do not suggest an integrated portfolio theory based investment model (Doherty et al., 2006).

Roques et al. (2008) express an application by using portfolio theory. They assume the environment is a free market. In this study, three base-load technologies (nuclear, coal, and CCGT), three different scenarios (different correlations between fuel, CO_2, and electricity prices) are considered. Huisman et al. (2009) showed an example of portfolio theory under circumstances of the purchase of electricity. In this study, they optimize an overall social standpoint by using this approach.

3.2 Limitations of Previous Approaches

The explained models in the passage above propose a method to set up a problem and to solve this according to each model. These models reflect optimization methods and their characteristics, but they have the following limitations. First of all, the linear programming optimization model does not incorporate recent changes in the nature of renewable energy planning and overall energy sources in a large scale (Kim et al., 2012). Krukanont (2007) considered various uncertainties to analyze the short-term energy planning and suggested several policy regimes but covered a limited renewable energy system. Moreover, the linear programming optimization model is needed to build an enormous database, and exogenous variables like final demand of energy and products are needed as inputs, so if we want to get useful analyzed results from the model, the model needs connection with other models. However, according to linear programming, which is a mathematical structure of the model, there is the risk that an unrealistic result could be drawn when no restriction is made in energy supply or energy technology. Although these days are dynamic environment, there are still classical energy plans to find the least-cost generating alternative in the US and Europe. However, it is probably too hard to identify the 30-year least-cost option. Furthermore, from a least-cost optimization model perspective, previous research did not reflect realistic condition about construction potential. In other words, previous research has drawn a realistically impossible portfolio as an optimal solution because it has not considered physically impossible situations. For example, realizable potential and feasible construction capacity of renewable energy sources are different each other, so they need to be reflected in the model, but many studies overlook realizable potential and set up technical potential as a restriction of renewable energy sources. Therefore, this research indicates that renewable energy is diffused through a technology diffusion pattern in the process of time and a realizable potential suitable for Korea situation as a constraint by using the survey of the experts and IEA (2010)

In the case of the mean-variance optimization model, risk is restricted by fluctuation that occurs by the change of cost, so it is difficult to reflect a situation except for the effects by costs. Because of energy characteristics, there exists various environmental/policy effects together, so energy planning should consider not only the cost, but also the risk for reflecting all situations. In other words, when there exists a riskless energy source regardless of the cost, new change is made, but it is difficult to explain the riskless energy source in the mean-variance optimization model. Moreover, this model focuses on the single-time horizon, so it cannot set up energy distribution assumption during a specific period. However, in fact, there are no cases like this, so it is another limitation. Actually, Awerbuch & Berger (2003b) drew a relationship between risk and return of 2010 future energy mix, projecting current situations and conditions from 2010 rather than reflecting future situations or environment conditions. It is difficult to form a future energy mix reflecting a future situation, but it is more meaningful to reflect the future direction of the energy mix rather than just reflecting the current situation. This kind of problem occurred when the risk in the future energy mix was estimated. That is, when the energy mix was established for a future situation, usually the current situation was just reflected in the future energy mix or the energy ratio was just decided by the researcher’s qualitative decision, so drawing the risk of energy mix by this method could result in a somewhat unrealistic mix according to the future cost and risk energy mix.

Additionally, from a cost-risk optimization model perspective, there are not many works of research about electricity generation composition and generation importance to use cost-risk optimization. In the case of Korea, research about electricity generation mix by the portfolio method or electricity generation mix planning is rare. First of all, Yoon (2008) analyzed which alternative electricity plant is economically better between the new bituminous power plant and the new LNG combined cycle power plant for Korea East West Power Co. However, this research consequently did not show which one is economically better exactly and simply showed that the new coal power plant is relatively better than the new LNG combined cycle plant in the change ratio of cost and risk and also showed that choice could be different in terms of the importance between cost and risk. Moreover, Yoon & Sonn (2008) proposed three alternative strategies for high oil prices—strategic stockpile, oil development, and oil price hedging—and just proposed an optimal budget allocation process for each budget allocation alternative. This research tried very few times to analyze the overall energy portfolio, including both traditional and non-traditional energy and considering their specific cost elements. Therefore, this research is a research of significance to analyze overall energy sources applying the specific cost elements of each energy source. Moreover, the existing cost-risk optimization research sets up electricity generation of energy sources as a ratio and expressed the optimal cost-risk efficient frontier based on the average cost and ratio of each energy source. However, this research has significance in applying a portfolio result drawn from the least-cost optimization model to the cost-risk optimization model and to propose a research process which can reflect actual electricity generation rather than a ratio of generation. Furthermore, this research provides more specific and practical analysis to provide various implications by drawing different optimal solutions from different models. Also, the existing energy or electricity portfolio research usually considers only the cost of electricity for drawing an electricity generation mix. Even though the equation of electricity cost contains carbon cost terms and reflects the external effect of carbon, it has limitations in that other external or environment effects could not be reflected. However, this research forms an overall electricity generation mix model that reflects external cost, environment effect, and variation of energy sources, fuel, and carbon price, to which previous research did not have access. With regard to deciding energy policy, one of the most important factors of consideration is the minimization of energy cost, and another factor is the minimization of the risk the energy sources may present. Therefore, this research proposes the long-term direction of the electricity demand-supply problem by composing an optimal portfolio by both cost and risk perspectives and proposes the life cycle cost for the electricity generation mix and its method.

3.3 Solutions for Energy Planning

Based on the limitations and applications of the linear programming optimization model and mean-variance optimization model for energy planning, the question arises of whether or not the energy mix, produced through this process, is practical and if energy planning meets its purpose. Therefore, according to the needs of a model that realizes a practical situation and can apply the policy/environmental effect, this study presents a model that connects linear programming optimization and mean-variance optimization model.

First, we suggested energy planning to minimize the social and environmental impacts by using the least-cost optimization model. We applied both conventional energy (e.g., coal, gas, and nuclear) and renewable energy (e.g., wind, hydro, solar, biomass) to the least-cost optimization model. Second, we considered the Korean government's policies and plans for improving the reality of analysis. Then, the uncertainty of fuel price and CO2 price and the learning rate of newly-constructed generating plants were applied to this study by using MCS. With MCS, uncertain variables were effectively estimated.

Third, in the case of renewable energy, the capabilities of the construction of generating a unit for sources of energy are largely various depending on the level of technology and the environment. In order to adjust and apply this to the circumstances in Korea, we used the technology diffusion theory and experts' survey. By using the estimated capabilities of energy sources, we applied them to the model. As a result, we could derive relatively more realistic and rational results. Previous research did not consider the potential supply of renewable energy and in turn ended up with unrealistic results. To improve this circumstance, the realizable potential of renewable energy sources were estimated and reflected annually.

Fourth, the result from the least-cost optimization model, year 2030 portfolio was used in the cost-risk optimization model. By doing this, we secured the objective reasons for the ratio of energy sources. This is the energy portfolio with stable supply considering the risk of energy sources and the correlation of energy sources, which is derived by using the energy distribution, which minimized the social and environmental impacts. This is a very important approach, as both the production and consumption of energy were considered. Thus, the analysis reflected two principles required for sustainable growth and suggested the way to constitute the realistic optimal portfolio in which the current situation is reflected.

This study obviously suggested on which area of the efficient frontier the portfolio should exist in order to have an optimal cost-risk portfolio, by using the result of the least cost optimization model. By doing so, we made a rational suggestion about how to constitute the energy portfolio to achieve sustainable growth.

Therefore, this study suggested the path that will be able to reach an optimum energy mix by connecting the models of each other even though the characteristic and the point of view regarding the optimization method of existing models are different.

The purpose of this study, as mentioned above, consisting of an energy mix that minimizes the social/environmental effect, generating energy consumption as well as supplying stable energy that is necessary for sustainable development. Thus, it should consider the problem of minimizing the cost by energy usage and the relationship and the degree of risk of these energies. Therefore, the method is setting a model that reflects the practical policy/environmental situation and presenting the energy planning that can minimize the effects generated by energy consumption. Based on this result, it is possible to form energy planning that helps stabilize the energy supply, applying the relationship between energy sources and the risk of energy cost change.

Then, the relatively high costs of renewable energy systems and the uncertain outlook of their rate of diffusion in the market make it difficult to rely heavily on them. The uncertain variations in production cost over time are especially challenging. To handle uncertainties, in this study, the concept of the learning rate was adopted so as to compute the costs of energy systems in the future, and MCS was performed. As mentioned above, the first aim of this study was to optimize plans of conventional and prospective renewable energy systems with respect to production cost. The production cost included investment, O&M, fuel, and CO2 costs. The results of the case study in which the proposed methodology was applied could provide useful economic insights and strategies of sustainable energy management for ambiguous environments.

To carry out the above mentioned objectives, this research analyzed effective allocation of energy sources for sustainable development. For this purpose, this research formed an optimal energy portfolio in the electricity generation industry with major energy sources—3 conventional energy sources (coal, natural gas, and nuclear) and 4 non-conventional energy sources (hydro, wind, photovoltaic, and biomass)—by using two different perspectives: the least-cost optimization model and cost-risk optimization model. Moreover, this research suggests a response strategy of the electricity generation industry related to climate change based on the results of this research by forecasting electricity portfolio change, carbon emission reduction, and cost change according to various economic, social, and policy changes related to climate change. So, this research differs from previous strategy research on climate change response, which usually suggests technical efficiency or the overall strategic direction of the electricity industry.

The strategy analysis method about the climate change response of the electricity industry and results drawn from their specific analysis proposed in this research are expected to be used as follows. First, baseline data could help to establish strategy or technology development direction of renewable energy adoption by climate change policies and to understand appropriate renewable energy sources to the Korean economical and technological environment or climate change or environment policies. As a result, this research is expected to contribute to the Korean renewable energy industry competitiveness responding actively to climate change or environmental policies. Second, this research is expected to provide baseline data for establishing various strategies to respond to climate change or environment policies by analyzing transition costs to renewable energy and comparing greenhouse gas reduction or reduction cost according to the expansion of renewable energy sources.

This research is a study of significance to suggest new strategy research analysis methodology in the frame of the electricity generation industry sector’s counterstrategy research related to climate change. Furthermore, the climate change counterstrategy research analysis methodology proposed in this research presents strong possibility for use with regard to drawing a counterstrategy considering domestic economic, social, and political change.

Chapter 4. The Model Formulation

The model used in this research and the specification of this model will be examined in this chapter. First of all, the least-cost optimization model for drawing minimized generation cost and the objective function of electricity generation constitution will be examined, and then the cost-risk optimization model for minimizing cost and risk mix considering cost and risk of each alternative under budget constraints will be examined.

4.1 Least-Cost Optimization Model

The least-cost optimization model is a method which decides the minimized cost of the objective function and the cost function under given constraints. The methods for finding an optimal solution and objective function and constraint conditions used in this research are as follows.

4.1.1 Methods for Finding Optimal Solution

Optimization deals with finding the optimal solution to problems. Generally, it can be expressed in the form of an objective function which needs to be optimized and a set of constraints which gives limitation to decision variables. Many optimization approaches are available. Linear programming is a classical tool and is the most popular optimization method that assumes the objective function and constraints are expressed in linear functions. However, practical problems in the real world are too complex to express in linear functions, so many researchers have developed solution procedures for complex systems that are referred to as simulation-based meta-heuristic optimization (Glover, 1996).

Simulation-based metaheuristic optimization is the process of searching for the best set of model specifications (i.e., input parameters and structural assumptions) in which the objective value is the output performance of the simulation model for the underlying system (Swisher et al., 2000). Simulation-based optimization has been widely used in different fields (Jain et al., 2011). In this paper, a simulation-based metaheuristic optimization approach is used for minimizing an objective function according to the operational constraints of the electric power system.

Optquest uses different optimization search strategies. Therefore, one of the most important phases for solving problems is to choose an efficient and suitable optimizer.

Table 3. Commercial Optimization Packages Embedded Within Simulation Software Products

Optimization Package	Vendor	Simulation Software	Search Strategy
OptQuest	OpTek.Inc	Crystal Ball, Arena, Flexim, Promodel, Quest, Simul8	Scatter search, Tabu search, Neural networks
SimRunner2	Promodel Corp	Promodel	Evolution strategies, Generic Algorithms
Witness Optimizer	Lanner Group Inc	Witness	Simulated annealing, Tabu search

AutoStat	Brooks Automation	AutoMod, AutoSched	Evolution strategies
Extend Optimizer	Imagine That	Extend	Evolution strategies

Source: Law (2007)

Several works of research have investigated the performance of these packages. Jafferali et al. (2005) compare Optquest and Simrunner, commercial optimizers, regarding quality of results and computational time. They find that Optquest produced better results when computation time is considerable. However, when computational time is limited, Simrunner is better. Jain et al. (2011) compare Optquest and Witness Optimizer. They find that both found near-global optimal solutions in an acceptable computation time. Specifically, they found that Optquest could provide a little better quality solutions when a large number of solution evaluations are allowed.

According to these studies, with considerable time to find an optimization portfolio for the electric power system, Optquest was used.

The Optquest package is consists of three famous search heuristics: scatter search as its main search strategy, tabu search as a secondary method, and neural networks as the last method. Scatter search applies heuristic processes to generate a starting set of solution vectors and designate a subset of best vectors to be reference solutions. Then the algorithm forms the linear combination of subsets of current reference points and generates new points. In the next step, the scatter search algorithm selects a combination of the best solutions, uses them as starting points for a new application of the heuristic processes, and repeats these steps until a specified number of iterations or stopping criteria are reached. Tabu search uses adaptive memory to prohibit the search from reinvestigating solutions that have already been evaluated and to guide the search to a globally optimal solution. Neural network is used to screen out solutions that are likely to be poor without allowing the simulation to evaluate them. The neural network is used as a prediction model to help the system accelerate the search by avoiding the need for evaluating objective function for a newly created reference point in situations during which the objective value can be predicted to be of low quality (Jain et al., 2011).

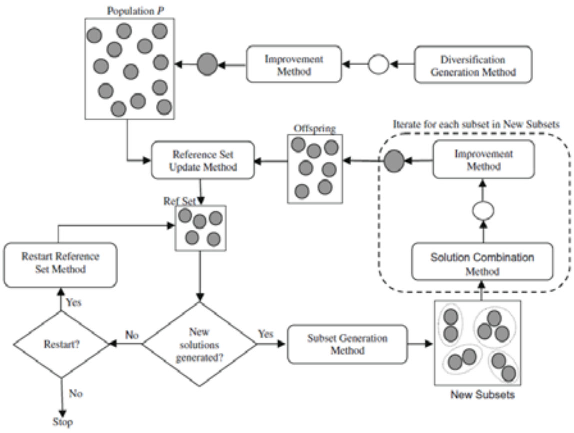
Each search heuristic is explained in detail as follows.

4.1.1.1 Scatter search[5]

Scatter search is introduced by Glover (1977) and it has been applied to complex optimization problems. The procedure of scatter search is as follows: 1) A diversification generation method is employed to generate a collection of diverse trial solutions, using an arbitrary trial solution (or seed solution) as an input, 2) An improvement method is applied to transform a trial solution into one or more enhanced trial solutions (neither the input nor the output solutions are required to be feasible, though the output solutions will more usually be expected to be so. If no improvement of the input trial solution results, the “enhanced” solution is considered to be the same as the input solution), 3) A reference set update method is applied to build and maintain a reference set consisting of the b

[5] This chapter is reorganized by citing Glover et al., (2003) and Moghaddam et al. (2010)

“best” solutions found (where the value of b is typically small; e.g., no more than 20), organized to provide efficient accessing by other parts of the method. Solutions gain membership to the reference set according to their quality or their diversity, 4) A subset generation method is employed to operate on the reference set and to produce a subset of its solutions as a basis for creating combined solutions, and 5) A solution combination method is used to transform a given subset of solutions produced by the Subset Generation Method into one or more combined solution vectors.



Source: Moghaddam et al. (2010)

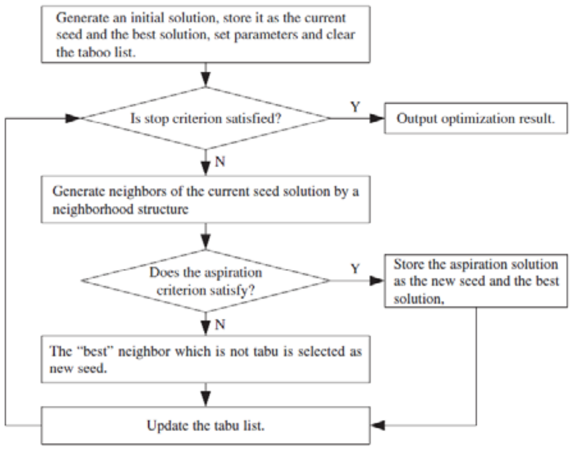
Figure 7. Sketch of Scatter Search Algorithm

4.1.1.2 Tabu search[6]

The tabu search, defined and developed by Glover (1996), and it has been applied to many combinatorial optimization problems. Tabu search is an enhancement of the well-known hill-climbing heuristic, which uses a memory function to avoid being trapped at a

[6] This chapter is reorganized by citing Zhang et al. (2007)

local minimum. The tabu search procedure is generally simple. The procedure starts with a feasible initial solution and stores it as the current seed and the best solution. The neighbors of the current seed are then produced by a neighborhood structure. These are candidate solutions. They are evaluated by an objective function and a candidate which is the best not tabu or that satisfies the aspiration criterion selected as the new seed solution. This selection is called a move and is added to the tabu list and another (the oldest one) move is removed from the tabu list if it is overloaded. If the new seed solution is better than the current best solution, it is stored as the new best solution. Iterations are repeated until a stop criterion is satisfied.



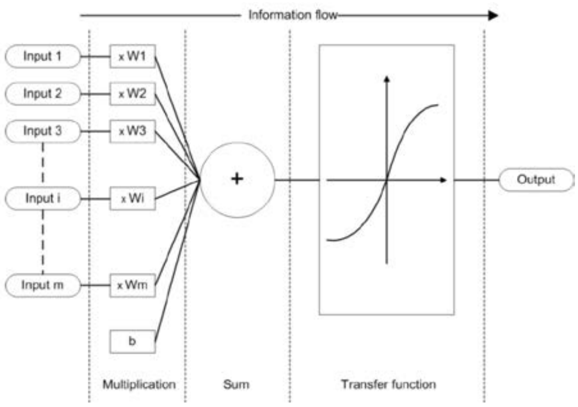
Source: Zhang et al. (2007)

Figure 8. Sketch of Tabu Search Algorithm

4.1.1.3 Neural network[7]

[7] This chapter is reorganized by citing Krenker et al., (2011)

Neural network is a mathematical model inspired by biological neural networks. Neural networks are used to model complex relationships between inputs and outputs or to find patterns in data. The basic building block of every neural network is the artificial neuron; that is, a simple mathematical model (function). Such a model has three simple sets of rules: multiplication, summation, and activation. At the entrance of the artificial neuron, the inputs are weighted, which means that every input value is multiplied with an individual weight. In the middle section of the artificial neuron is the sum function of all weighted inputs and bias. At the exit of the artificial neuron, the sum of the previously weighted inputs and bias passes through the activation function that is also called the transfer function.



Source: Krenker et al. (2011)

Figure 9. Working principle of Neuron Networks

The basic neuron networks model described in mathematical description is as follows.

$$y(k) = F\left(\sum_{i=0}^{m} w_i(k)\cdot x_i(k) + b\right)$$

- $x_i(k)$ is input value in discrete time k where i goes from 0 to m
- $w_i(k)$ is weight value in discrete time k where i goes from 0 to m
- b is bias
- F is a transfer function
- $y_i(k)$ is output value in discrete time k

As seen from a model of an artificial neuron and its above equation, the major unknown variable of our model is its transfer function. Transfer function defines the properties of the artificial neuron and can be any mathematical function. We choose it on the basis of the problem that the artificial neuron (artificial neural network) needs to solve, and in most cases, we choose it from the following set of functions: step function, linear function, and nonlinear Sigmoid function.

4.1.2 Objective Function

According to the method commonly practiced for economic evaluation, the total cost of the production can be expressed as the summation of the investment, O&M, fuel, and carbon costs (Douglas 1988; Cormio et al., 2003; Koo et al., 2011).

$$Prodiction\ Cost = Investment\ Cost + Fixed\ Cost + Fuel\ Cost + Carbon\ Cost \quad (1)$$

$$Investment\ Cost = \sum_{t=1}^{N_t} \frac{1}{(1+d)^t} \times Capital\_C \times I_t \quad (2)$$

$$O\&M\ Cost = \sum_{t=1}^{N_t} \frac{1}{(1+d)^t} \times O\&M\_C \times C_t \quad (3)$$

$$Fuel\ Cost = \sum_{t=1}^{N_t} \frac{1}{(1+d)^t} \times Fuel\_C \times C_t \times \tau \quad (4)$$

$$Carbon\ Cost = \sum_{t=1}^{N_t} \frac{1}{(1+d)^t} \times CO2\_C_t \times C_t \times \tau \times R \quad (5)$$

N_t	total years (2012-2030) [-]
d	discount rate [-]
C_t	cumulative capacity [MW]
I_t	installed capacity [MW]
τ	capacity factor [h] = 8760 × utilization factor
$Investment\_C$	investment cost [USD/MW]
$O\&M\_C$	O&M cost [USD/MW]
$Fuel\_C$	fuel cost [USD/MWh]
$CO2\_C$	CO2 cost [$/tCO2]
R	emission rate [tone/MWh]

Among the variables described above, investment cost could bring about a cost reduction effect through learning by doing. Kobos et al. (2006) show that performance improves as capacity or a product expands. Soderholm & Sundqvist (2007) assert that learning can also be regarded as the cost-reducing effect in energy systems. Empirical studies showed that learning by doing is influenced by cumulative capacity, C_t

(Soderholm & Sundqvist, 2007; McDonald & Schrattenholzer, 2001; Koo et al., 2012). Cumulative capacity and the investment cost reflected learning effect can be expressed as follows.

$$C_t = C_0 + \sum_{t=1}^{N_t} I_t \quad (6)$$

$$Investment\ Cost = \sum_{t=1}^{N_t} \frac{1}{(1+d)^t} \times \left(\frac{C_t}{C_0} \right)^{\alpha_t} \times Capital\_C \times I_t \quad (7)$$

C_0 means the initial generation capacity in the base year, and α_t refers to the learning effect according to the time. The learning effect has an influence just on investment cost, because O&M, fuel, and carbon cost do not depend on experience (Koo et al., 2011). $\alpha_{e,t}$ varies according to the specific energy system, and expression of this is as follows.

$$\alpha_{e,t} = \frac{\ln\left(1 - \frac{\beta_{e,t}}{100}\right)}{\ln 2} \quad (8)$$

$\beta_{e,t}$ is the learning rate for the each energy system of interest at time t. In this research, learning rates data of Soderholm & Sundqvist (2007), McDonald & Schrattenholzer (2001) are used. For the reliable estimation of learning rate, the value is sampled using by Monte Carlo method. Therefore, constituted energy production cost function with applying equation (7) is as follows.

$$
\begin{aligned}
&\textit{Production Cost} \\
&= \sum_{e=1}^{N_e}\sum_{t=1}^{N_t}\frac{1}{(1+d)^t}\times \left\{ \begin{aligned} &\left(\frac{C_{e,t}}{C_{e,0}}\right)^{\alpha_{e,t}} \times I_{e,t} \times Investment\_C_e + \\ &C_{e,t}\left(O\&M\_C_e + \tau_e \times Fuel\_C_{e,t} + \tau_e \times R_e \times CO2\_C_t\right) \end{aligned} \right\} \quad (9)
\end{aligned}
$$

$$
I_{e,t} = \underset{\forall e,t}{\arg min}\ (Total\,Cost)
$$

4.1.3 Constraints

Constraints are divided into physical constraints and policy constraints. Physical constraints consist of renewable energy generation limit and energy demand, and policy constraints consist of renewable energy supply obligation and photovoltaic system supply obligation by RPS and CO2 emission reduction management.

4.1.3.1 Physical Constraints

4.1.3.1.1 Realizable Limits of Renewable Energy Sources

Unlike traditional energy, renewable energy is handled in this research like hydroelectric, wind power, photovoltaic, and biomass, as it cannot be constructed unlimitedly. Therefore, this research set up the generation potential[8] of renewable energy

---

[8] It represents the actual amount of renewable energy that can be generated in each year.

during each year considering the realizable potential[9] of each renewable energy source to reflect realistic electricity generation.

Expressions of generation constraint of each renewable energy source reflecting realizable potential in each year are as follows.

$$\sum_{hydro}\sum_{t=1}^{N_t} I_{e,t} + C_{hydro,0} \le RP_{hydro,t} \qquad (10)$$

$$\sum_{wind}\sum_{t=1}^{N_t} I_{e,t} + C_{wind,0} \le RP_{wind,t} \qquad (11)$$

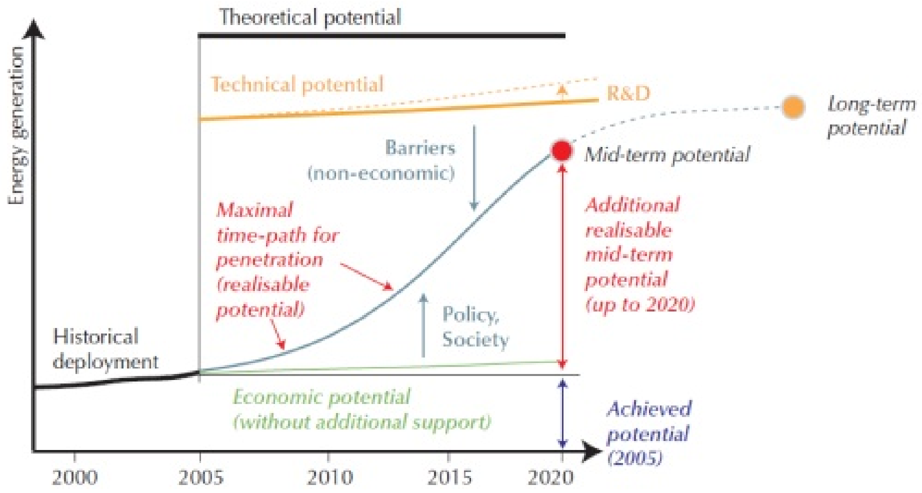
$$\sum_{solar}\sum_{t=1}^{N_t} I_{e,t} + C_{solar,0} \le RP_{solar,t} \qquad (12)$$

$$\sum_{biomass}\sum_{t=1}^{N_t} I_{e,t} + C_{biomass,0} \le RP_{biomass,t} \qquad (13)$$

$RP_{e,t}$	Realizable potential of each energy (2012-2030) [-]

Renewable energy generates electricity under the realizable potential constraints described above. According to IEA (2008), realizable potential of renewable energy sources follow a technology diffusion model like Fig. 10. Therefore, generation potential of each renewable energy source sets a ceiling with realizable potential and can be estimated every year.

[9] The realizable potential represents the maximum achievable potential, assuming that all existing barriers can be overcome and all development drivers are active. In this respect, general parameters such as market growth rates and planning constraints are taken into account. It is important to note that realizable potential is also time dependent; it must relate to a certain year.



Source: IEA (2008)

Figure 10. Metrics relating to RET Potentials

For estimation, realizable potential of each renewable energy sources is set by the 2010 New & Renewable energy and IEA (2008) data, and then generation potential is estimated by using a survey of the experts. The generation potential of each renewable energy source will be explained concretely in paragraph 4.3.2

4.1.3.1.2 Energy Demand (Korea's 5th Basic Plan of Long Term Electricity Supply & Demand)

The energy planning should be able to satisfy the energy demand. This research sets up industrial, residential, commercial electricity demand, and supply based on the 5th electricity demand and supply program data. The equation of this is as follows.

$$\sum_{e=1}^{N_e}\sum_{t=1}^{N_t}\left\{(1+k)C_{e,t}\times\tau_e\right\}\geq\psi\sum_{t=1}^{N_t}\sum_{sector}\left\{(1+g)^t ED_{sector,t}\right\} \quad (14)$$

$ED_{sector,t}$	energy demand of each sector (2012-2030) [MWh]
ψ	level of energy supply target [-]
g	energy demand growth rate [-]
k	loss factor [-]

$ED_{sector,t}$ is the energy demand of each sector. g and ψ are used for estimating future energy demand. g is the energy demand growth rate and ψ is the level of energy supply target, which can be regarded as a buffer. k is the loss factor, due to the transmission loss and internal use of electricity.

4.1.3.1 Politic Constraints

4.1.3.1.1 Total Supply of Renewable Energy

RPS is a system that imposes renewable energy supply obligation at a certain rate of total electricity generation to electricity producers. It is implemented in Korea from 2012, and photovoltaic, wind power, hydroelectric, fuel cell, ocean energy, etc., are applicable energy sources. Supply obligators should supply 2% of the total electricity generation with renewable energy generation in 2012 and 10% of the total electricity generation with renewable energy in 2020.

Constraint condition like this situation is expressed as an equation as follows.

$$\left(\sum_{RE}\sum_{t=1}^{t} I_{e,t} + C_{e,0}\right)\times \tau_e \geq RPS_t \times \left(\sum_{e=1}^{N_e}\sum_{t=1}^{t} I_{e,t} + C_{e,0}\right)\times \tau_e,\ \forall t \quad (15)$$

RPS_t	obligation rate of renewable energy supply (2012-2030)

4.1.3.1.2 Supply of Solar PV

The Korean government set solar PV obligation supply and plans to supply solar PV energy by 2017.

$$\left(\sum_{t=1}^{t} I_{PV,t} + C_{PV,0}\right)\times \tau_{PV} \geq RPS_{PV,t},\ \forall t \quad (16)$$

$RPS_{PV,t}$	obligation amount of Polar PV (2012-2017)

4.1.3.1.3 CO_2 Reduction Quantity

Greenhouse gas reduction target management is a system to manage the greenhouse reduction plan by assigning businesses which emit much greenhouse gas as managed businesses and deciding a reduction target for each managed business based on low-carbon green growth law. Korea decided sectorial, industrial, yearly greenhouse reduction target on July 2011. This reduction plan will reduce greenhouse gases in the industrial sector by 18.2%, the energy conversion sector (electricity generation) by 26.7%, the transportation sector by 34.3%, the construction sector by 26.9%, and the forestry and fishery sector by 5.2% according to the 2020 emission estimation business as usual (BAU), and overall nationally 30% of it will be reduced by the plan until 2020. The energy conversion sector including the electricity generation industry is set to be reduced by 26.7% of 2020 greenhouse gas BAU according to the plan. The 2020 BAU of energy conversion sector is estimated at 255 million tCO2, and reduction obligation quantity is estimated at 68 million tCO2.

Therefore, this research will estimate the electricity generation of each energy source to minimize the electricity generation cost by reflecting RPS and greenhouse gas reduction target management as described above. The equation reflecting greenhouse gas reduction target management is as follows.

$$CO2trd_t = CO2tg_t - \sum_{e=1}^{N_e} \left(C_{e,t} \times R_e \times \tau_e \right), \ \forall t \quad (17)$$

$CO2trd_t$	amount of CO2 emission traded [tone]
$CO2tg_t$	CO2 emission target [tone]

$CO2trd_t$ in equation (17) means yearly CO2 trading volume. This can be reflected as cost in production cost of equation (9), explained above. The final equation of total cost function applying this is as follows.

$$
\begin{aligned}
&Total\ Cost \\
&= \sum_{e=1}^{N_e} \sum_{t=1}^{N_t} \frac{1}{(1+d)^t} \times \left\{ \begin{aligned} &\left(\frac{C_{e,t}}{C_{e,0}} \right)^{\alpha_{e,t}} \times I_{e,t} \times Investment\_C_e - \left(CO2\_C_t \times CO2trd_t \right) \\ &+ C_{e,t} \left(O\&M\_C_e + \tau_e \times Fuel\_C_{e,t} + \tau_e \times R_e \times CO2\_C_t \right) \end{aligned} \right\} \quad (18)
\end{aligned}
$$

$$
I_{e,t} = \underset{\forall e,t}{\arg min}\ (Total\, Cost)
$$

4.2 Cost-Risk Optimization Model

The cost-risk optimization model decides an alternative which minimizes cost and risk mix considering the cost and risk of each alternative in given budget constraints.

4.2.1 Objective Function

Portfolio theory was initially conceived in the context of financial portfolios, where it relates expected portfolio return to expected portfolio risk, defined as the year-to-year variation of portfolio returns. It is assumed that choosing the least risk portfolio among portfolios will have the same level of expected cost or choosing the least-cost portfolio among portfolios will have the same level of risk.

The portfolio of minimum cost can be determined by minimizing portfolio cost. Average cost can be expressed as follows.

$$Expected\ Portfolio\ Cost = \sum_{e=1}^{N_e} X_e \cdot CT_e \quad (19)$$

$$X_{e,t} = \frac{C_{e,t}}{\sum_{e=1}^{N_e} C_{e,t}} \quad (20)$$

$$CT_e = \sum_{e=1}^{N_e} C_{e,k} = Investment\ Cost_e + O\,\&\,M\ Cost_e + Fuel\ Cost_e + Carbon\ Cost_e \quad (21)$$

X_e	the share of energy e in portfolio
CT_e	expected levelized generating costs of energy e [$/MWh]
$C_{e,k}$	cost component k of energy e

Portfolio risk is always estimated as the standard deviation (σ) of the holding period returns (HPRs) of future generating cost streams. The HPR is defined as follows.

$$HPR = \frac{EV - BV}{BV} \quad (22)$$

EV	ending value
BV	beginning value

EV can be taken as the cost in year *t+1* and BV as the cost in year *t*. HPRs measure the rate of change in the cost stream from one year to the next. The total risk of energy e is composed of the risks of different cost categories k.

$$\sigma_e = \sqrt{\sum_{k=1}^{N_k} \sigma_{e,k}^2} \quad (23)$$

σ_e	cost risk of energy e [\$/MWh]
$\sigma_{e,k}$	cost risk of cost category k of energy e [\$/MWh]

Correlations exist between the different cost categories k of the different energies i. The following formulation for the correlation ρ_{ih} between the total costs of two energies i and h, with cost components k,

$$\rho_{ih} = \frac{\sum_{k=1}^{N_k}\sum_{l=1}^{N_l} \rho_{kl,ih} \cdot \sigma_{i,k} \cdot \sigma_{h,l}}{\sigma_i \cdot \sigma_h} \quad (24)$$

$\rho_{kl,ih}$	correlation between cost categories k and l, for energies i and h [-]

Therefore, expected portfolio risk is as follows.

$$Min\,Expected\ Portfolio\,Risk = \sigma_p = \sqrt{\sum_{i=1}^{N_i}\sum_{h=1}^{N_h} X_i \cdot X_h \cdot \rho_{ih} \cdot \sigma_i \cdot \sigma_h} \quad (25)$$

4.2.2 Constraints

In this research, the following constraints for cost-risk optimization model analysis are added to constraints set previously used by the least-cost optimization model.

$$\sum_{e=1}^{N_e} X_{e,t} = 1 \quad (26)$$

First of all, equation (26) means that the sum of the ratio of all energy sources should be 1. The existing cost-risk optimization model assumes the ratio of each energy source and applies these to constraints and objective function directly. However, this research applies the ratio of each energy source generation to total energy generation. The second constraint equation (27) is a constraint condition of the ratio of each energy source. The ratio of all energy sources should be greater than 0 and smaller than 1.

$$0 \le X_{e,t} \le 1 \quad (27)$$

The last constraint is related to the expected portfolio cost explained previously by equation (19). The sum of each energy source generation ratio multiplied by the expected cost of it means the total average cost. The equation demonstrating this is as follows.

$$E(c_p) = \sum_{e=1}^{N_e} X_e \cdot E(c_i) \quad (28)$$

Three constraints explained above and the constraints used for the least-cost optimization model in paragraph 4.1.3 are used to estimate the cost-risk optimization model. Risks of renewable energy generation technologies are low because they are fuel-less O&M-cost, low-risk, passive, and investment intensive. On the other hand, risks of fossil fuel generation are high because of the variation of fuel cost. Also, the cost of fossil fuels is correlated with each other, so fossil fuel-oriented mix is exposed to the large risk of fuel cost. However, renewable energy technologies use separate natural energy sources, so exposed risk is relatively low.

This research applies the estimated electricity generation of each energy source by the least-cost optimization model in 4.1.3 to the cost-risk optimization model to figure out how effective the portfolio by least-cost optimization model is compared to the portfolio by cost-risk optimization and to find out how effective the portfolio is that considers a tradeoff between cost and risk.

4.3 Data

4.3.1 Production Cost

Many previous studies (Douglas, 1988; Cormio et al., 2003; Koo et al., 2011) expressed the total cost of the production as the summation of the investment, O&M, fuel, and carbon costs. This research uses data for each energy source to calculate the production cost from various works of research. A description of each source of data is found in Appendix 2. The data about each energy source is as follows.

Table 4. Investment, O&M Cost, CO2 Emission Rate, Capacity Factor, Initial Capacity

Energy Sources	Investment cost* [$/MW]	O&M cost* [$/MWh]	CO2 emission rate** [t/MWh]	Capacity factor*** [h]	Initial capacity‡ [MW]
Gas	673000	4.45	1,154	7,621	21740
Coal	929000	4.04	1,965	7,446	25128
Nuclear	1924000	9.68	631	7,884	18715
Hydro	3951700	18.81	234	4,642	1717
Wind	3498000	22.12	127	2,890	406
Solar	4600000	40.38	57	2,190	554
Biomass	4334000	48.05	793	7,271	96.8

Source: * Conventional Energy: IEA (2010), Renewables: KEPCO (2010), ** Kim et al., (2012), *** EIA (2012), ‡ EPSIS (Electric Power Statistics Information System, http://epsis.kpx.or.kr)

The fuel cost of each energy sources is as follows.

Data of IEA (2010) and Korea Power Exchange is used for fuel cost. This research uses MCS to generate fuel cost of each energy sources reflecting uncertainty.

Table 5. Mean and Standard Deviation of Fuel cost

[$/MWh]	Coal	Gas	Nuclear	Hydro	Wind	Solar	Biomass†
Mean	40	110	4	0[10]	0[4]	0[4]	24
Std.	3	5	1	0	0	0	5

Source: EPSIS (Electric Power Statistics Information System, http://epsis.kpx.or.kr), †: Kim et al (2012)

[10] In case of hydro, wind, solar, fuel price for electricity generation is assumed to be zero.

Learning rate of each energy sources in equation (8) are also treated as uncertain variable like fuel price, and then learning rate is generated yearly by MCS. The learning rate of each energy source is as follows.

Table 6. Learning Rate of Energy

	Coal	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Mean	6.3	10.6	5.9	3.8	13.1	28.2	15
Std.	2.4	9.2	0.1	1.9	5.2	6.6	0.3

Source: Kim et al., (2012)

4.3.2 Realizable Potential

This research sets up yearly renewable energy generation potential considering the realizable potential of each renewable energy source, including nuclear, to reflect the realistic generation of renewable energy.

Previous portfolio research reflected the unrealistic situation in which conventional energy is not produced anew by not considering realistic conditions of each nation such as a construction environment to produce energy[11]. However, in the case of renewable energy, the current renewable energy technology, current construction conditions, and expected future situation should be reflected to consider various realistic conditions for power plant construction.

[11] Plenty of least-cost optimization models show the result that conventional energy is not generated under renewable portfolio standard restriction, because conventional energy cost is much more expensive than renewable energy by carbon trading price.

For this reason, the technology diffusion model, which considers realizable limits proposed by IEA (2008), is reflected in this research. The yearly generation potential of each renewable energy source imposed a ceiling on realizable potential is estimated by a survey of the experts. Data about the 2010 New & Renewable energy is used for realizable potential of renewable energy sources. An experts' survey was conducted among 50 experts in the electricity generation sector. This survey presented the current installed capacity of each renewable energy source and its realizable potential and then asked what percentage of realizable potential will be the yearly generation potential for each renewable energy source until 2030 by considering renewables' technology level and realistic construction conditions.

The estimated yearly generation potential of renewable energy sources by using Gompertz model with survey data is as follows.

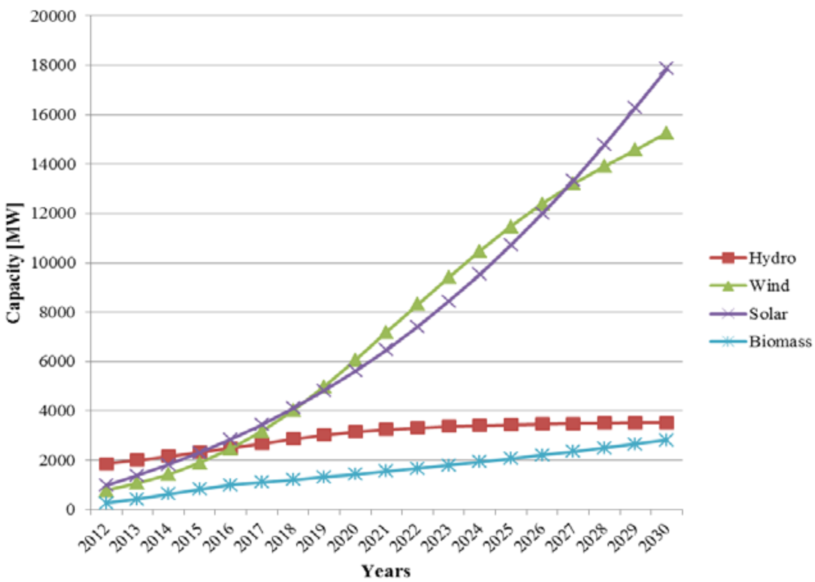


Figure 11. Potential Limits of Renewable Energy

Realizable limit and generation limit of each renewable energy sources including nuclear energy are organized in the following table.

Table 7. Realizable Limit, Generation Limit of Renewable Energy

Energy Sources	Realizable Limit † [MW]	Generation Limit [MW] 2015	2020	2025	2030
Nuclear	-	23953	30532	37278	43926
Hydro	23821	2319	3138	3439	3513
Wind	57340	1882	6053	11468	15257
Solar	2071838	2304	5609	10717	17865
Biomass	14896	817	1423	2062	2809

Source: † Korea Energy Management Corporation (2010)

4.3.3 Energy Demand

This research forecasts electricity demand based on the 5th electricity demand and supply plan, because the 6th electricity demand and supply plan has not yet been announced. According to the 5th electricity demand and supply plan, electricity demand is estimated to increase by 3% yearly. Therefore, this research assumes that electricity demand increases by 3% yearly from the 2009 electricity demand and sets up electricity demand from 2011 to 2030. In addition, data used in equation (14) are organized within the table below.

Table 8. Demand, Growth rate, Loss Factor, Discount Rate

Energy Demand [MWh]	Energy Growth rate	Energy supply target level	Loss factor	Discount rate
474,158,832	3%	1.1	0.06	0.05

Source: Ministry of Knowledge Economy (2010)

4.3.4 RPS Obligation Rate and Solar PV Supply

Korea implemented RPS from 2012. According to policy, 10% of total electricity generation should be supplied by renewable energy until 2022. This research assumes that the renewable energy supply obligation ratio will be 11% by 2030. In addition, photovoltaic supply obligation will exist for 5 years by 2017. The organized data regarding these figures are given in the table below.

Table 9. RPS Obligation Rate

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
RPS rate	2%	3%	3%	4%	4%	5%	6%	7%	8%	9%
Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	
RPS rate	10%	10%	10%	10%	10%	10%	10%	10%	11%	

Source: Korea Energy Management Corporation (2012)

Table 10. Solar PV Obligation Supply [GWh]

Year	2012	2013	2014	2015	2016	2017
RPS	276	591	907	1235	1577	1577

Source: Korea Energy Management Corporation (2012)

4.3.5 CO2 Price and Emission Target

Yearly CO2 target used in equation (18) are as follows.

Table 11. CO2 Target [Mtone]

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
$CO2tg_t$	289	281.2	273.4	265.6	257.8	250.0	242.2	234.4	226.6	218.8
Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
$CO2tg_t$	211.0	203.2	195.4	187.6	179.8	172.0	164.2	156.4	148.6	140.0

Source: National Energy Committee of Korea (2008)

CO2 trading cost is calculated based on recent CO2 price.

Table 12. Mean and Deviation of CO_2 Price

[$/t$CO_2$]	CO_2
Mean	7.4
Std.	0.6

Source: BlueNext Statistics (http://www.bluenext.eu)

CO_2 trading cost is generated by MCS to reflect uncertain situations like fuel cost and learning rate.

4.3.6 Data for Cost-Risk Optimization Model

The cost-risk optimization model uses the same data we used previously for the least-cost optimization model. In addition, data to reflect the risk of each energy source are used. First of all, data about investment cost risk, O&M cost risk, fuel cost risk, CO_2 cost risk, and standard deviation (risk) by variation of expense elements and correlation between expenses elements are used (White, 2007). Additional explanation regarding risk and correlations is organized in Appendix 2.

Table 13 shows technology risks. There are many risks that can influence the value of conventional and non-conventional energy as part of an overall portfolio of resources to satisfy electricity demand. Therefore, to set an optimal portfolio, it is very important to incorporate the risks that affect costs. The definition of technology risks follows the definition of Jansen et al. (2006). Portfolio risk is always estimated as the standard deviation (σ) of the holding period returns (HPRs)[12] of future generating cost streams. As mentioned above in equation (22), EV can be taken as the cost in year *t+1* and BV as the cost in year *t*. HPRs measure the rate of change in the cost stream from one year to the next. Annual price observations were used for eliminating seasonal variations. Technology risks are reorganized by using data from Awerbuch et al. (2005) and other studies. Additional explanation of technology risks is given in Appendix 2. These values are used for correlation between fossil fuel costs, O&M costs for different technologies, and CO2 costs.

Table 13. Technology Risks

Generating Resource	Investment Cost	Fuel Cost	O&M Cost	CO2 Cost
Gas	0.20	0.291	0.105	0.26
Coal	0.35	0.049	0.054	0.26
Nuclear	0.40	0.346	0.055	-
Hydro	0.35	0.000	0.153	-
Wind	0.20	0.000	0.080	-
Solar	0.10	0.000	0.034	-
Biomass	0.20	0.133	0.108	-

Source: White (2007)

The values of the standard deviations and correlations of CO2 prices follow the concept of Green (2006). In his study, he indicated the CO2 price in relation to gas and

[12] HPR=(EV-BV)/BV (EV: ending value, BV: beginning value)

coal prices. This relationship is used to derive the HPR standard deviation of CO2. It is also used for correlation with fossil fuels. Table 14 shows the correlation coefficients between the various fuels. In a large percentage of cases, positive correlation exists between fuels—most fuels are substitutes for one another—with the exception of nuclear fuel. A number of studies (e.g., Awerbuch & Berger, 2003; Roques et al., 2006) found a negative correlation between nuclear and fossil fuels.

Table 14. Fuel and CO2 HPR Correlation

Generating Resource	Coal	Biomass	Gas	Nuclear	CO2
Coal	1.00	0.39	0.53	-0.25	-0.49
Biomass	0.39	1.00	0.30	-0.27	0.00
Gas	0.53	0.30	1.00	-0.16	0.68
Nuclear	-0.25	-0.27	-0.16	1.00	0.00
CO2	-0.49	0.00	0.68	0.00	1.00

Source: White (2007)

O&M correlation coefficients in Table 15 are reorganized by using White (2007)

Table 15. O&M Correlation Coefficients

Generating Resource	Gas	Coal	Nuclear	Hydro	Wind	Solar	Bio
Gas	1.00	0.25	0.24	-0.04	0.00	0.05	0.32
Coal	0.25	1.00	0.00	0.03	-0.22	-0.39	0.18
Nuclear	0.00	0.24	1.00	-0.41	-0.07	0.35	0.65

Hydro	0.03	-0.04	-0.41	1.00	0.29	0.30	-0.18
Wind	-0.22	0.00	-0.07	0.29	1.00	0.05	-0.18
Solar	-0.39	0.05	0.35	0.30	0.05	1.00	0.25
Biomass	0.18	0.32	0.65	-0.18	-0.18	0.25	1.00

Source: White (2007)

4.3.7 External Costs

The most commonly used ways to estimate external costs of electricity generation are damage cost approach and control cost approach. Moreover, in order to decide the value of a specific issue, there is a way to develop relative weights about environmental issues according to the votes of experts or consumers and multiply weight by total damage costs. This research reflects the external costs by putting previous literatures about external costs together. Organized data about these are as follows.

Table 16. Descriptive Statistics of Externality Costs

[US cents/kWh]	Coal	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Mean	14.87	5.02	8.63	3.84	0.29	0.69	5.20
SD	16.89	4.73	18.62	8.40	0.20	0.57	6.11

Source: Data was reorganized by using Sundqvist (2004)

4.3.8 Environmental Costs for Air Pollution

Environmental costs analyze not only the effects of air pollution and human body harm, but also damage of crops and tangible property caused by pollutants from generation sources. Environmental costs could be expressed as multiplying social marginal costs of air pollution of each pollutant by air pollutant emissions. However, Korea does not have a reliable estimation result of environmental costs, which could be socially agreed upon, so foreign estimation results which have public confidence are used in this study.

Table 17. Environmental Costs of Air Pollutant

[USD/MWh]	SOx	NOx	TSP
Coal	1074.906	124.034	0.421
Gas	0	65.495	0
Wind	6.0388	3.6515	0.009
Solar	38.044	6.723	0.034

Source: Data was reorganized by using Markandya (1998)

Chapter 5. Analysis of the Proposed Model

In this chapter, we optimized the electricity portfolio including conventional energy (coal, gas, and nuclear), non-conventional energy (hydro, wind, solar PV), and biomass energy by using the least-cost optimization model and cost-risk optimization model. The analysis system to minimize production cost and to compose energy sources by achieving a given policy goal under physical restriction and policy condition is brought in as follows. There are total three kinds of analysis models as shown in the following table.

Table 18. Classification of Models

	Model 1	Model 2	Model 3
Including Factors	Nuclear Energy Social Cost	Model 1 + External Costs	Model 1 + Pollution Costs

5.1 Least-Cost Optimization Model

5.1.1 Results: Model 1 (Social Cost of Nuclear Energy)

The basic model of this research reflects the social cost of nuclear energy to generation cost. The social cost of nuclear energy refers to the policy cost or processing cost after an accident, which was calculated by Japan after the Fukushima nuclear accident. The least-cost analysis result of this model is as follows.

5.1.1.1 Electricity Capacity [MW] (Model 1)

Table 19. Yearly Additional Electricity Capacity (Model 1)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
2012	-	-	-	141	234	356	-
2013	-	-	-	149	293	396	-
2014	-	-	1,178	157	264	440	137
2015	-	-	1,293	164	455	488	202
2016	-	-	1,308	172	575	540	168
2017	-	-	1,317	180	707	596	118
2018	-	-	1,319	188	844	656	99
2019	-	-	1,316	154	971	721	106
2020	-	-	1,317	122	1,072	790	112
2021	357	-	1,333	95	1,130	863	118
2022	406	-	1,345	73	1,135	939	124
2023	472	-	1,353	56	1,086	1,019	128
2024	540	-	1,357	42	1,060	1,101	132
2025	608	-	1,357	32	1,001	1,184	135
2026	698	-	1,353	24	917	1,268	138
2027	804	-	1,345	18	816	1,351	144
2028	909	-	1,333	13	708	1,433	150
2029	1,002	-	1,317	9	666	1,510	154
2030	1,075	-	1,298	7	680	1,583	159

According to the analysis of the least-cost optimization perspective of model 1, coal as a method among conventional energy doesn't have any new additional electricity capacity yearly, but in the case of nuclear energy and gas, there is a new addition of electricity capacity every year. In the case of non-conventional energy like solar, additional electricity capacity increases continuously. With wind, additional electricity capacity increases at first; however, it eventually decreases, and in the case of hydro, additional capacity decreases continuously. The cumulative electricity capacity of each energy source is as follows.

Table 20. Yearly Cumulative Electricity Capacity (Model 1)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	21,740	25,128	18,715	1,717	406	554	97
2012	21,740	25,128	18,715	1,858	640	910	97
2013	21,740	25,128	18,715	2,007	933	1,306	97
2014	21,740	25,128	19,893	2,164	1,197	1,746	233
2015	21,740	25,128	21,186	2,328	1,652	2,234	435
2016	21,740	25,128	22,494	2,500	2,227	2,774	603
2017	21,740	25,128	23,811	2,680	2,934	3,370	721
2018	21,740	25,128	25,130	2,868	3,778	4,026	820
2019	21,740	25,128	26,446	3,022	4,749	4,747	926
2020	21,740	25,128	27,763	3,144	5,821	5,537	1,038
2021	22,097	25,128	29,096	3,239	6,951	6,400	1,156
2022	22,502	25,128	30,441	3,312	8,086	7,339	1,280
2023	22,975	25,128	31,794	3,368	9,172	8,358	1,408
2024	23,515	25,128	33,151	3,410	10,232	9,459	1,540
2025	24,123	25,128	34,508	3,442	11,233	10,643	1,675
2026	24,821	25,128	35,861	3,466	12,150	11,911	1,813
2027	25,625	25,128	37,206	3,484	12,966	13,262	1,957
2028	26,534	25,128	38,539	3,497	13,674	14,695	2,107
2029	27,535	25,128	39,856	3,506	14,340	16,205	2,261
2030	28,611	25,128	41,154	3,513	15,020	17,788	2,420

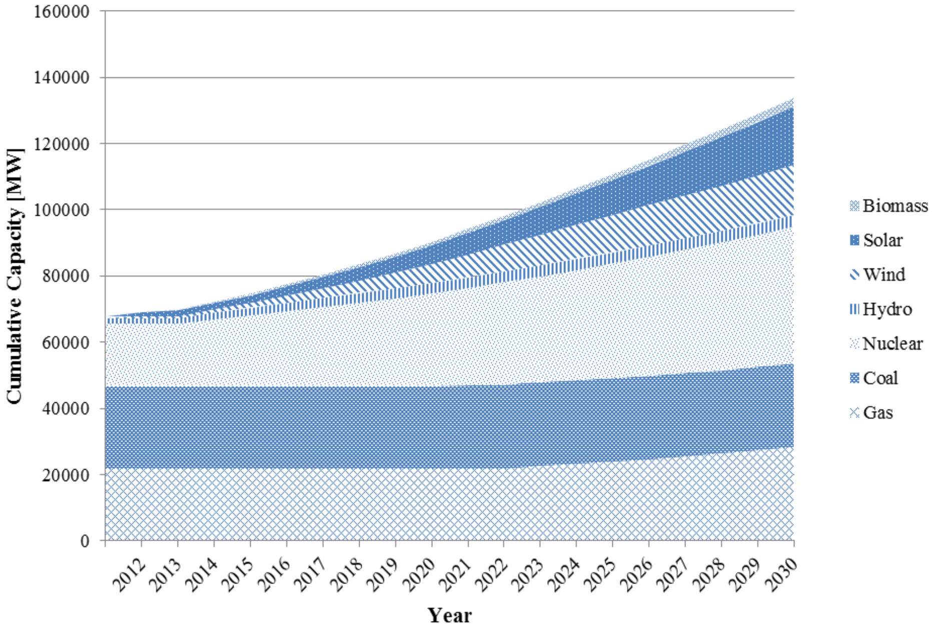


Figure 12. Yearly Cumulative Electricity Capacity (Model 1)

Table 21. The Proportion of Yearly Cumulative Electricity Capacity (Model 1)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	31.80%	36.76%	27.38%	2.51%	0.59%	0.81%	0.14%
2012	31.47%	36.37%	27.09%	2.69%	0.93%	1.32%	0.14%
2013	31.09%	35.94%	26.76%	2.87%	1.33%	1.87%	0.14%
2014	30.15%	34.85%	27.59%	3.00%	1.66%	2.42%	0.32%
2015	29.10%	33.64%	28.36%	3.12%	2.21%	2.99%	0.58%
2016	28.06%	32.44%	29.04%	3.23%	2.87%	3.58%	0.78%
2017	27.05%	31.26%	29.62%	3.33%	3.65%	4.19%	0.90%
2018	26.04%	30.10%	30.10%	3.44%	4.53%	4.82%	0.98%
2019	25.06%	28.96%	30.48%	3.48%	5.47%	5.47%	1.07%
2020	24.11%	27.87%	30.79%	3.49%	6.46%	6.14%	1.15%

2021	23.49%	26.71%	30.93%	3.44%	7.39%	6.80%	1.23%
2022	22.94%	25.62%	31.03%	3.38%	8.24%	7.48%	1.31%
2023	22.48%	24.59%	31.11%	3.30%	8.97%	8.18%	1.38%
2024	22.09%	23.61%	31.15%	3.20%	9.61%	8.89%	1.45%
2025	21.78%	22.69%	31.16%	3.11%	10.14%	9.61%	1.51%
2026	21.56%	21.82%	31.14%	3.01%	10.55%	10.34%	1.57%
2027	21.42%	21.01%	31.10%	2.91%	10.84%	11.09%	1.64%
2028	21.37%	20.24%	31.04%	2.82%	11.01%	11.83%	1.70%
2029	21.37%	19.50%	30.94%	2.72%	11.13%	12.58%	1.76%
2030	21.41%	18.80%	30.80%	2.63%	11.24%	13.31%	1.81%

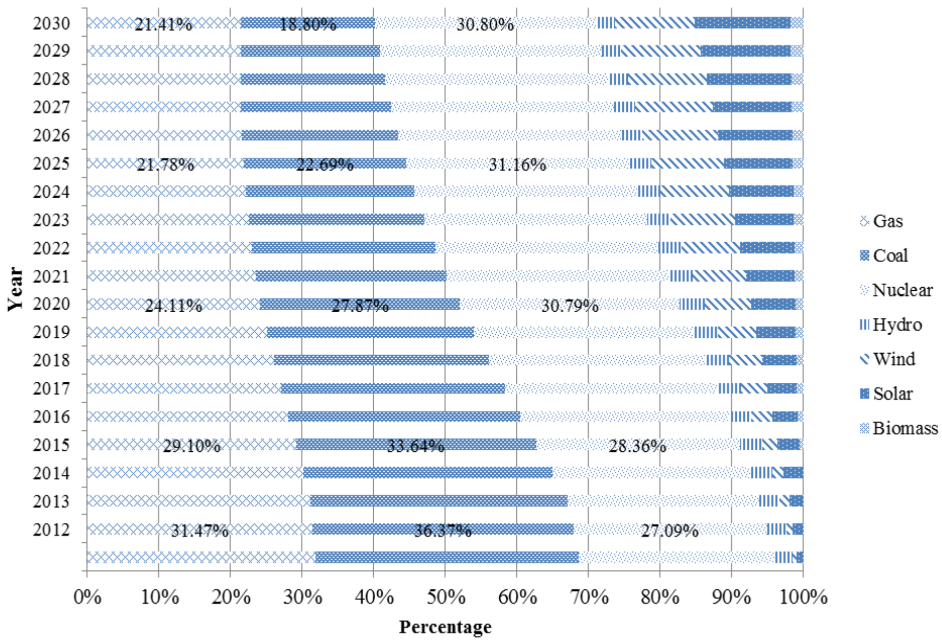


Figure 13. The Proportion of Yearly Cumulative Electricity Capacity (Model 1)

The above table and figure present the cumulative generation capacity proportion of each energy source in Model 1. In the case of coal, its proportion decreases continually, while in the cases of nuclear, wind, solar, and biomass, proportion increases. In the case of gas, proportion is decreased to begin with; however it maintains its proportion from 2023.

5.1.1.2 Electricity Generation [MWh] (Model 1)

The electricity generation reflecting capacity factor is as follows.

Table 22. Yearly Cumulative Electricity Generation (Model 1)

[MWh]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	161,876,040	187,103,088	114,591,945	7,520,460	1,173,340	1,213,260	466,382
2012	161,876,040	187,103,088	114,591,945	8,138,040	1,849,600	1,992,900	466,382
2013	161,876,040	187,103,088	114,591,945	8,790,660	2,696,370	2,860,140	466,382
2014	161,876,040	187,103,088	121,803,613	9,478,320	3,459,330	3,823,740	1,124,065
2015	161,876,040	187,103,088	129,720,652	10,196,640	4,774,280	4,892,460	2,097,301
2016	161,876,040	187,103,088	137,729,536	10,950,000	6,436,030	6,075,060	2,906,725
2017	161,876,040	187,103,088	145,793,527	11,738,400	8,479,260	7,380,300	3,475,249
2018	161,876,040	187,103,088	153,869,764	12,561,840	10,918,420	8,816,940	3,952,231
2019	161,876,040	187,103,088	161,927,632	13,236,360	13,724,610	10,395,930	4,462,939
2020	161,876,040	187,103,088	169,991,623	13,770,720	16,822,690	12,126,030	5,002,555
2021	164,531,728	187,103,088	178,153,582	14,186,820	20,088,390	14,016,000	5,571,079
2022	167,552,082	187,103,088	186,389,017	14,506,560	23,368,540	16,072,410	6,168,511
2023	171,070,277	187,103,219	194,673,436	14,751,840	26,507,080	18,304,020	6,785,215
2024	175,091,878	187,103,219	202,982,347	14,935,800	29,570,480	20,715,210	7,421,191
2025	179,618,651	187,103,219	211,291,258	15,075,960	32,463,370	23,308,170	8,071,621
2026	184,816,040	187,103,219	219,575,677	15,181,080	35,113,500	26,085,090	8,736,505

2027	190,802,723	187,103,219	227,811,112	15,259,920	37,471,740	29,043,780	9,430,297
2028	197,571,170	187,103,219	235,973,071	15,316,860	39,517,860	32,182,050	10,152,997
2029	205,028,757	187,103,219	244,037,062	15,356,280	41,442,600	35,488,950	10,894,969
2030	213,036,462	187,103,219	251,984,716	15,386,940	43,407,800	38,955,720	11,661,031

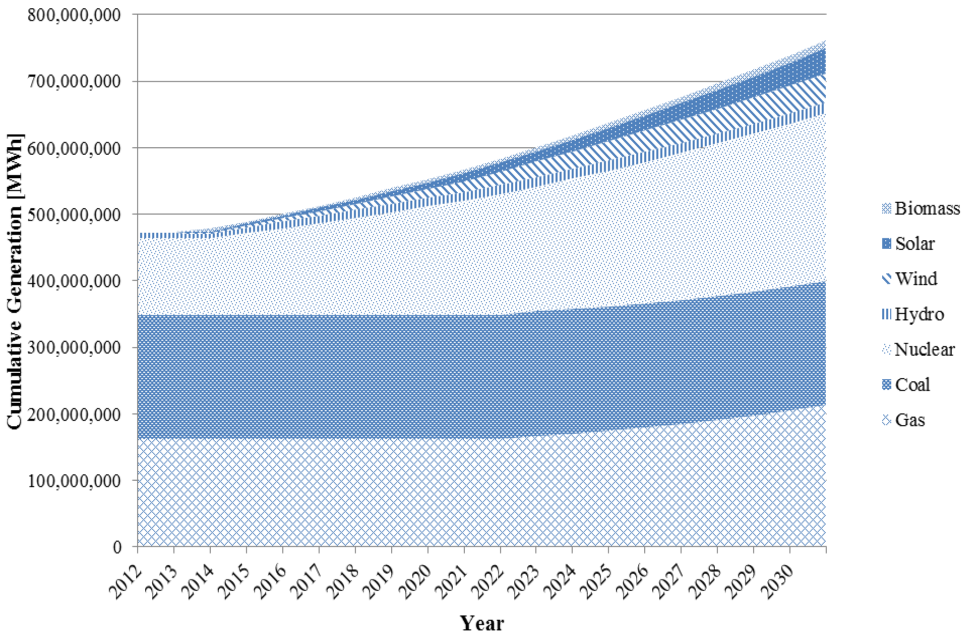


Figure 14. Yearly Cumulative Electricity Generation (Model 1)

Table 23. The Proportion of Yearly Cumulative Electricity Generation (Model 1)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	34.16%	39.48%	24.18%	1.59%	0.25%	0.26%	0.10%
2012	34.01%	39.31%	24.07%	1.71%	0.39%	0.42%	0.10%
2013	33.84%	39.11%	23.95%	1.84%	0.56%	0.60%	0.10%
2014	33.13%	38.29%	24.93%	1.94%	0.71%	0.78%	0.23%
2015	32.33%	37.37%	25.91%	2.04%	0.95%	0.98%	0.42%

2016	31.55%	36.47%	26.84%	2.13%	1.25%	1.18%	0.57%
2017	30.78%	35.58%	27.73%	2.23%	1.61%	1.40%	0.66%
2018	30.03%	34.71%	28.54%	2.33%	2.03%	1.64%	0.73%
2019	29.29%	33.85%	29.30%	2.39%	2.48%	1.88%	0.81%
2020	28.57%	33.02%	30.00%	2.43%	2.97%	2.14%	0.88%
2021	28.19%	32.06%	30.52%	2.43%	3.44%	2.40%	0.95%
2022	27.87%	31.12%	31.00%	2.41%	3.89%	2.67%	1.03%
2023	27.63%	30.22%	31.44%	2.38%	4.28%	2.96%	1.10%
2024	27.45%	29.33%	31.82%	2.34%	4.64%	3.25%	1.16%
2025	27.34%	28.48%	32.16%	2.29%	4.94%	3.55%	1.23%
2026	27.31%	27.65%	32.45%	2.24%	5.19%	3.86%	1.29%
2027	27.38%	26.85%	32.69%	2.19%	5.38%	4.17%	1.35%
2028	27.52%	26.07%	32.87%	2.13%	5.51%	4.48%	1.41%
2029	27.73%	25.31%	33.01%	2.08%	5.61%	4.80%	1.47%
2030	27.97%	24.57%	33.09%	2.02%	5.70%	5.12%	1.53%

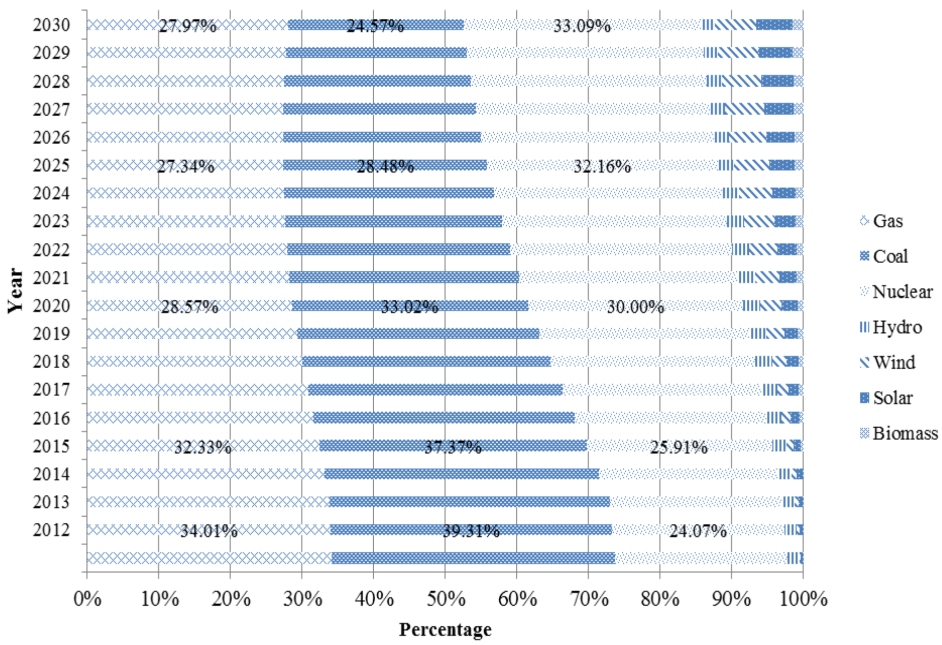


Figure 15. The Proportion of Yearly Cumulative Electricity Generation (Model 1)

The results drawn from the electricity generation in Model 1 indicate that the proportion of conventional energy increased as compared to electricity capacity on account of differences in each energy capacity factor. When compared to generation capacity, the change of proportion is an approximate 7% decrease in gas, 15% decrease in coal, and 9% increase in nuclear. In the case of renewable energy, the change of proportion is an approximate 5% increase in wind and solar, 1.5% increase in biomass, and similar levels to the present level in hydro.

5.1.2 Results: Model 2 (Model 1 + External Costs)

Next, external costs are reflected in a basic model as additional cost. Results of previous research are reflected as external costs according to the IEA (1995) classification standard as in Fig. 5. Information about external costs of previous research is organized in Table 15. The analysis result of the least cost in model 2 is organized as follows.

5.1.2.1 Electricity Capacity [MW] (Model 2)

The result of the least-cost optimization analysis of Model 2 is very similar to that of Model 1. In other words, coal among conventional energy doesn't have any increase in electricity capacity yearly, but in the case of nuclear and gas, there is a new addition of electricity capacity every year. In the case of non-conventional energy, they all have additional electricity capacity. However, the rate of incensement is different. In the case of only wind, the rate of electricity capacity increased at first; however, it decreased beginning in 2019. Additional and cumulative electricity capacity by energy source reflecting electricity capacity is shown as follows.

Table 24. Yearly Additional Electricity Capacity (Model 2)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
2012	-	-	-	141	234	356	-
2013	-	-	-	149	293	396	-
2014	-	-	1,172	157	264	440	137
2015	-	-	1,293	164	455	488	202
2016	-	-	1,308	172	575	540	168
2017	-	-	1,317	180	707	596	118
2018	-	-	1,319	188	844	656	99
2019	-	-	1,316	154	971	721	106
2020	-	-	1,317	122	1,072	790	112
2021	362	-	1,333	95	1,130	863	118
2022	406	-	1,345	73	1,135	939	124
2023	464	-	1,353	56	1,086	1,019	128
2024	534	-	1,357	42	1,060	1,101	132
2025	611	-	1,357	32	1,001	1,184	135
2026	702	-	1,353	24	917	1,268	138
2027	802	-	1,345	18	816	1,351	144
2028	911	-	1,333	13	708	1,433	150
2029	1,004	-	1,317	9	666	1,510	154
2030	1,074	1	1,298	7	680	1,583	159

Table 25. Yearly Cumulative Electricity Capacity (Model 2)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	21,740	25,128	18,715	1,717	406	554	97
2012	21,740	25,128	18,715	1,858	640	910	97
2013	21,740	25,128	18,715	2,007	933	1,306	97
2014	21,740	25,128	19,887	2,164	1,197	1,746	233
2015	21,740	25,128	21,180	2,328	1,652	2,234	435
2016	21,740	25,128	22,488	2,500	2,227	2,774	603
2017	21,740	25,128	23,805	2,680	2,934	3,370	721
2018	21,740	25,128	25,124	2,868	3,778	4,026	820
2019	21,740	25,128	26,440	3,022	4,749	4,747	926
2020	21,740	25,128	27,757	3,144	5,821	5,537	1,038
2021	22,102	25,128	29,090	3,239	6,951	6,400	1,156
2022	22,507	25,128	30,435	3,312	8,086	7,339	1,280
2023	22,972	25,136	31,788	3,368	9,172	8,358	1,408
2024	23,506	25,136	33,145	3,410	10,232	9,459	1,540
2025	24,117	25,136	34,502	3,442	11,233	10,643	1,675
2026	24,819	25,136	35,855	3,466	12,150	11,911	1,813
2027	25,620	25,136	37,200	3,484	12,966	13,262	1,957
2028	26,531	25,136	38,533	3,497	13,674	14,695	2,107
2029	27,535	25,136	39,850	3,506	14,340	16,205	2,261
2030	28,608	25,137	41,148	3,513	15,020	17,788	2,420

Figures 16 and 17 present the cumulative generation capacity and its proportion of each form of energy in Model 2. In the case of coal, its proportion decreased continually; however, in case of nuclear, wind, solar, and biomass, their proportion increased. Similar to Model 1, in the case of gas, its proportion decreased to begin with, but it maintained its proportion.

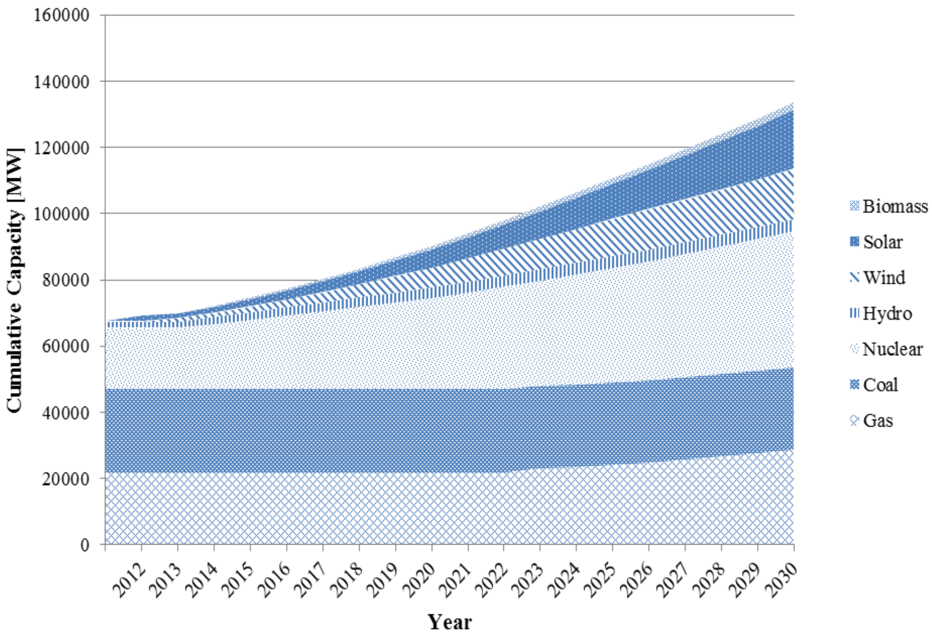


Figure 16. Yearly Cumulative Electricity Capacity (Model 2)

Table 26. The Proportion of Yearly Cumulative Electricity Capacity (Model 2)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	31.80%	36.76%	27.38%	2.51%	0.59%	0.81%	0.14%
2012	31.47%	36.37%	27.09%	2.69%	0.93%	1.32%	0.14%
2013	31.09%	35.94%	26.76%	2.87%	1.33%	1.87%	0.14%
2014	30.15%	34.85%	27.58%	3.00%	1.66%	2.42%	0.32%
2015	29.10%	33.64%	28.35%	3.12%	2.21%	2.99%	0.58%
2016	28.07%	32.44%	29.03%	3.23%	2.88%	3.58%	0.78%
2017	27.05%	31.26%	29.62%	3.33%	3.65%	4.19%	0.90%
2018	26.04%	30.10%	30.09%	3.44%	4.53%	4.82%	0.98%
2019	25.06%	28.97%	30.48%	3.48%	5.47%	5.47%	1.07%
2020	24.11%	27.87%	30.78%	3.49%	6.46%	6.14%	1.15%

2021	23.50%	26.71%	30.92%	3.44%	7.39%	6.80%	1.23%
2022	22.95%	25.62%	31.03%	3.38%	8.24%	7.48%	1.31%
2023	22.48%	24.59%	31.10%	3.30%	8.97%	8.18%	1.38%
2024	22.09%	23.62%	31.14%	3.20%	9.61%	8.89%	1.45%
2025	21.78%	22.70%	31.15%	3.11%	10.14%	9.61%	1.51%
2026	21.55%	21.83%	31.14%	3.01%	10.55%	10.34%	1.57%
2027	21.42%	21.01%	31.10%	2.91%	10.84%	11.09%	1.64%
2028	21.37%	20.24%	31.03%	2.82%	11.01%	11.83%	1.70%
2029	21.37%	19.51%	30.93%	2.72%	11.13%	12.58%	1.76%
2030	21.41%	18.81%	30.79%	2.63%	11.24%	13.31%	1.81%

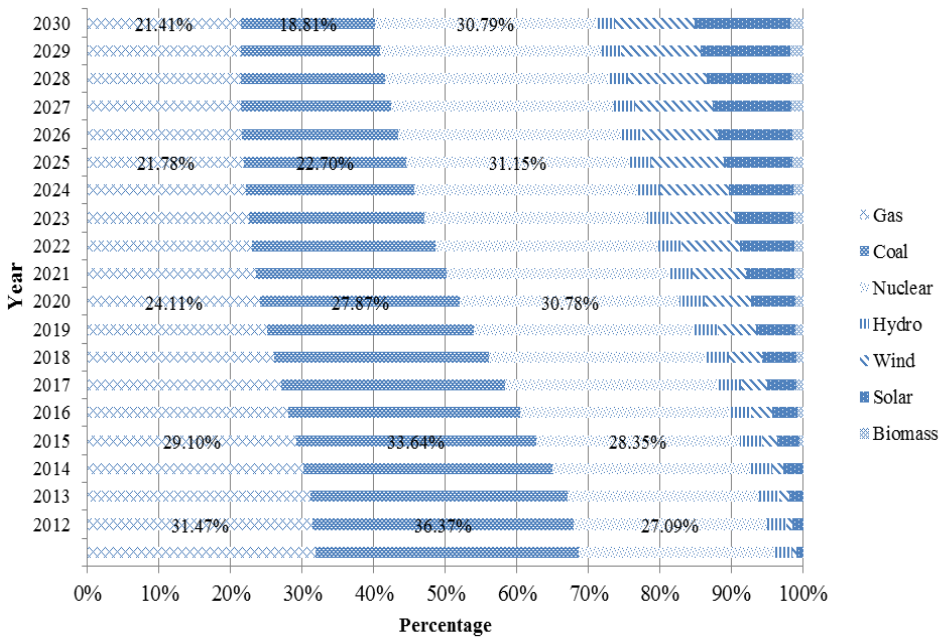


Figure 17. The Proportion of Yearly Cumulative Electricity Capacity (Model 2)

5.1.2.2 Electricity Generation [MWh] (Model 2)

Table 27. Yearly Cumulative Electricity Generation (Model 2)

[MWh]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	161,876,040	187,103,088	114,591,945	7,520,460	1,173,340	1,213,260	466,382
2012	161,876,040	187,103,088	114,591,945	8,138,040	1,849,600	1,992,900	466,382
2013	161,876,040	187,103,088	114,591,945	8,790,660	2,696,370	2,860,140	466,382
2014	161,876,040	187,103,088	121,765,581	9,478,320	3,459,330	3,823,740	1,124,065
2015	161,876,040	187,103,088	129,682,620	10,196,640	4,774,280	4,892,460	2,097,301
2016	161,876,040	187,103,088	137,691,504	10,950,000	6,436,030	6,075,060	2,906,725
2017	161,876,040	187,103,088	145,755,495	11,738,400	8,479,260	7,380,300	3,475,249
2018	161,876,040	187,103,088	153,831,732	12,561,840	10,918,420	8,816,940	3,952,231
2019	161,876,040	187,103,088	161,889,600	13,236,360	13,724,610	10,395,930	4,462,939
2020	161,876,040	187,103,088	169,953,591	13,770,720	16,822,690	12,126,030	5,002,555
2021	164,569,760	187,103,088	178,115,550	14,186,820	20,088,390	14,016,000	5,571,079
2022	167,590,114	187,103,088	186,350,985	14,506,560	23,368,540	16,072,410	6,168,511
2023	171,048,301	187,163,154	194,635,404	14,751,840	26,507,080	18,304,020	6,785,215
2024	175,023,482	187,163,154	202,944,315	14,935,800	29,570,480	20,715,210	7,421,191
2025	179,575,555	187,163,154	211,253,226	15,075,960	32,463,370	23,308,170	8,071,621
2026	184,799,356	187,163,154	219,537,645	15,181,080	35,113,500	26,085,090	8,736,505
2027	190,767,785	187,163,154	227,773,080	15,259,920	37,471,740	29,043,780	9,430,297
2028	197,548,768	187,163,154	235,935,039	15,316,860	39,517,860	32,182,050	10,152,997
2029	205,023,974	187,163,154	243,999,030	15,356,280	41,442,600	35,488,950	10,894,969
2030	213,018,666	187,169,549	251,946,684	15,386,940	43,407,800	38,955,720	11,661,031

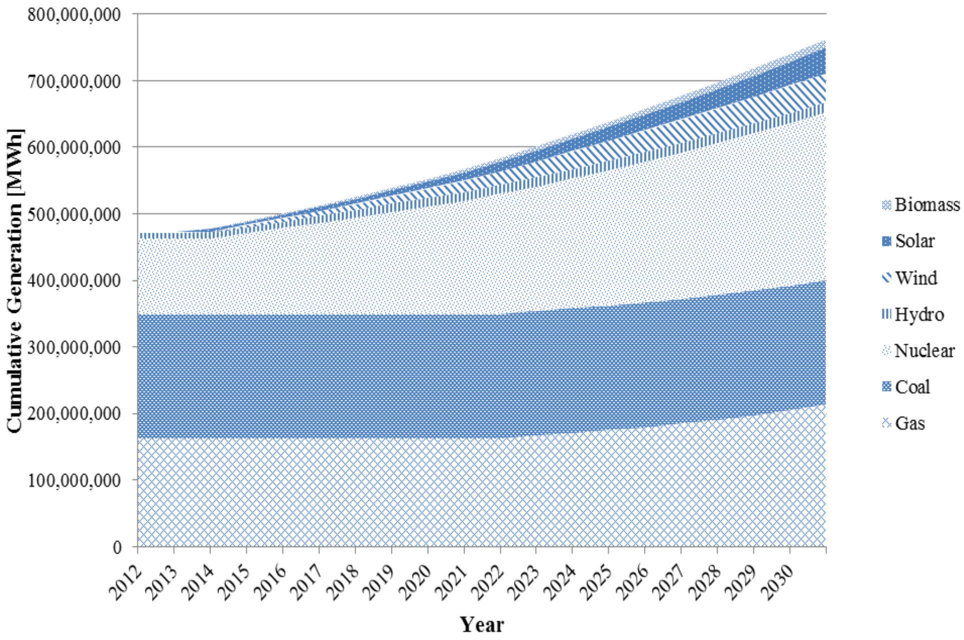


Figure 18. Yearly Cumulative Electricity Generation (Model 2)

Table 28. The Proportion of Yearly Cumulative Electricity Generation (Model 2)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	34.16%	39.48%	24.18%	1.59%	0.25%	0.26%	0.10%
2012	34.01%	39.31%	24.07%	1.71%	0.39%	0.42%	0.10%
2013	33.84%	39.11%	23.95%	1.84%	0.56%	0.60%	0.10%
2014	33.13%	38.29%	24.92%	1.94%	0.71%	0.78%	0.23%
2015	32.33%	37.37%	25.90%	2.04%	0.95%	0.98%	0.42%
2016	31.55%	36.47%	26.84%	2.13%	1.25%	1.18%	0.57%
2017	30.79%	35.58%	27.72%	2.23%	1.61%	1.40%	0.66%
2018	30.03%	34.71%	28.54%	2.33%	2.03%	1.64%	0.73%
2019	29.29%	33.85%	29.29%	2.39%	2.48%	1.88%	0.81%
2020	28.57%	33.02%	29.99%	2.43%	2.97%	2.14%	0.88%

2021	28.20%	32.06%	30.52%	2.43%	3.44%	2.40%	0.95%
2022	27.88%	31.12%	31.00%	2.41%	3.89%	2.67%	1.03%
2023	27.62%	30.23%	31.43%	2.38%	4.28%	2.96%	1.10%
2024	27.44%	29.35%	31.82%	2.34%	4.64%	3.25%	1.16%
2025	27.34%	28.49%	32.16%	2.29%	4.94%	3.55%	1.23%
2026	27.31%	27.66%	32.45%	2.24%	5.19%	3.86%	1.29%
2027	27.37%	26.86%	32.68%	2.19%	5.38%	4.17%	1.35%
2028	27.52%	26.07%	32.87%	2.13%	5.51%	4.48%	1.41%
2029	27.73%	25.31%	33.00%	2.08%	5.61%	4.80%	1.47%
2030	27.97%	24.58%	33.08%	2.02%	5.70%	5.12%	1.53%

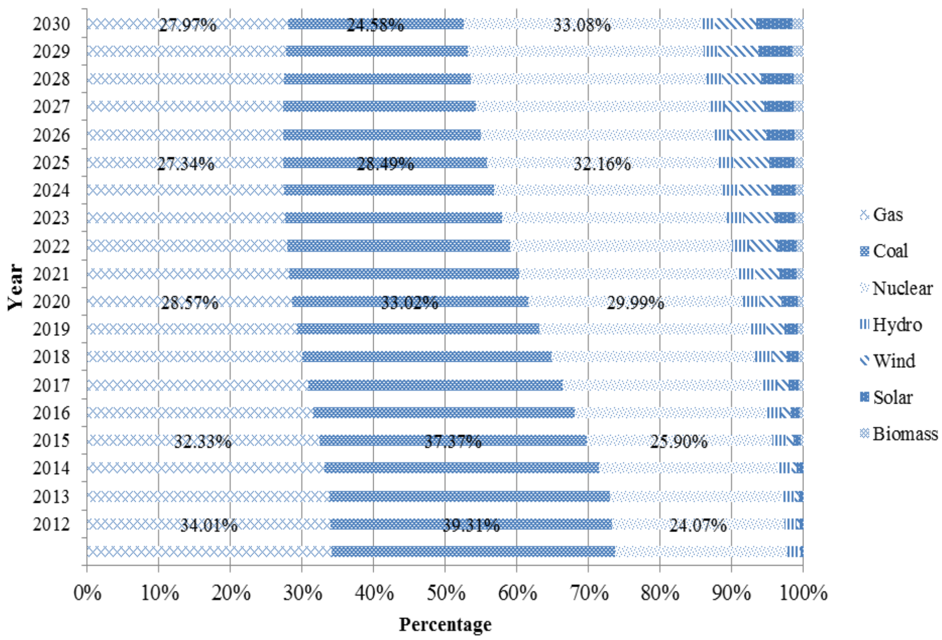


Figure 19. The Proportion of Yearly Cumulative Electricity Generation (Model 2)

Based on the results from the electricity generation of Model 2, the proportion of conventional energy increased as compared to electricity capacity. When compared to the generation capacity, the change of proportion is an approximate 6% decrease in gas, 15% decrease in coal, and 9% increase in nuclear energy. In the case of renewable energy, the change of proportion is an approximate 5% increase in wind and solar, 1.5% increase in biomass, and a similar level to the present in hydro.

5.1.3 Results: Model 3 (Model 1 + Pollution Costs)

The last model is analyzed to reflect pollution costs with generation cost to a basic model. Pollution costs are drawn from the presented data in Table 16. The analysis result of the least cost of Model 3 is organized as follows.

5.1.3.1 Electricity Capacity [MW] (Model 3)

Table 29. Yearly Additional Electricity Capacity (Model 3)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
2012	-	-	-	141	234	356	-
2013	-	-	-	149	293	396	-
2014	-	-	1,176	157	264	440	137
2015	-	-	1,293	164	455	488	202
2016	-	-	1,308	172	575	540	168
2017	-	-	1,317	180	707	596	118
2018	-	-	1,319	188	844	656	99
2019	-	-	1,316	154	971	721	106
2020	-	-	1,317	122	1,072	790	112
2021	358	-	1,333	95	1,130	863	118

2022	406	-	1,345	73	1,135	939	124
2023	474	-	1,353	56	1,086	1,019	128
2024	533	-	1,357	42	1,060	1,101	132
2025	609	-	1,357	32	1,001	1,184	135
2026	705	-	1,353	24	917	1,268	138
2027	808	-	1,345	18	816	1,351	144
2028	903	-	1,333	13	708	1,433	150
2029	1,003	-	1,317	9	666	1,510	154
2030	1,032	41	1,298	7	680	1,583	159

The result of the least-cost optimization analysis of Model 3 is also very similar to that of Model 1. Coal among conventional energy doesn't have any incensements in electricity capacity yearly, but in the case of nuclear and gas, there is a new addition of electricity capacity every year. All forms of non-conventional energy have additional electricity capacity. However, the rate of incensement is different. In the case of only wind, the rate of electricity capacity increased at first but decreased beginning in 2019. The cumulative electricity capacity by energy source reflected in electricity capacity is as follows.

Table 30. Yearly Cumulative Electricity Capacity (Model 3)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	21,740	25,128	18,715	1,717	406	554	97
2012	21,740	25,128	18,715	1,858	640	910	97
2013	21,740	25,128	18,715	2,007	933	1,306	97
2014	21,740	25,128	19,891	2,164	1,197	1,746	233

2015	21,740	25,128	21,184	2,328	1,652	2,234	435
2016	21,740	25,128	22,492	2,500	2,227	2,774	603
2017	21,740	25,128	23,809	2,680	2,934	3,370	721
2018	21,740	25,128	25,128	2,868	3,778	4,026	820
2019	21,740	25,128	26,444	3,022	4,749	4,747	926
2020	21,740	25,128	27,761	3,144	5,821	5,537	1,038
2021	22,098	25,128	29,094	3,239	6,951	6,400	1,156
2022	22,504	25,128	30,439	3,312	8,086	7,339	1,280
2023	22,978	25,128	31,792	3,368	9,172	8,358	1,408
2024	23,512	25,128	33,149	3,410	10,232	9,459	1,540
2025	24,120	25,128	34,506	3,442	11,233	10,643	1,675
2026	24,825	25,128	35,859	3,466	12,150	11,911	1,813
2027	25,633	25,128	37,204	3,484	12,966	13,262	1,957
2028	26,536	25,128	38,537	3,497	13,674	14,695	2,107
2029	27,539	25,128	39,854	3,506	14,340	16,205	2,261
2030	28,571	25,169	41,152	3,513	15,020	17,788	2,420

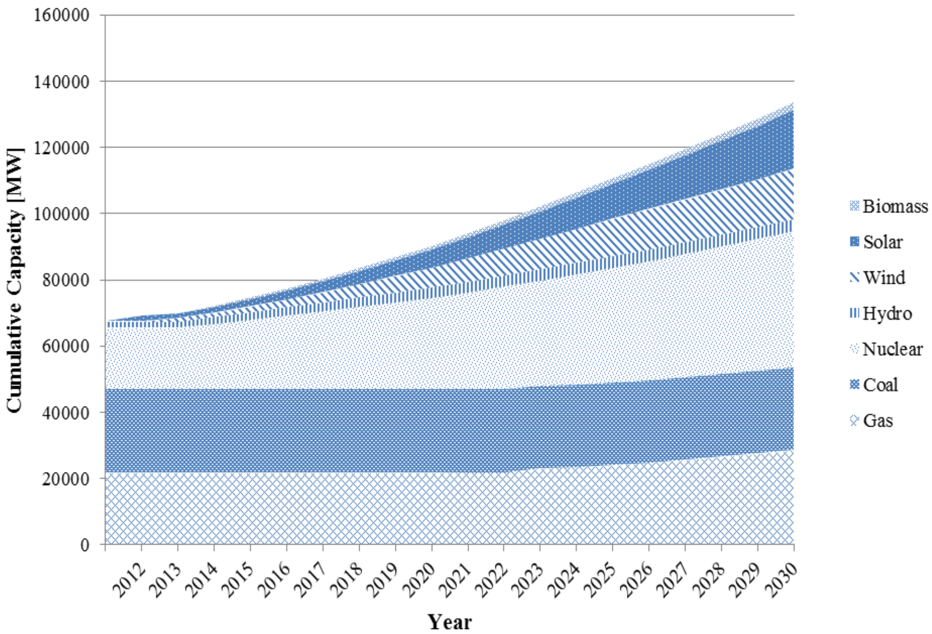


Figure 20. Yearly Cumulative Electricity Capacity (Model 3)

Table 31. The Proportion of Yearly Cumulative Electricity Capacity (Model 3)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	31.80%	36.76%	27.38%	2.51%	0.59%	0.81%	0.14%
2012	31.47%	36.37%	27.09%	2.69%	0.93%	1.32%	0.14%
2013	31.09%	35.94%	26.76%	2.87%	1.33%	1.87%	0.14%
2014	30.15%	34.85%	27.59%	3.00%	1.66%	2.42%	0.32%
2015	29.10%	33.64%	28.36%	3.12%	2.21%	2.99%	0.58%
2016	28.06%	32.44%	29.04%	3.23%	2.87%	3.58%	0.78%
2017	27.05%	31.26%	29.62%	3.33%	3.65%	4.19%	0.90%
2018	26.04%	30.10%	30.10%	3.44%	4.53%	4.82%	0.98%
2019	25.06%	28.96%	30.48%	3.48%	5.47%	5.47%	1.07%
2020	24.11%	27.87%	30.79%	3.49%	6.46%	6.14%	1.15%

2021	23.49%	26.71%	30.93%	3.44%	7.39%	6.80%	1.23%
2022	22.94%	25.62%	31.03%	3.38%	8.24%	7.48%	1.31%
2023	22.48%	24.59%	31.11%	3.30%	8.97%	8.18%	1.38%
2024	22.09%	23.61%	31.15%	3.20%	9.61%	8.89%	1.45%
2025	21.78%	22.69%	31.16%	3.11%	10.14%	9.61%	1.51%
2026	21.56%	21.82%	31.14%	3.01%	10.55%	10.34%	1.57%
2027	21.43%	21.00%	31.10%	2.91%	10.84%	11.09%	1.64%
2028	21.37%	20.24%	31.03%	2.82%	11.01%	11.83%	1.70%
2029	21.38%	19.50%	30.93%	2.72%	11.13%	12.58%	1.76%
2030	21.38%	18.83%	30.79%	2.63%	11.24%	13.31%	1.81%

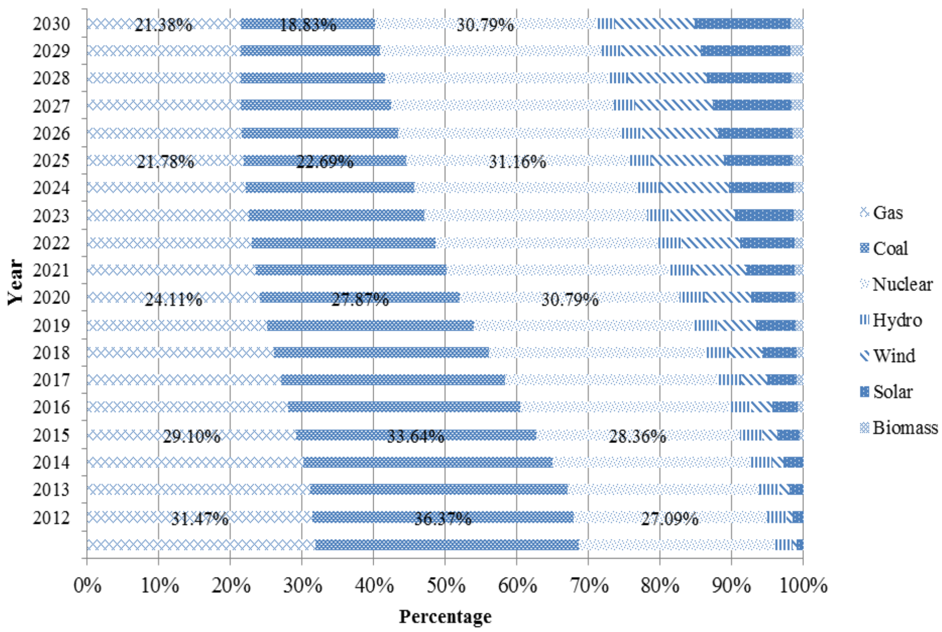


Figure 21. The Proportion of Yearly Cumulative Electricity Capacity (Model 1)

The above table and figure present the cumulative generation capacity proportion of each form of energy in Model 3. In the case of coal, its proportion decreased continually;

however, in the cases of nuclear, wind, solar, and biomass energy, the proportion increased. In the case of gas, proportion decreased to begin with like coal; however, it maintained its proportion.

5.1.3.2 Electricity Generation [MWh] (Model 3)

Table 32. Yearly Cumulative Electricity Generation (Model 3)

[MWh]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	161,876,040	187,103,088	114,591,945	7,520,460	1,173,340	1,213,260	466,382
2012	161,876,040	187,103,088	114,591,945	8,138,040	1,849,600	1,992,900	466,382
2013	161,876,040	187,103,088	114,591,945	8,790,660	2,696,370	2,860,140	466,382
2014	161,876,040	187,103,088	121,792,932	9,478,320	3,459,330	3,823,740	1,124,065
2015	161,876,040	187,103,088	129,709,971	10,196,640	4,774,280	4,892,460	2,097,301
2016	161,876,040	187,103,088	137,718,855	10,950,000	6,436,030	6,075,060	2,906,725
2017	161,876,040	187,103,088	145,782,846	11,738,400	8,479,260	7,380,300	3,475,249
2018	161,876,040	187,103,088	153,859,083	12,561,840	10,918,420	8,816,940	3,952,231
2019	161,876,040	187,103,088	161,916,951	13,236,360	13,724,610	10,395,930	4,462,939
2020	161,876,040	187,103,088	169,980,942	13,770,720	16,822,690	12,126,030	5,002,555
2021	164,542,410	187,103,088	178,142,901	14,186,820	20,088,390	14,016,000	5,571,079
2022	167,562,763	187,103,088	186,378,336	14,506,560	23,368,540	16,072,410	6,168,511
2023	171,095,688	187,103,089	194,662,755	14,751,840	26,507,080	18,304,020	6,785,215
2024	175,066,883	187,103,089	202,971,666	14,935,800	29,570,480	20,715,210	7,421,191
2025	179,601,204	187,103,089	211,280,577	15,075,960	32,463,370	23,308,170	8,071,621
2026	184,847,196	187,103,089	219,564,996	15,181,080	35,113,500	26,085,090	8,736,505
2027	190,864,676	187,103,089	227,800,431	15,259,920	37,471,740	29,043,780	9,430,297
2028	197,585,527	187,103,089	235,962,390	15,316,860	39,517,860	32,182,050	10,152,997
2029	205,055,390	187,103,089	244,026,381	15,356,280	41,442,600	35,488,950	10,894,969
2030	212,738,406	187,407,834	251,974,035	15,386,940	43,407,800	38,955,720	11,661,031

Based on the results from electricity generation of Model 3, it can be seen that the proportion of conventional energy increased as compared to electricity capacity. When compared to generation capacity, the change of proportion is an approximate 6% decrease in gas, 15% decrease in coal, and 9% increase in nuclear energy. In the case of renewable energy, the change of proportion is approximately a 5% increase in wind and solar, 1.5% increase in biomass, and similar levels to that at present in hydro energy as in Model 1.

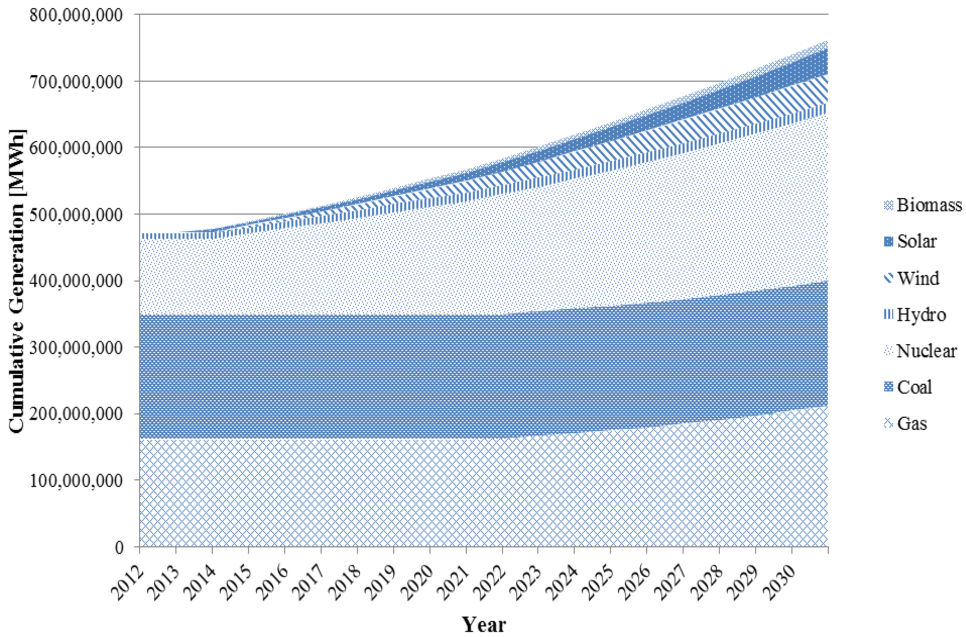


Figure 22. Yearly Cumulative Electricity Generation (Model 3)

Table 33. The Proportion of Yearly Cumulative Electricity Generation (Model 3)

[MW]	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Initial	34.16%	39.48%	24.18%	1.59%	0.25%	0.26%	0.10%
2012	34.01%	39.31%	24.07%	1.71%	0.39%	0.42%	0.10%

2013	33.84%	39.11%	23.95%	1.84%	0.56%	0.60%	0.10%
2014	33.13%	38.29%	24.92%	1.94%	0.71%	0.78%	0.23%
2015	32.33%	37.37%	25.91%	2.04%	0.95%	0.98%	0.42%
2016	31.55%	36.47%	26.84%	2.13%	1.25%	1.18%	0.57%
2017	30.78%	35.58%	27.72%	2.23%	1.61%	1.40%	0.66%
2018	30.03%	34.71%	28.54%	2.33%	2.03%	1.64%	0.73%
2019	29.29%	33.85%	29.29%	2.39%	2.48%	1.88%	0.81%
2020	28.57%	33.02%	30.00%	2.43%	2.97%	2.14%	0.88%
2021	28.19%	32.06%	30.52%	2.43%	3.44%	2.40%	0.95%
2022	27.87%	31.12%	31.00%	2.41%	3.89%	2.67%	1.03%
2023	27.63%	30.22%	31.44%	2.38%	4.28%	2.96%	1.10%
2024	27.45%	29.34%	31.82%	2.34%	4.64%	3.25%	1.16%
2025	27.34%	28.48%	32.16%	2.30%	4.94%	3.55%	1.23%
2026	27.32%	27.65%	32.45%	2.24%	5.19%	3.86%	1.29%
2027	27.38%	26.85%	32.68%	2.19%	5.38%	4.17%	1.35%
2028	27.53%	26.07%	32.87%	2.13%	5.51%	4.48%	1.41%
2029	27.73%	25.31%	33.00%	2.08%	5.61%	4.80%	1.47%
2030	27.94%	24.61%	33.09%	2.02%	5.70%	5.12%	1.53%

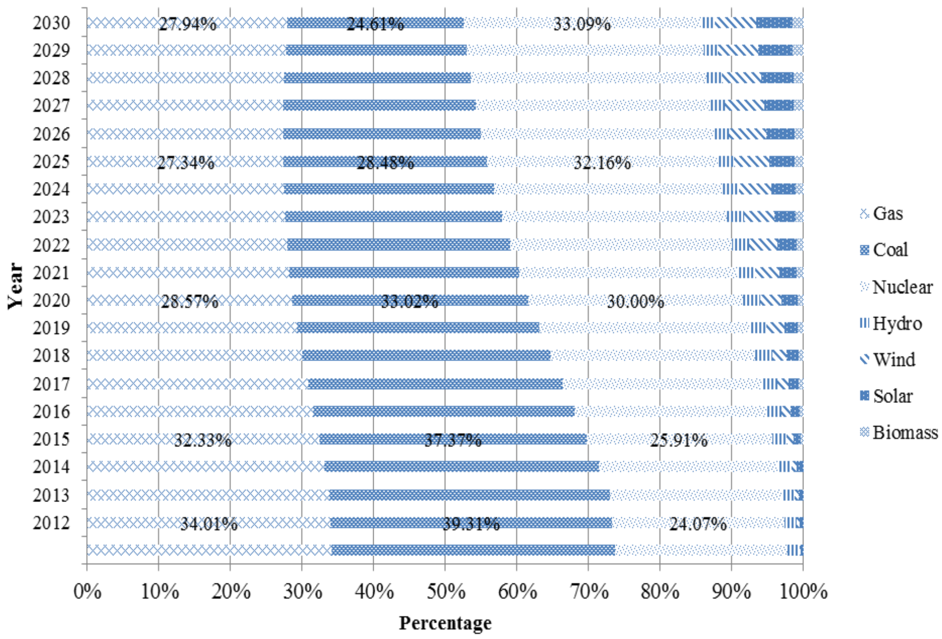


Figure 23. The Proportion of Yearly Cumulative Electricity Generation (Model 3)

5.2 Cost-Risk Optimization Model

In this paragraph, an estimated result of the 2030 portfolio in paragraph 4.1 is analyzed using the cost-risk optimization model. In other words, this paragraph figures out how the 2030 portfolio drawn with least-cost perspective could be changed by considering the risk of each energy source. Furthermore, using the cost-risk optimization model, the particular form an optimal portfolio has is analyzed to consider both cost and risk together.

5.2.1 Results: Model 1 (Social Cost of Nuclear Energy)

The generation cost of each energy source is used for analysis as follows.

Table 34. Expected Levelized Generating Costs of Energy (Model 1)

	Gas	**Coal**	**Nuclear**	**Hydro**	**Wind**	**Solar**	**Biomass**
$/MWh	130.51	74.08	53.73	123.15	138.74	388.15	175.74
KRW/kWh	143.56	81.49	59.10	135.46	152.62	426.96	193.31

Table 35. Result of Cost-Risk Optimization Model (Model 1)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	28,611	25,128	41,154	3,513	15,020	17,788	2,420
%	21.41%	18.80%	30.80%	2.63%	11.24%	13.31%	1.81%
Generation (MWh)	213,036,462	187,103,219	251,984,716	15,386,940	43,407,800	38,955,720	11,661,031
%	27.97%	24.57%	33.09%	2.02%	5.70%	5.12%	1.53%

As cost-risk is analyzed using the 2030 result of Model 1, the average risk is 0.2350, and average cost is 105.4 USD/MWh. The 2030 result of Model 1 is not on the efficient frontier. This means that the result of the cost-risk optimization model by using the portfolio of the least-cost optimization model is not optimal from a cost-risk perspective. Efficient frontiers by cost-risk portfolio analysis of Model 1 is shown in the following figure, and the least risk and least-cost generation capacity and generation mix are shown in the following table.

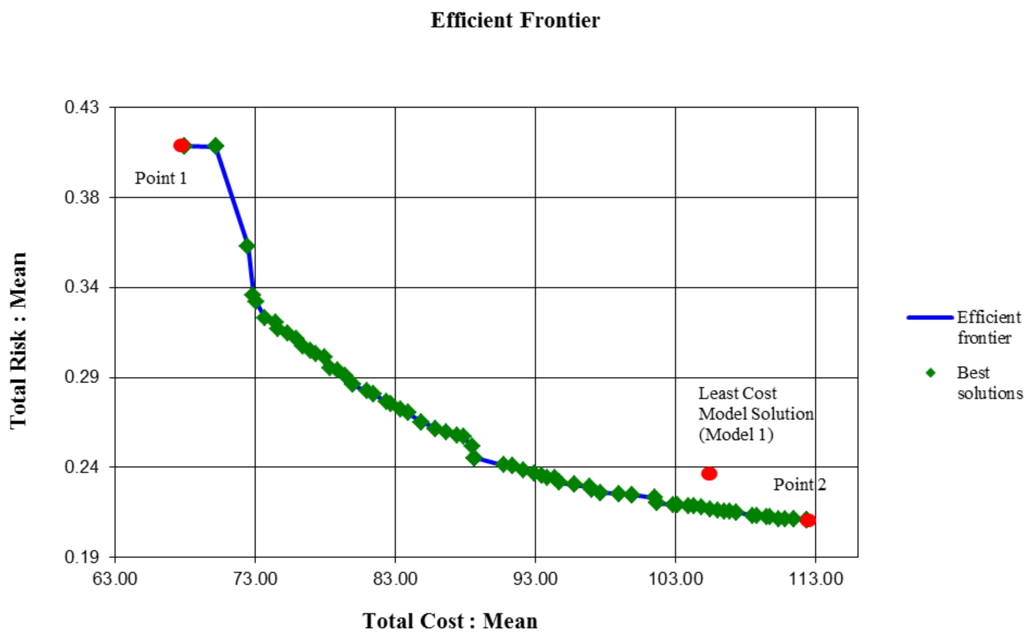


Figure 24. Efficient Frontier of Model 1

Table 36. Least Risk Solution of Model 1 (Point 2)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	30,381	26,315	27,343	11,604	9,988	12,311	13,551
%	23.10%	20.01%	20.79%	8.82%	7.60%	9.36%	10.31%
Generation (MWh)	226,216,926	195,941,490	167,421,189	50,825,520	28,865,320	26,961,090	65,288,718
%	29.71%	25.73%	21.99%	6.67%	3.79%	3.54%	8.57%

The 2030 portfolio average risk of the least risk model 1 is 0.208, and the average cost of the least risk model 1 is 112.34 USD/MWh.

Table 37. Least Cost Solution of Model 1 (Point 1)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	265	20,403	85,556	11,604	41	33	6,798
%	0.21%	16.36%	68.61%	9.31%	0.03%	0.03%	5.45%
Generation (MWh)	1,973,190	151,920,738	523,859,388	50,825,520	118,490	72,270	32,752,764
%	0.26%	19.95%	68.79%	6.67%	0.02%	0.01%	4.30%

The 2030 portfolio average risk of the least-cost model 1 is 0.412, and the average cost of the least-cost model 1 is 67.92 USD/MWh.

5.2.2 Results: Model 2 (Model 1 + External Costs)

The generation cost of each energy source used for analyzing Model 2 is as follows.

Table 38. Expected Levelized Generating Costs of Energy (Model 2)

	Gas	**Coal**	**Nuclear**	**Hydro**	**Wind**	**Solar**	**Biomass**
$/MWh	173.61	214.18	124.93	156.75	141.84	396.55	225.24
KRW/kWh	190.97	235.60	137.42	172.42	156.03	436.20	247.76

Table 39. Result of Cost-Risk Optimization Model (Model 2)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	28,608	25,137	41,148	3,513	15,020	17,788	2,420

%	21.41%	18.81%	30.79%	2.63%	11.24%	13.31%	1.81%
Generation (MWh)	213,018,666	187,169,549	251,946,684	15,386,940	43,407,800	38,955,720	11,661,031
%	27.97%	24.58%	33.08%	2.02%	5.70%	5.12%	1.53%

As cost-risk is analyzed using the 2030 result of Model 1, the average risk is 0.2350, and the average cost is 177.5 USD/MWh. Fig. 25 shows that the 2030 result of Model 2 is not on the efficient frontier as well. This also means that the result of the cost-risk optimization model by using the portfolio of the least-cost optimization model is not an optimal portfolio from a cost-risk perspective. Efficient frontiers determined through a cost-risk portfolio analysis in Model 2 is shown in the following figure, and the least risk generation capacity and generation mix is shown in the following table.

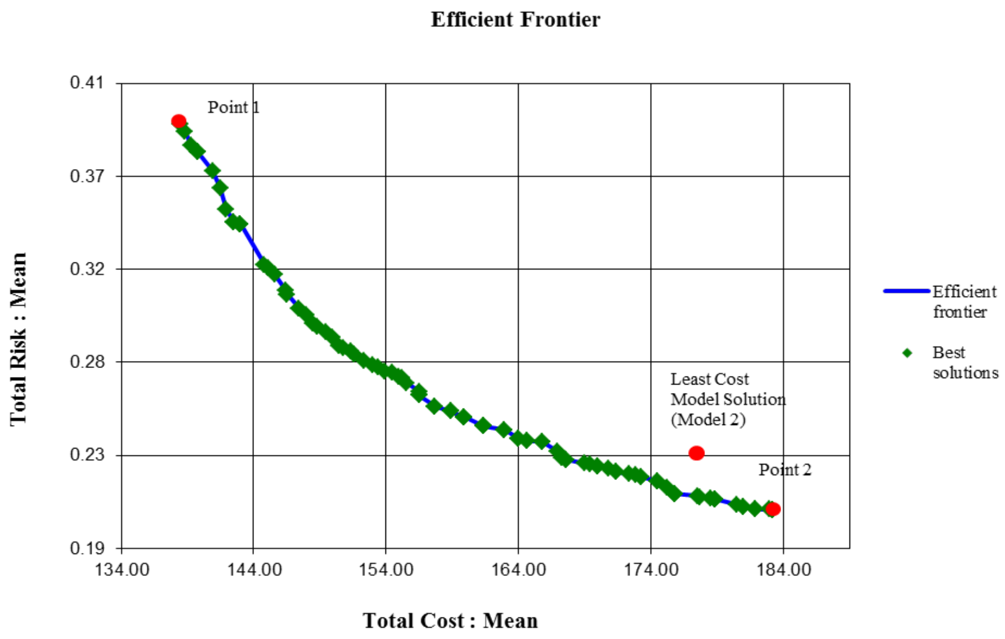


Figure 25. Efficient Frontier of Model 2

Table 40. Least Risk Solution of Model 2 (Point 2)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	31,292	25,643	27,053	11,604	9,988	12,311	13,550
%	23.81%	19.51%	20.58%	8.83%	7.60%	9.37%	10.31%
Generation (MWh)	227,073,216	193,514,094	169,007,046	50,825,520	28,865,320	26,961,090	65,283,900
%	30.60%	25.07%	21.75%	6.67%	3.79%	3.54%	8.57%

The 2030 portfolio average risk of the least risk in Model 2 is 0.21, and the average cost of the least risk in Model 2 is 183.18 USD/MWh.

Table 41. Least Cost Solution of Model 2 (Point 1)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	20,418	503	85,556	11,604	9,988	82	872
%	15.83%	0.39%	66.31%	8.99%	7.74%	0.06%	0.68%
Generation (MWh)	152,032,428	3,745,338	523,859,388	50,825,520	28,865,320	179,580	4,201,296
%	19.91%	0.49%	68.59%	6.66%	3.78%	0.02%	0.55%

The 2030 portfolio average risk of the least cost in Model 2 is 0.39, and the average cost of the least cost in Model 2 is 138.43 USD/MWh.

5.2.3 Results: Model 3 (Model 1 + Pollution Costs)

The generation cost of each energy source used for analyzing Model 3 is as follows.

Table 42. Expected Levelized Generating Costs of Energy (Model 3)

	Gas	**Coal**	**Nuclear**	**Hydro**	**Wind**	**Solar**	**Biomass**
$/MWh	196.01	1,273.45	53.73	123.15	148.44	432.95	175.74
KRW/kWh	215.61	1,400.79	59.10	135.46	163.29	476.24	193.31

The analysis result of Model 3 is as follows.

Table 43. Result of Cost-Risk Optimization Model (Model 3)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	28,571	25,169	41,152	3,513	15,020	17,788	2,420
%	21.38%	18.83%	30.79%	2.63%	11.24%	13.31%	1.81%
Generation (MWh)	212,738,406	187,407,834	251,974,035	15,386,940	43,407,800	38,955,720	11,661,031
%	27.94%	24.61%	33.09%	2.02%	5.70%	5.12%	1.53%

As cost risk is analyzed using the 2030 result of Model 3, average risk is 0.2350 and average cost is 421.7 USD/MWh. Fig. 26 shows that the 2030 result of Model 3 is not on the efficient frontier, as in Models 1 and 2. This also means that the result of the cost-risk optimization model by using the portfolio of the least-cost optimization model is not an optimal portfolio from a cost-risk perspective. Efficient frontiers according to the cost-risk portfolio analysis of Model 3 is shown in the following figure, and the least risk generation capacity and generation mix is as in the following table.

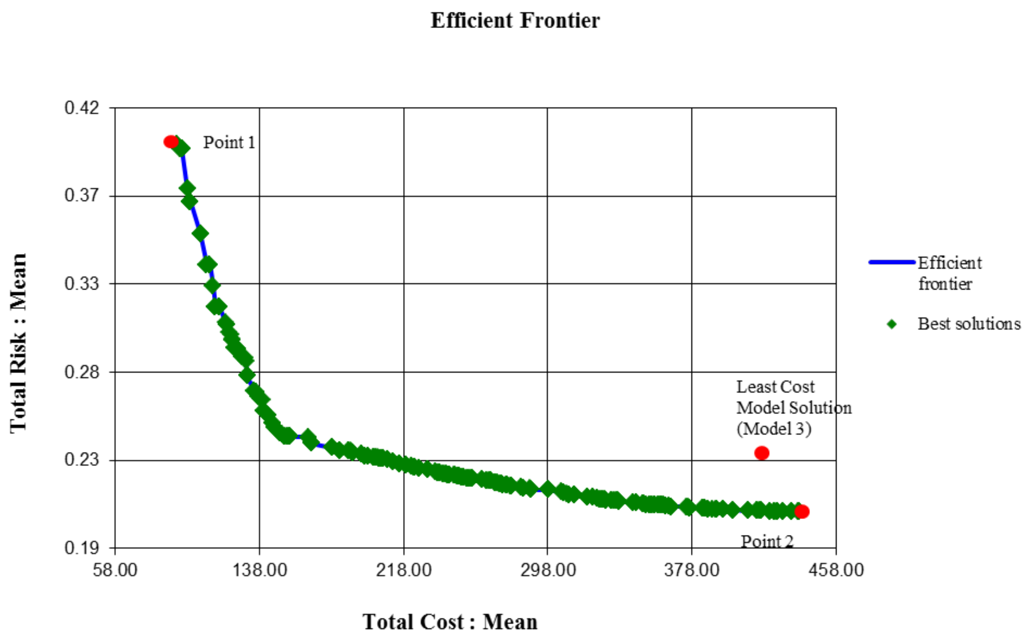


Figure 26. Efficient Frontier of Model 3

Table 44. Least Risk Solution of Model 3 (Point 2)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	30,643	25,919	27,505	11,604	9,988	12,311	13,550
%	23.30%	19.71%	20.91%	8.82%	7.59%	9.36%	10.30%
Generation (MWh)	228,167,778	192,992,874	168,413,115	50,825,520	28,865,320	26,961,090	65,283,900
%	29.96%	25.34%	22.12%	6.67%	3.79%	3.54%	8.57%

The 2030 portfolio average risk of the least risk model 3 is 0.20871, and the average cost of the least risk in Model 3 is 437.588 USD/MWh.

Table 45. Least Risk Solution of Model 3 (Point 1)

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	12,183	521	85,556	11,604	9,988	41	13,550
%	9.13%	0.39%	64.11%	8.70%	7.48%	0.03%	10.15%
Generation (MWh)	90,714,618	3,879,366	523,859,388	50,825,520	28,865,320	89,790	65,283,900
%	11.88%	0.51%	68.61%	6.66%	3.78%	0.01%	8.55%

The 2030 portfolio average risk of the least cost in Model 3 is 0.396, and the average cost of the least cost in Model 3 is 92.41 USD/MWh.

Chapter 6. Conclusion and Discussion

This chapter shows the meaning, contribution, limitation, and future direction of this research based on the analyzed results presented in Chapter 5. First of all, the analyzed results by both least-cost and cost-risk optimization methods are compared, and the contributions and limitations of this research are presented.

6.1 Discussion

6.1.1 Least-Cost Optimization Model

From the results of Model 1, the ratio of gas generation in 2011 is 34.16% and in 2030 is 27.97%, and the ratio of coal generation in 2011 is 39.48% and in 2030 is 24.57%; both are decreased. However, the ratio of nuclear generation in 2011 is 24.18% and in 2030 is increased to 33.09%, wind shows the biggest rate of increase among renewable energy, and hydro shows the lowest rate of increase. The results of Model 2 show that the ratio of gas generation in 2011 is 34.16% and in 2030 is 27.97%, and the ratio of coal generation in 2011 is 39.48% and in 2030 is 24.58%; both are decreased. The ratio of nuclear generation in 2011 is 24.18% and in 2030 is increased to 33.08%, wind shows the biggest rate of increase among renewable energy, and hydro shows the lowest rate of increase. Lastly, from the results of model 3, the ratio of gas generation in 2011 is 34.16% and in 2030 is 27.94%, and the ratio of coal generation in 2011 is 39.48% and in 2030 is 24.61%; both are decreased. The ratio of nuclear generation in 2011 is 24.18% and in

2030 is increased to 33.09%, wind shows the biggest rate of increase among renewable energy, solar PV shows the second biggest, and hydro show the lowest. These are explained in the following figure.

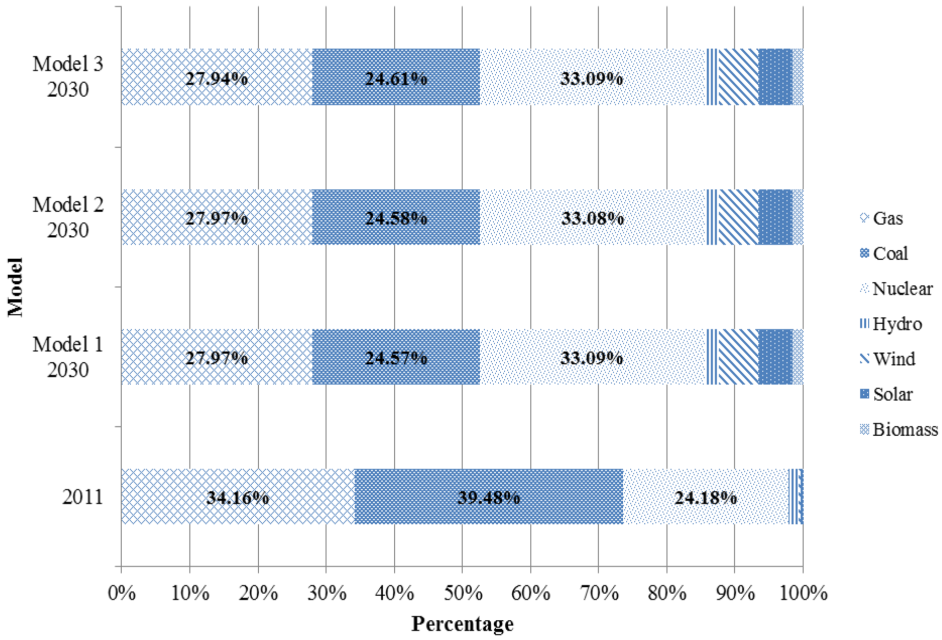


Figure 27. The Proportion of Energy Sources in Current and 2030

From the least-cost analysis result of each model, even though external cost or pollution cost is reflected by the generation costs in the model, their electricity generation portfolios are all similar to each other. This means that the electricity generation portfolio drawn by the model proposed in this research is an optimal portfolio of the least-cost analysis perspective, and additional cost elements have little impact on the composing portfolio. An optimal electricity generation portfolio from a least-cost perspective decreases the generation ratio of coal and gas generally, but the generation ratio of gas is increased from 2020 regardless of the analysis model. This can be inferred from the increase in electricity demand and limitation of realistic capacity installation. Moreover, renewable energy supply obligation in the 6th electricity demand and supply plan cannot be known now, but it is estimated that the renewable energy ratio will not be greatly increased considering the current generation technology or expensive construction costs. Therefore, electricity generation using gas or coal will be expected to increase in the years ahead.

6.1.1 Cost-Risk Optimization Model

6.1.1.1 Model 1 (Social Cost of Nuclear Energy)

Next, from the analysis result of cost risk, a portfolio drawn from the least-cost analysis is not on the efficient frontier, and it is located in the curve, so we could know that it is not an optimal portfolio considering the risk of each energy source. Therefore, an optimal portfolio considering risk is drawn by finding the efficient frontier. Efficient frontier could be found by keeping the same risk level while cost is changing or by keeping the same cost level while risk is changing. The electricity generation composition of Model 1 reflected risk as in the following table.

Table 46. Optimal Portfolio of Model 1 under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	23,189	43,220	38,807	11,604	9,004	41	13,550
%	16.63%	31.00%	27.84%	8.32%	6.46%	0.03%	9.72%
Generation (MWh)	172,665,294	321,816,120	237,615,261	50,825,520	26,021,560	89,790	65,283,900
%	19.75%	36.81%	27.18%	5.81%	2.98%	0.01%	7.47%
Risk	0.235			**Cost**	93.09 USD/MWh		

Table 47. Optimal Portfolio of Model 1 under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	28,495	31,621	26,565	11,604	9,988	6,510	13,550
%	22.20%	24.64%	20.70%	9.04%	7.78%	5.07%	10.56%
Generation (MWh)	212,173,770	235,449,966	162,657,495	50,825,520	28,865,320	14,256,900	65,283,900
%	27.57%	30.60%	21.14%	6.60%	3.75%	1.85%	8.48%
Risk	0.2147			**Cost**	105.4 USD/MWh		

From the result, in the case of forming a portfolio by keeping the same level of cost while risk is changed, risk is changed from 0.235 to 0.21, representing a 9% decrease, and in the case of a portfolio keeping the same level of risk while cost is changed, cost is changed from 105.4 USD/MWh to 93.09 USD/MWh, representing a 10% decrease. The 2030 result analyzed by least-cost perspective is compared with these results as follows. In the case of forming an optimal portfolio by keeping cost while risk is changed from the least-cost model, low risk renewable energy generation is increased by 8%. On the other hand, in the case of forming an optimal portfolio by keeping risk while cost is changed, high-risk conventional energy generation is increased.

As we have seen above, in order for the portfolio derived from least-cost model analysis to move up to the efficient frontier line, either the risk should decrease to 0.2147 with given cost or the cost should decrease to 93.09 USD/MWh with the given risk. The figure below is the illustration of this. In the figure, the red line means movements with given risk or cost each. Also, from the least-cost model analysis with given risk or cost, if we move the opposite ends of the result, the yellow line indicates the feasible optimal portfolio which lies between the two opposite points at the ends.

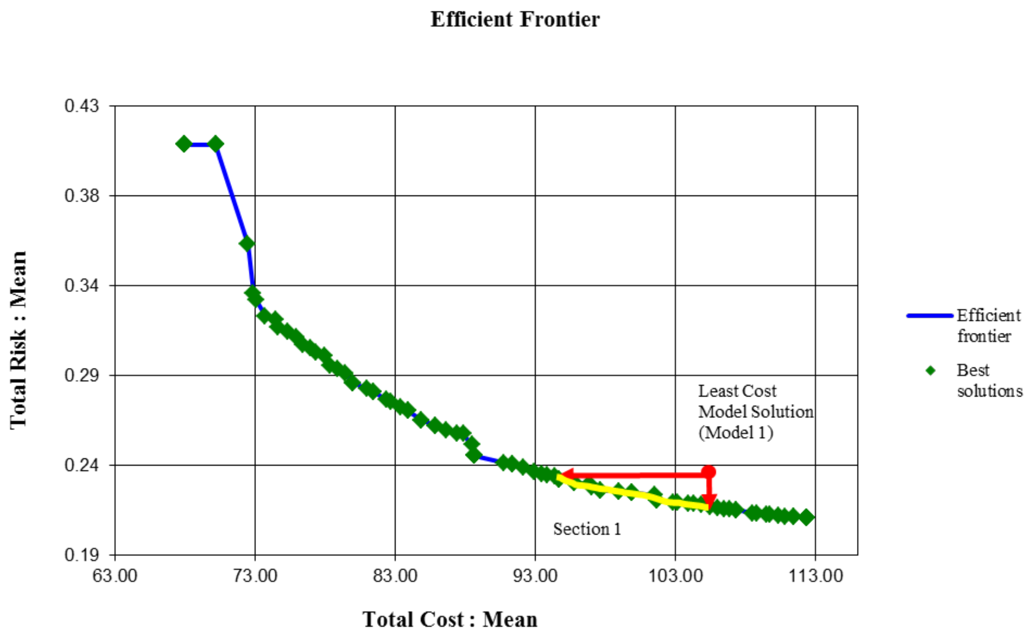


Figure 28. Efficient Frontier and Least Cost Solution of Model 1

Therefore, the portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in the case of Model 1, the optimal portfolio exists on the efficient frontier in which the risk is between 0.2147 and 0.235, and the cost is between 93.09 and 105.4 USD/MWh.

Fig. 29 illustrates the result of the least-cost analysis of Model 1 and the ratio of the amount produced from each source of energy when risk or cost is given and moved to efficient frontier. In the results, when the risk decreases (with given cost) the ratio of gas remains almost the same, while the coal largely increases and the nuclear largely

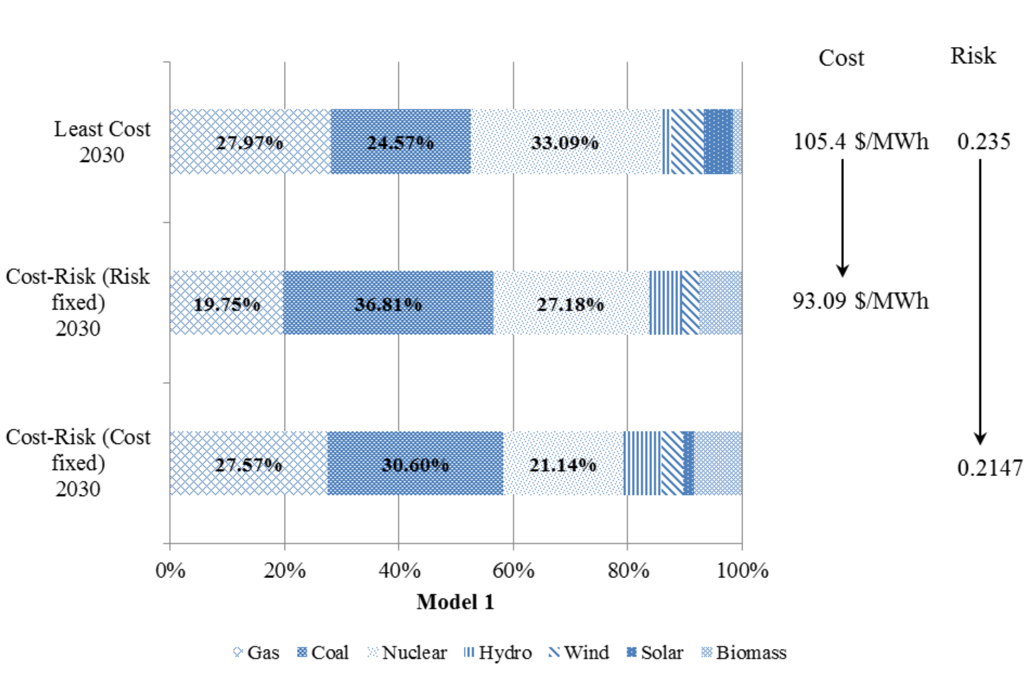


Figure 29. The Proportion of the Energy Sources of Model 1 in 2030

decreases. Also, the ratio of renewable energy largely increases by about 8%. This is because the risk of coal and renewable energy sources is relatively smaller than that of nuclear energy.

6.1.1.2 Model 2 (Model 1 + External Costs)

The results of Model 2 are shown in the following table.

Table 48. Optimal Portfolio of Model 2 under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	39,009	20,138	37,849	11,604	7,871	41	7,271
%	31.51%	16.27%	30.58%	9.37%	6.36%	0.03%	5.87%
Generation (MWh)	290,461,014	149,947,548	231,749,427	50,825,520	22,747,190	89,790	35,031,678
%	37.20%	19.20%	29.68%	6.51%	2.91%	0.01%	4.49%
Risk	0.235			**Cost**	167.27 USD/MWh		

Table 49. Optimal Portfolio of Model 2 under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	30,120	23,645	33,118	11,604	8,534	8,051	13,550
%	23.42%	18.38%	25.75%	9.02%	6.63%	6.26%	10.53%
Generation	224,273,520	176,060,670	202,781,514	50,825,520	24,663,260	17,631,690	65,283,900

(MWh)							
%	29.45%	23.12%	26.63%	6.67%	3.24%	2.32%	8.57%
Risk	0.2152			Cost	177.52 USD/MWh		

From the result, in the case of forming a portfolio by keeping the same level of cost while risk is changed, risk is changed from 0.235 to 0.215, representing about a 9% decrease, and in the case of a portfolio keeping the same level of risk while cost is changed, cost is changed from 177.52 USD/MWh to 167.27 USD/MWh, representing a 5.6% decrease. The 2030 result analyzed through least-cost perspective is compared with these results as follows. In the case of forming an optimal portfolio by keeping cost while risk is changed from the least-cost model, low-risk renewable energy generation is increased by 6%. On the other hand, in the case of forming an optimal portfolio by keeping risk while cost is changed, high-risk conventional energy generation is increased.

In the case of Model 2, in order for the portfolio derived from the least-cost model analysis to move up to the efficient frontier line, either the risk should decrease to 0.2152 with the given cost or the cost should decrease to 167.27 USD/MWh with the given risk. Fig. 30 below is the illustration of this. In the figure, the red line indicates movements with given risk or cost each. Also, from the least-cost model analysis with given risk or cost, if we move the opposite ends of the result, the yellow line indicates the feasible optimal portfolio which lies between the two opposite points at the ends.

Therefore, the portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in case of Model 2, the optimal portfolio exists on the efficient frontier in which the risk is between 0.2152 and 0.235 and the cost is between 167.27 and 177.52 USD/MWh.

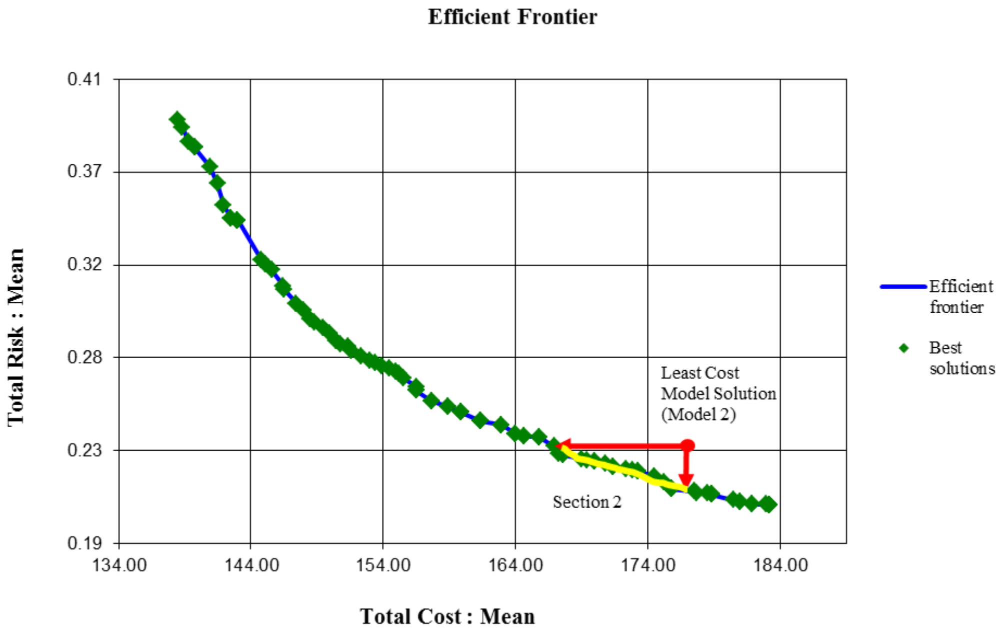


Figure 30. Efficient Frontier and Least Cost Solution of Model 2

Fig. 31 illustrates the result of the least-cost analysis of Model 2 and the ratio of the amount produced from each source of energy when risk or cost is given and moved to the efficient frontier. In the case of Model 2, the portfolio's coal generation importance on the efficient frontier is relatively decreased from the least-cost portfolio's coal generation importance, because the generation cost of coal is increased by external cost. The range of external costs proposed in this research is not identified clearly, so it is difficult to internalize the external costs in generation cost because various results suggest different levels of external effects. However, this research has significance in reflecting the relative size of the external costs of each energy source.

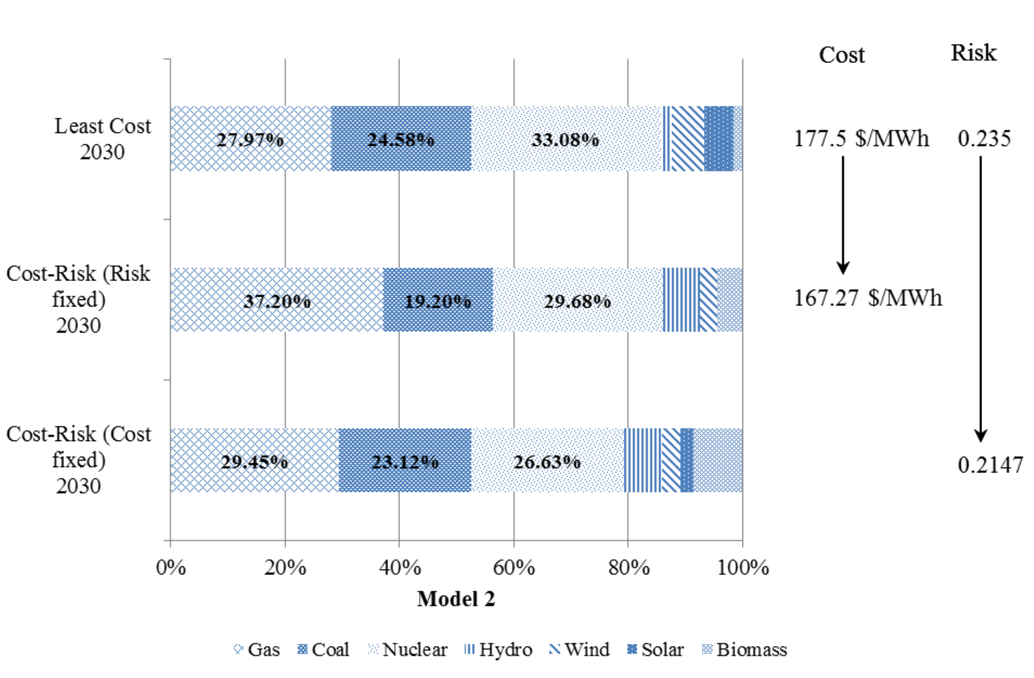


Figure 31. The Proportion of the Energy Sources of Model 2 in 2030

6.1.1.3 Model 3 (Model 1 + Pollution Costs)

The result of Model 3 is shown in the following table.

Table 50. Optimal Portfolio of Model 3 under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	40,004	5,655	40,764	11,604	9,988	12,311	13,550
%	29.88%	4.22%	30.45%	8.67%	7.46%	9.20%	10.12%
Generation (MWh)	297,869,784	42,107,130	249,597,972	50,825,520	28,865,320	26,961,090	65,283,900
%	39.12%	5.53%	32.78%	6.67%	3.79%	3.54%	8.57%
Risk	0.235			**Cost**	208.9 USD/MWh		

Table 51. Optimal Portfolio of Model 3 under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	31,335	24,324	28,603	11,604	9,988	12,311	13,550
%	23.79%	18.47%	21.72%	8.81%	7.58%	9.35%	10.29%
Generation (MWh)	233,320,410	181,116,504	175,136,169	50,825,520	28,865,320	26,961,090	65,283,900
%	30.64%	23.78%	23.00%	6.67%	3.79%	3.54%	8.57%
Risk	0.2091			**Cost**	421.709 USD/MWh		

From the result, in the case of forming a portfolio by keeping the same level of cost while risk is changed, risk is changed from 0.235 to 0.209, representing about an 11.8% decrease, and in the case of a portfolio keeping the same level of risk while cost is changed, cost is changed from 421.7 USD/MWh to 208.9 USD/MWh, about a 40% decrease.

In the case of Model 3, in order for the portfolio derived from the least-cost model analysis to move up to the efficient frontier line, either the risk should decrease to 0.209

with the given cost or the cost should decrease to 208.9 USD/MWh with the given risk. Fig. 32 below is the illustration of this. In the figure, the red line indicates movements with given risk or cost each. Also, from the least-cost model analysis with given risk or cost, if we move the opposite ends of the result, the yellow line indicates the feasible optimal portfolio which lies between the two opposite points at the ends.

Therefore, the portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in the case of Model 3, the optimal portfolio exists on the efficient frontier in which the risk is between 0.2091 and 0.235, and the cost is between 208.9 and 421.709 USD/MWh.

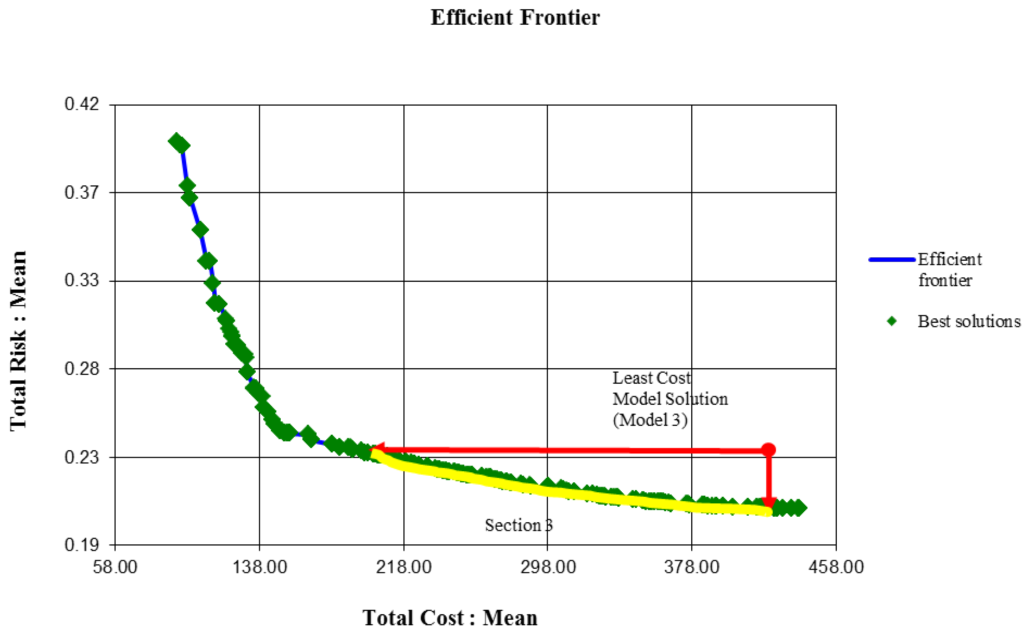


Figure 32. Efficient Frontier and Least Cost Solution of Model 3

The 2030 result analyzed by least-cost perspective is compared with these results as follows. In the case of forming an optimal portfolio by keeping cost while risk is changed from the least-cost model, low-risk renewable energy generation is increased by 8%. On the other hand, in the case of forming an optimal portfolio by keeping risk while cost is changed, high-risk conventional energy generation is increased, but the increasing width is smaller than the case of Models 1 and 2. This case is similar to that of Model 2, as it occurs because pollution cost of conventional energy is far greater than the pollution cost of renewable energy.

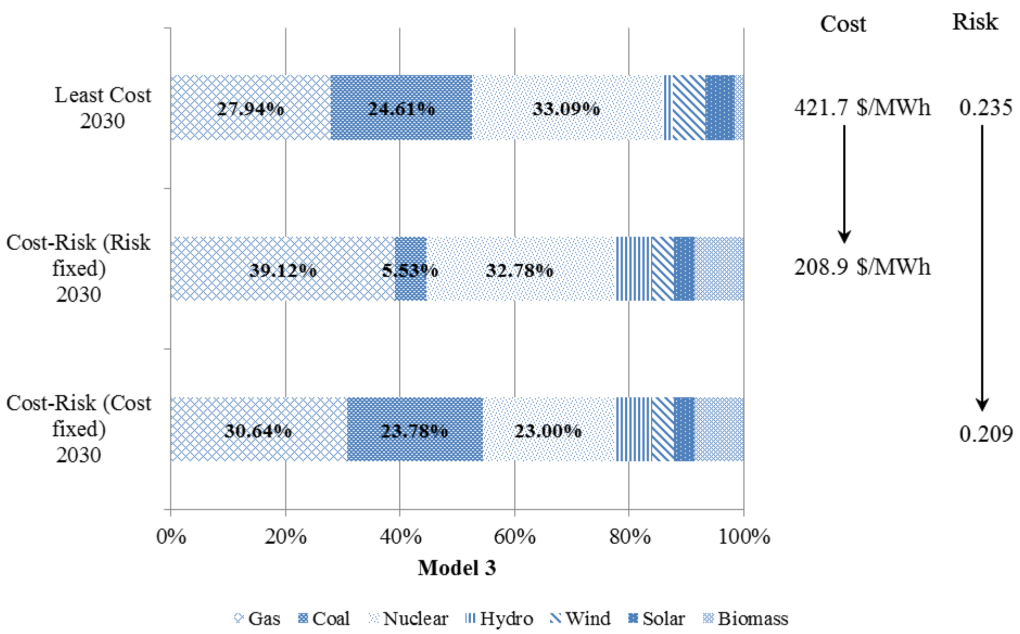


Figure 33. The Proportion of the Energy Sources of Model 3 in 2030

From above analysis results, we can infer the energy source allocation of Korea's electricity industry. First of all, in the current generating cost system, we can determine that the electricity generation of coal is more than optimal for the electricity generation of coal drawn by the proposed model in this study. According to the proposed model in this study, the electricity generation of coal is expected to be excess supply. Furthermore, we could determine that the decreasing coal generation is substituted by gas and nuclear energy. This means that gas and nuclear energy have comparative advantages in carbon emissions and carbon cost than coal energy. However, the gas prices used in this study reflect cross subsidiary, so if the price system is changed, the importance of gas generation could be changed. In the case of gas, gas generation is currently unfavorable economically. Gas generation is useful socially to solve transmission network problems, which occur during serious social conflict. Gas is expected to be a reasonable alternative environmentally considering the nuclear waste problem and greenhouse gas emission by coal. The appearance of shale gas is expected to be important for solving the uncertainty of stable electricity supply and electricity management. This research used the social cost estimation of nuclear energy drawn from the Japanese Fukusima nuclear accident. The social cost estimated by Japan only included accident risk response cost and policy cost. The maximum amount of damages by the Fukusima nuclear accident fit into the sample plant, so the amount of damages may increase in the future. In the case of Korea, 400 tons of nuclear waste is emitted every year, so handling nuclear waste, especially high-level radioactive waste, securing public acceptance, and transmission network construction problems by nuclear plant location are very important. The social cost of nuclear energy includes waste handling, public inconvenience, transmission network construction, and conflict costs to be drawn to reevaluate nuclear energy generation economically. Accordingly, it is expected that uncertain importance of nuclear generation minutely will be reflected. Moreover, nuclear generation importance is expected to be lowered by this model. In the case of renewable energy, control of renewable energy supply progress is also needed. For example, the obligation proportion of renewable energy generation is 2% of all generation in 2012; it is expected to reach 10% after 2022. However, it was pointed out that the yearly obligation of renewable energy is set excessively higher than realistic supply progress. Therefore, it could cause a capacity shortage in the future. Renewable energy generation is calculated by the renewable energy capacity, multiplying by the capacity factor, and the capacity factor of renewable energy could fluctuate. Uncertainty of stable electricity supply could be increased, so careful examination of renewable energy sources is needed to control renewable energy supply progress. As renewable energy produces electricity sporadically, electricity instability is also increased. Therefore, energy sources which can handle supply and demand insecurity are needed for a stable electricity supply.

6.2 Scenario Analysis

In this passage, a scenario analysis was done to figure out how the electricity portfolio is changed by constraint conditions like the uncertainty of the energy industry and national policy change. To reflect the uncertain situation of the electricity industry, this research analyzed the cases of that basic model; Model 1's CO2 price is 15$/ton and 30$/ton. Then, to reflect the national policy change, this research analyzed that RPS obligation is kept as 10% in 2022's obligation until 2030, and that RPS obligation is increased slightly from 2022's 10% to 12%for 2030. First of all, the analysis of CO2 price change is as follows.

6.2.1 Electricity Portfolio according to CO2 Price Change

To figure out the energy portfolio of CO2 price change, Model 1 was set up for CO2 price as 15$/ton (Model 1-1a) and 30$/ton (Model 1-1b), and both cases were analyzed. Current CO2 prices are about 7$/ton, but this could be increased in the future, so we analyzed both situations proposed above. First of all, when CO2 price is $15, the 2030 optimal electricity portfolio's range and efficient frontier are drawn by using the least-cost optimization model's results as follows.

Table 52. Optimal Portfolio of Model 1-1a under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	32,032	39,731	37,638	11,591	7,678	1,902	5,817
%	23.49%	29.13%	27.60%	8.50%	5.63%	1.39%	4.27%

Generation (MWh)	238,510,272	295,837,026	230,457,474	50,768,580	22,189,420	4,165,380	28,026,306
%	27.42%	34.01%	26.49%	5.84%	2.55%	0.48%	3.22%
Risk	0.235			Cost	94.81 USD/MWh		

Table 53. Optimal Portfolio of Model 1-1a under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	21,180	31,378	32,463	11,483	9,988	12,311	13,550
%	16.00%	23.71%	24.53%	8.68%	7.55%	9.30%	10.24%
Generation (MWh)	157,706,280	233,640,588	198,770,949	50,295,540	28,865,320	26,961,090	65,283,900
%	20.71%	30.68%	26.10%	6.60%	3.79%	3.54%	8.57%
Risk	0.216			Cost	106.63 USD/MWh		

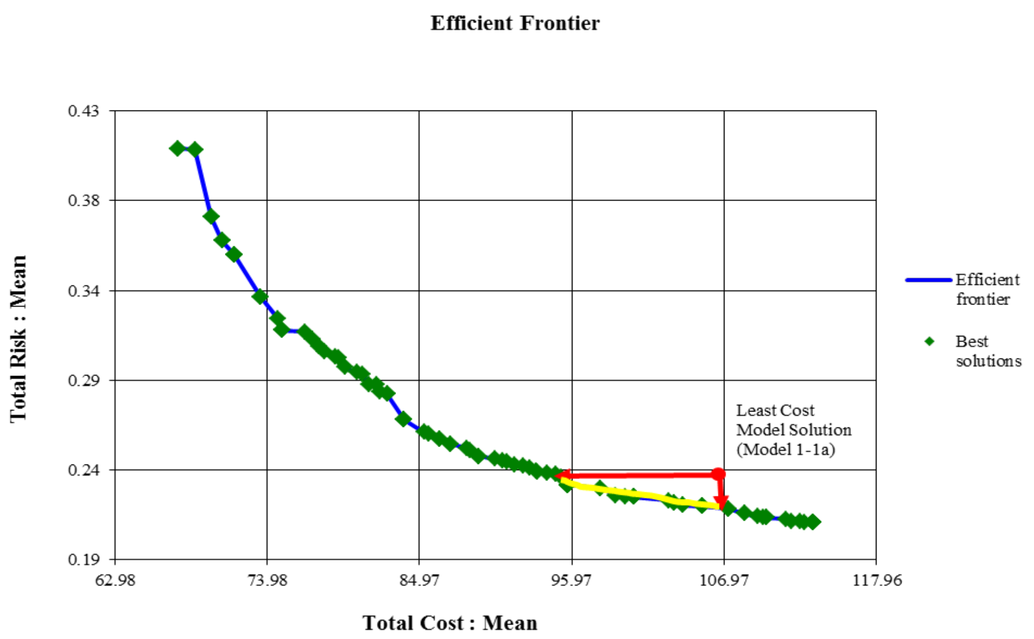


Figure 34. Efficient Frontier and Least Cost Solution of Model 1-1a

The portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in the case of Model 1-1a, the optimal portfolio exists on the efficient frontier in which the risk is between 0.216 and 0.235 and the cost is between 94.81 and 106.63 USD/MWh. Fig. 35 illustrates the results of the least-cost analysis of Model 1-1a and the ratio of the amount produced from each source of energy when risk or cost is given and moved to the efficient frontier.

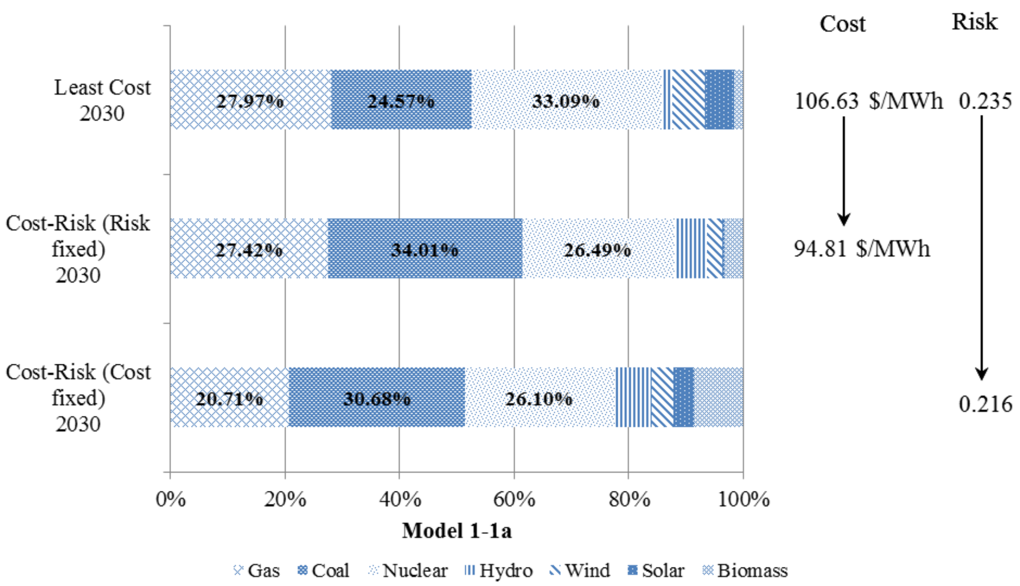


Figure 35. The Proportion of the Energy Sources of Model 1-1a in 2030

Next, in the case that CO2 price is $30, the electricity portfolio is as follows.

Table 54. Optimal Portfolio of Model 1-1b under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	25,984	36,223	36,725	11,604	7,486	2,247	6,782
%	20.45%	28.51%	28.91%	9.13%	5.89%	1.77%	5.34%
Generation (MWh)	193,476,864	269,716,458	224,867,175	50,825,520	21,634,540	4,920,930	32,675,676
%	24.24%	33.79%	28.17%	6.37%	2.71%	0.62%	4.09%
Risk	0.235			Cost	96.85 USD/MWh		

Table 55. Optimal Portfolio of Model 1-1b under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	34,187	31,590	34,159	11,596	7,351	9,463	13,516
%	24.10%	22.27%	24.08%	8.17%	5.18%	6.67%	9.53%
Generation (MWh)	254,556,402	235,219,140	209,155,557	50,790,480	21,244,390	20,723,970	65,120,088
%	29.71%	27.45%	24.41%	5.93%	2.48%	2.42%	7.60%
Risk	0.218			Cost	108.87 USD/MWh		

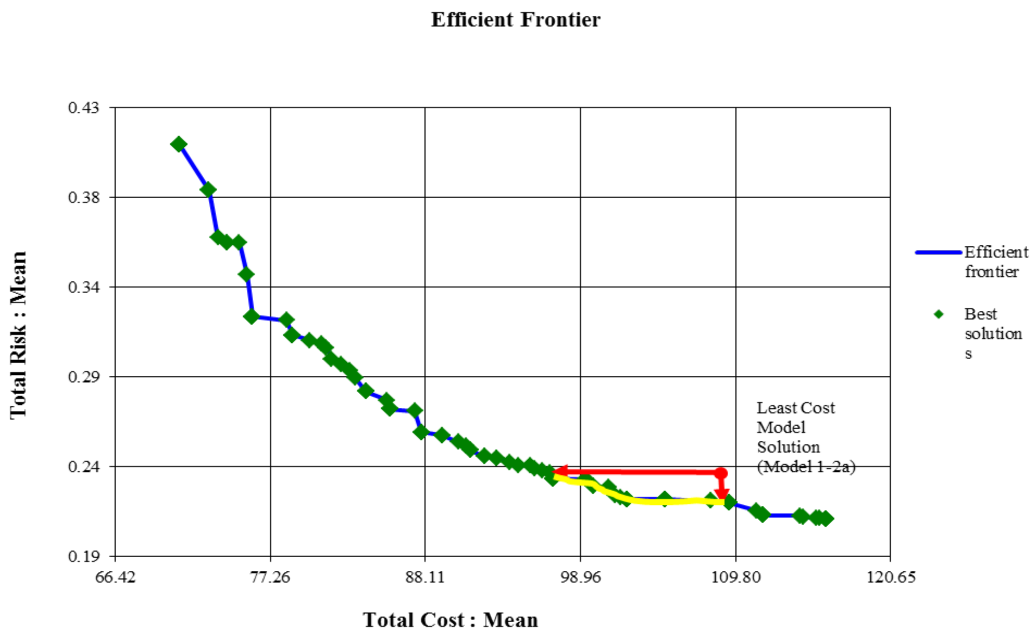


Figure 36. Efficient Frontier and Least Cost Solution of Model 1-1b

The portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in the case of Model 1-1b, the optimal portfolio exists on the efficient frontier in which the risk is between 0.218 and 0.235 and the cost is between 96.85 and 108.87 USD/MWh. Fig. 37 illustrates the results of the least-cost analysis of Model 1-1b and the ratio of the amount produced from each source of energy when risk or cost is given and moved to the efficient frontier.

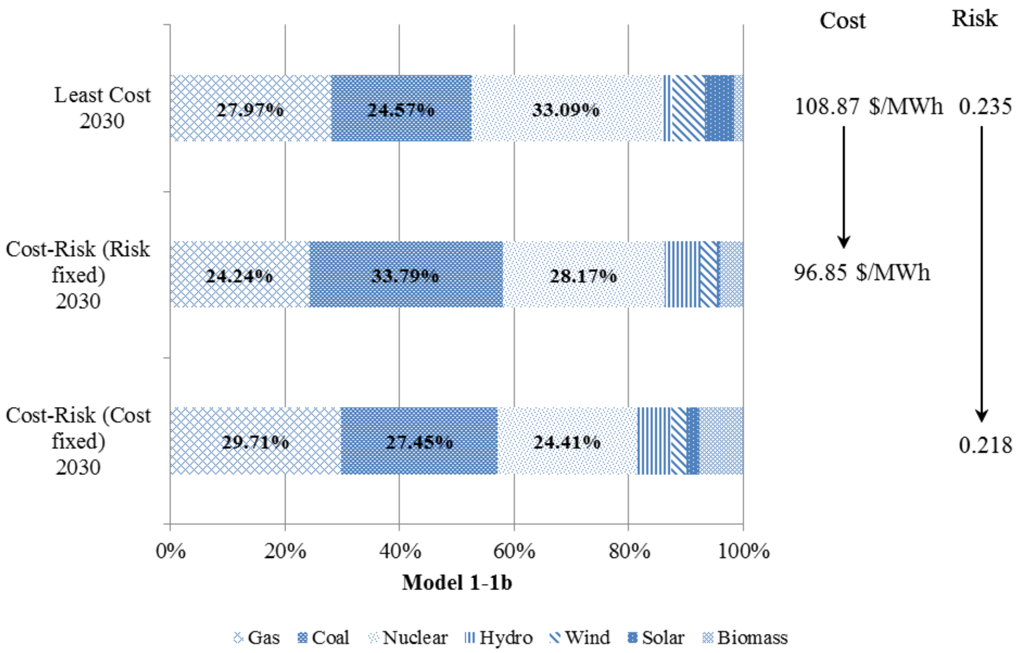


Figure 37. The Proportion of the Energy Sources of Model 1-1b in 2030

As examined in the above results, when carbon price is increasing, the importance of coal is greatly deceasing compared to other energy resources regardless whether cost fixed or risk fixed. Moreover, decreasing coal's generation importance is divided into gas energy and nuclear energy, and change in the three models' risk according to their cost is as follows. When carbon price is increasing, risk is increasing, and optimal generation cost is also changed. This result will help to forecast the risk according to carbon price change and to set up appropriate generation cost.

Table 56. Efficient Frontiers – Sensitivity Analysis on Different Cost of Model 1-1

Cost [USD/MWh]	Model 1-1a			Model 1-1b		
	Base Model	New Risk	Risk Difference	Base Model	New Risk	Risk Difference
94	0.2271	0.2354	3.3%	0.2271	0.2431	6.2%
96	0.2253	0.2291	1.7%	0.2253	0.2373	5.3%
98	0.2206	0.2291	3.8%	0.2206	0.2318	5.0%
100	0.2183	0.2226	2.0%	0.2183	0.2278	4.3%
102	0.2165	0.2226	2.8%	0.2165	0.2217	2.4%
104	0.2149	0.2194	2.1%	0.2149	0.2208	2.7%
106	0.2132	0.2176	2.1%	0.2132	0.2206	3.5%
108	0.2114	0.2162	2.3%	0.2114	0.2206	4.4%
110	0.2096	0.2117	1.0%	0.2096	0.2187	4.3%

6.2.2 Electricity Portfolio according to RPS Obligation Rate Change

Next, electricity portfolio according to change of RPS obligation ratio was analyzed. Korea currently decides RPS obligation ratio as 11% until 2030. This research analyzed the energy portfolio in the case that RPS obligation ratio is kept as 10% from 2022 to 2030 (Model 1-2a) and in the case that RPS obligation ratio is set up as 12% until 2030 (Model 1-2b). First of all, the energy portfolio in the case that RPS obligation ratio is 10% (Model 1-2a) is as follows.

Table 57. Optimal Portfolio of Model 1-2a under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	40,742	41,129	44,804	11,604	7,257	2,307	6,350
%	26.42%	26.67%	29.06%	7.53%	4.71%	1.50%	4.12%

Generation (MWh)	303,364,932	306,246,534	274,334,892	50,825,520	20,972,730	5,052,330	30,594,300
%	30.60%	30.89%	27.67%	5.13%	2.12%	0.51%	3.09%
Risk	0.237			Cost	94.34 USD/MWh		

Table 58. Optimal Portfolio of Model 1-2a under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	28,825	28,114	29,670	11,604	9,988	4,978	13,550
%	22.75%	22.18%	23.41%	9.16%	7.88%	3.93%	10.69%
Generation (MWh)	214,630,950	209,336,844	181,669,410	50,825,520	28,865,320	10,901,820	65,283,900
%	28.18%	27.49%	23.86%	6.67%	3.79%	1.43%	8.57%
Risk	0.214			Cost	103.95 USD/MWh		

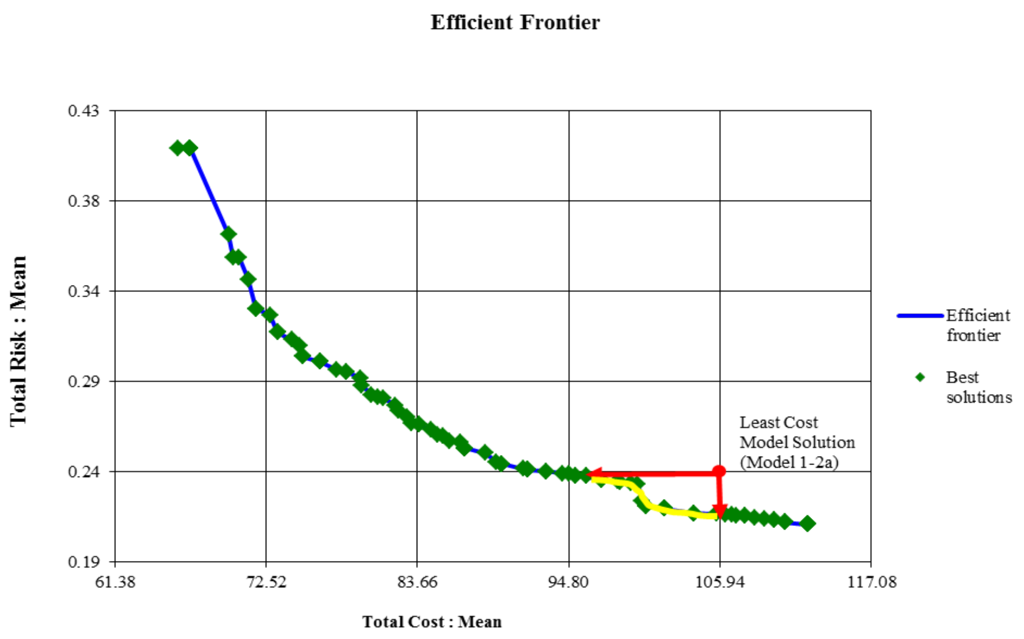


Figure 38. Efficient Frontier and Least Cost Solution of Model 1-2a

Therefore, the portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in case of Model 1-2a, the optimal portfolio exists on the efficient frontier in which the risk is between 0.214 and 0.237 and the cost is between 94.34 and 103.95 USD/MWh. Fig. 39 illustrates the result of the least-cost analysis of Model 1-2a and the ratio of the amount produced from each source of energy when risk or cost is given and moved to the efficient frontier.

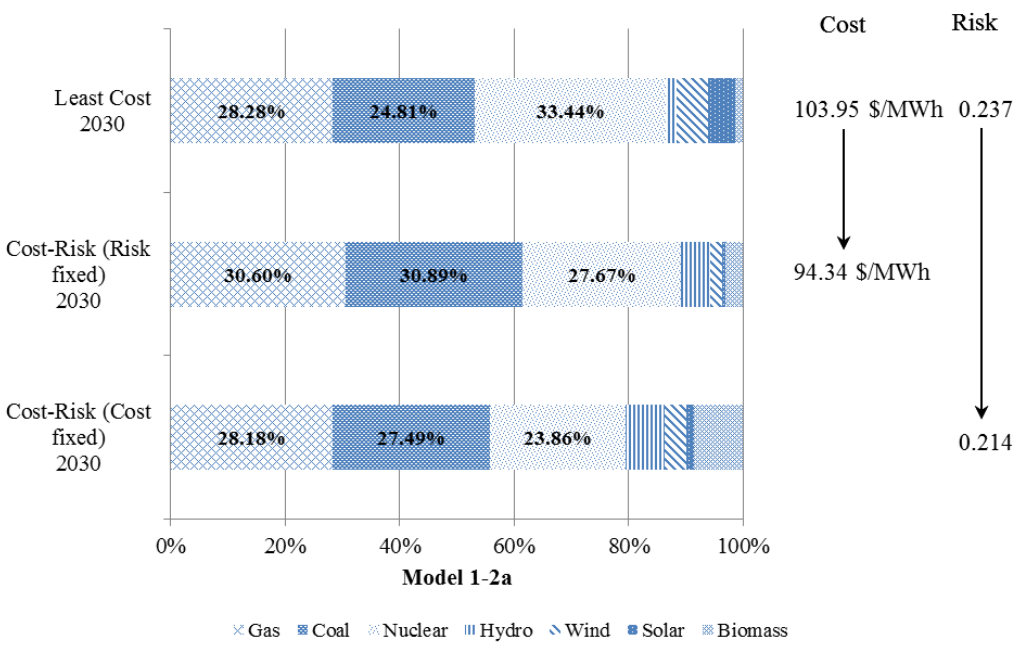


Figure 39. The Proportion of the Energy Sources of Model 1-2a in 2030

Next, the energy portfolio in the case that RPS obligation ratio is 12% (Model 1-2b) is as follows.

Table 59. Optimal Portfolio of Model 1-2b under fixing risk

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	29,323	27,687	28,477	11,604	9,988	8,071	13,550
%	22.78%	21.51%	22.13%	9.02%	7.76%	6.27%	10.53%
Generation (MWh)	218,339,058	206,157,402	174,364,671	50,825,520	28,865,320	17,675,490	65,283,900
%	28.67%	27.07%	22.90%	6.67%	3.79%	2.32%	8.57%
Risk	0.232			Cost	93.94 USD/MWh		

Table 60. Optimal Portfolio of Model 1-2b under fixing cost

	Gas	Coal	Nuclear	Hydro	Wind	Solar	Biomass
Capacity (MW)	24,033	39,550	34,318	9,906	9,186	41	13,377
%	18.43%	30.33%	26.32%	7.60%	7.04%	0.03%	10.26%
Generation (MWh)	178,949,718	294,489,300	210,129,114	43,388,280	26,547,540	89,790	64,450,386
%	21.88%	36.00%	25.69%	5.30%	3.25%	0.01%	7.88%
Risk	0.212			Cost	106.2 USD/MWh		

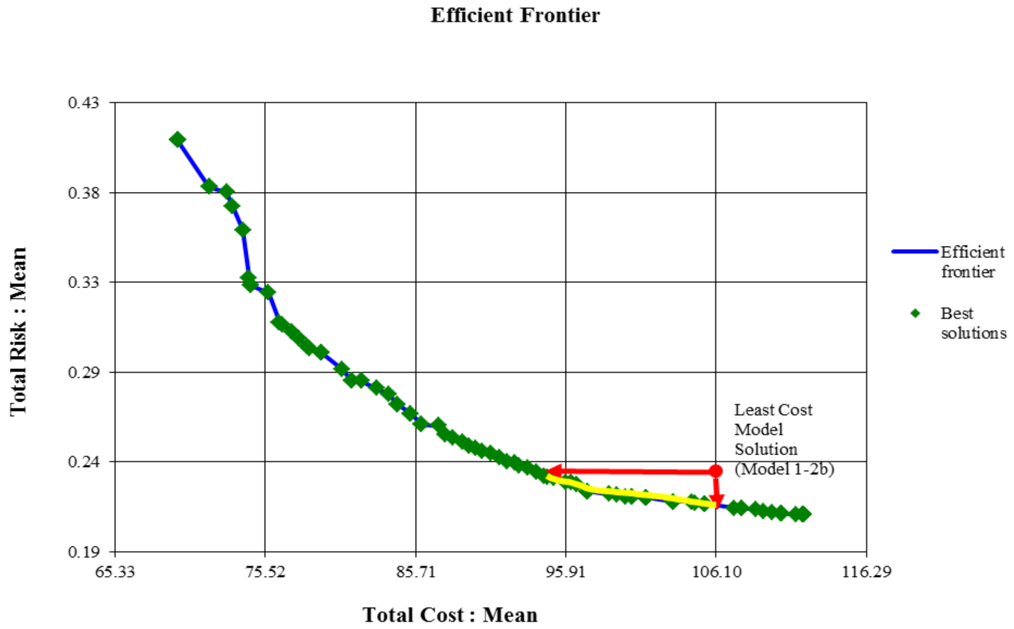


Figure 40. Efficient Frontier and Least Cost Solution of Model 1-2b

The portfolio analyzed in the least-cost optimization model, considering the correlation of energy sources and the risk of energy sources, can be the optimal portfolio within the yellow area. That is, in the case of Model 1-2b, the optimal portfolio exists on the efficient frontier in which the risk is between 0.212 and 0.232 and the cost is between 93.94 and 106.2 USD/MWh. Fig. 41 illustrates the result of the least-cost analysis of Model 1-2b and the ratio of the amount produced from each source of energy when risk or cost is given and moved to the efficient frontier.

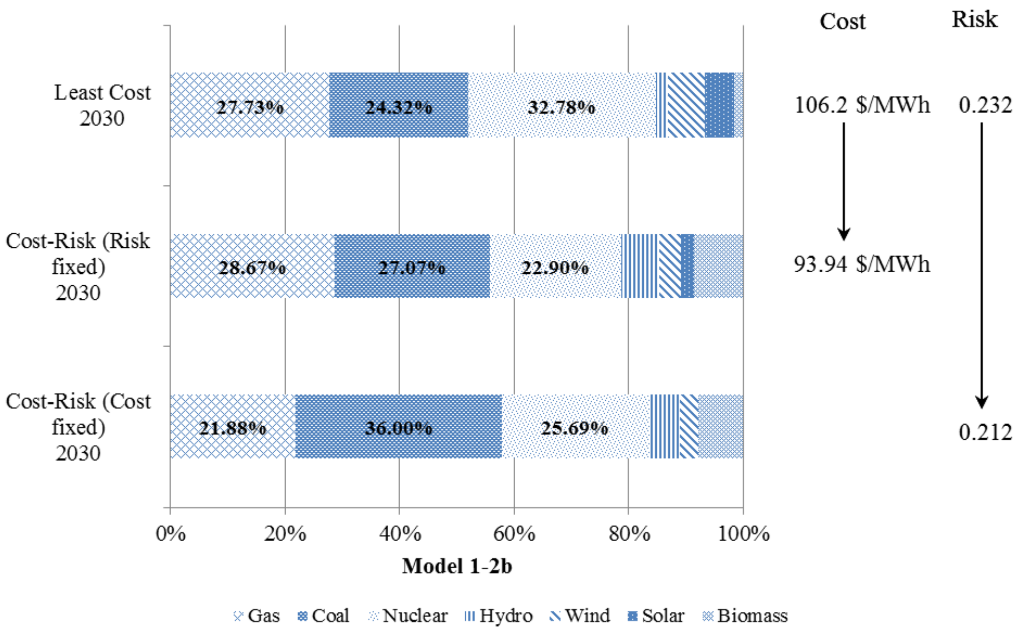


Figure 41. The Proportion of the Energy Sources of Model 1-2b in 2030

As the above results indicate, in the case of Model 1-2a's risk-fixed conditions, the importance of renewable energy is decreased and the importance of coal and gas is increased for the decreasing total cost. However, in the case of a cost-fixed model, the importance of nuclear energy is radically decreased and the importance of renewable energy is increased. In the case of 1-2b, as risk is kept, ythe importance of nuclear energy is radically decreased to reduce cost. This shows that the optimal energy portfolio is drawn, when the importance of coal is increased as the importance of renewable energy is slightly increased. Next, the basic model and the new model's change ratio of risk according to their cost are examined. The analyzed results show that, as RPS obligation ratio is increased, risk is decreased. This result is expected to help to establish appropriate RPS policy.

Table 61. Efficient Frontiers – Sensitivity Analysis on Different Cost of Model 1-2

Cost [USD/MWh]	Model 1-2a			Model 1-2b		
	Base	New Risk	Risk Difference	Base	New Risk	Risk Difference
94	0.2271	0.2354	3.8%	0.2271	0.2431	1.2%
96	0.2253	0.2291	4.4%	0.2253	0.2373	0.3%
98	0.2206	0.2291	5.4%	0.2206	0.2318	0.2%
100	0.2183	0.2226	5.6%	0.2183	0.2278	-0.1%
102	0.2165	0.2226	0.3%	0.2165	0.2217	0.6%
104	0.2149	0.2194	1.1%	0.2149	0.2208	0.2%
106	0.2132	0.2176	0.6%	0.2132	0.2206	0.6%
108	0.2114	0.2162	0.9%	0.2114	0.2206	0.3%
110	0.2096	0.2117	0.7%	0.2096	0.2187	0.2%

6.3 Implications

The objective of this research is to form an energy portfolio that makes efficient allocation of energy resources for sustainable development. The Korean electricity generation industry is analyzed from two different perspectives: least-cost and cost-risk optimization. For this analysis, physical and policy constraints are reflected to form a realistic portfolio. Specifically, in the case of renewable energy, this research is different from other portfolio research in reflecting the technical level and the limited construction condition of each renewable energy source. A survey of electricity area experts is used to reflect the realizable level of each renewable energy source, and the realizable potential of renewable energy sources which follow technology diffusion pattern is estimated by using the survey results.

Moreover, this research is analyzed with two different models: the least-cost optimization and cost-risk optimization models, which can reflect the characteristics of energy sources. Even though demand of carbon reduction policy is high for sustainable development and climate change, many countries could not implement this into their systems, because it is economically infeasible. Many works of research with a least-cost model have been conducted to solve this problem, but the situation that considers only cost is unrealistic, and it is easy to ignore the correlation among various energy sources. Moreover, it is difficult to reflect enough physical and policy constraints in the cost-risk optimization model and to set up the initial importance of each energy source. However, the analysis method that this research suggested analyzes the least-cost optimization model reflecting enough realistic physical and policy constraints, and then the energy portfolio, which reflects risk and correlation of energy sources, is formed to apply a cost-risk optimization model which can reflect correlation among energy sources to the result of the least-cost model. Cost-effectiveness, correlation, and risk of energy sources are reflected together through this research model, so realistic and realizable energy portfolios can be proposed by the model.

6.3.1 Policy Perspective

Korea’s electricity generating cost does not include carbon cost now. In other words, the effects incurred from carbon are not included in the generating cost, so it is difficult to forecast effects incurred by carbon. However, this research uses a levelized cost of energy (LCOE) to reflect the carbon effects incurred by the electricity supply of each energy source. According to the analyzed result by this research reflecting the carbon price, among conventional energy, the electricity generation of coal is decreased, and the generation of gas is increased in the process of time. It is expected that the cost of carbon emission reduces the generation of coal. In the case that external cost and pollution cost are reflected, the importance of coal generation is decreased much more. That is, in the current generating cost system, we could know that electricity generation by coal is more than the optimal generation drawn by the proposed model in this study. Therefore, according to the proposed model in this study, electricity generation of coal is expected to be of excess supply.

Decreasing coal generation is substituted by gas and nuclear energy. Gas and nuclear energy have comparative advantages in carbon emission and carbon cost than coal energy. However, the gas prices used in this study reflect cross subsidiary, so if the price system is changed, the importance of gas generation could be changed. Gas generation is unfavorable economically in the current situation, but gas generation is useful socially to solve the transmission network problem which incurs serious social conflict. Moreover, gas is expected to be a reasonable alternative environmentally, considering the nuclear waste problem and greenhouse gas emission by coal. The appearance of shale gas is expected to be especially important in solving the uncertainty of stable electricity supply and electricity management.

In the case of nuclear generation, this research used the social cost estimation of nuclear energy drawn from the Japanese Fukusima nuclear accident. However, the social cost estimated by Japan only included the accident risk response cost and policy cost. This social cost value held the maximum amount of damages by the Fukusima nuclear accident fitting into a sample plant, so the amount of damages may increase in the future. In the case of Korea, 400 tons of nuclear waste are emitted every year, so handling nuclear waste, especially high levels of radioactive waste, securing public acceptance, and transmission of the network construction problems by location of nuclear plant are very important.

The social cost of nuclear energy includes waste handling, public inconvenience, and transmission network construction, and conflict costs need to be drawn to reevaluate nuclear energy generation economically; then it is expected to reflect the uncertain importance of nuclear generation minutely. Korea’s long-term electricity supply and demand plan has a plan to expand the importance of nuclear energy of all generation to 48% until 2024 in order to satisfy the growing electricity demand stably. However, after the Fukusima nuclear accident, concern about nuclear energy stability is growing, and the transmission grid allocation and stability could be risky and cause an unstable electricity supply because nuclear plants are located far from customers. Moreover, it is desirable to pursue various energy sources than deepen one energy source for electricity supply stability, because there is no connected grid with neighboring countries. Therefore, the importance of nuclear energy in the electricity generation mix is needed to be reduced for electricity system stability, and the appropriate generation level by using fossil fuel is needed to be kept like the proposed result of this study.

Renewable energy supply progress is also needed to be controlled. The government implemented RPS from 2012 and regulated the renewable energy generation importance of all generation as 2% yearly in 2012 and 10% yearly after 2022. However, it is pointed out that yearly obligation of renewable energy is set excessively higher than the realistic supply progress. This could cause capacity shortage in the future.

Renewable energy generation is calculated by the renewable energy capacity multiplying capacity factor, and the capacity factor of renewable energy could fluctuate, so uncertainty of stable electricity supply could be increased. Therefore, careful examination about renewable energy sources is needed to control renewable energy supply progress. As renewable energy produces electricity sporadically, electricity instability is also increased. Therefore, energy sources which can handle supply and demand insecurely are needed for stable electricity supply.

6.3.2 Least-Cost Optimization Model Perspective

We suggested an energy portfolio to minimize the social and environmental impacts by using the least-cost optimization model. We especially considered both conventional energy such as coal, gas, and nuclear energy as well as renewable energy. Also, by reflecting the Korean government's policies and plans, the reality of the analysis model was improved.

In addition, the uncertainty of fuel price and CO_2 price and the learning rate relevant to newly constructed generating units were considered in this study by using MCS. It is difficult to precisely reflect the tendency of the price of fuel and CO_2 and the learning rate in the model. Therefore, with MCS, such uncertain variables were effectively estimated.

In the case of renewable energy, the capability of the construction of generating unit for each source of energy largely varies depending on the level of technology and the environment. In order to adjust and apply this to the circumstances in Korea, we used the theory presented by IEA (2008), which was integrated to the technology diffusion theory and experts survey. We estimated the realizable potential of renewable energy in Korea and reflected it in the model. As a result, we could derive relatively more realistic and rational results. Previous studies did not consider the potential supply of renewable energy and in turn ended up with unrealistic results. In this study, in order to improve these results, the realizable potential of renewable energy sources were estimated and reflected annually.

6.3.3 Cost-Risk Optimization Model Perspective

The previous cost-risk optimization model lacked the reasons for setting the ratio of energy, since it used the current production capacity or the future ratio of amount produced subjectively expected by the researcher. In this study, however, the year 2030 portfolio analyzed from the least-cost optimization model was used, which provided the objective reasons for the ratio of energy sources. This is the energy portfolio with stable supply considering the risk of energy sources and the correlation of energy sources, which is derived by using the energy distribution, which minimized the social and environmental impacts. It is significant that both the production and consumption of energy were considered. Thus, the analysis reflected two principles required for sustainable growth and suggested a way to constitute the realistic optimal portfolio in which the current situation is reflected.

Previous portfolio analysis considered only three limitations: (1) the sum of investment ratio must be 1, (2) the expected cost of portfolio equals the expected cost of individual investment multiplied by the ratio of investment, and (3) the investment ratio of individual investment ranges from 0 to 100%. However, this study suggested a specific and realistic cost-risk optimization model which reflects all of the limitations previously mentioned in the least-cost optimization model.

Additionally, the previous cost-risk optimization model merely set the weights of cost and risk under qualitative assessment or mainly performed sensitivity analysis with the changing weights of cost and risk and did not suggest the rational range of cost and risk. For this reason, the range of portfolio constituted under the consideration of cost-risk ended up too broad. For example, Avista, NorthWestern, and PacifiCorp performed stochastic analysis to generate numerous cost outcomes and candidate portfolios. As a result, each candidate portfolio had an expected cost and risk. Avista’s optimization process assigned equal weight to cost and risk while constructing the preferred portfolio. NorthWestern subjectively weighted cost (70% weight on the mean cost) higher than risk (30% weight on the 95th percentile cost) to draw a risk-adjusted cost for each candidate portfolio. However, PacifiCorp evaluated the cost/risk tradeoff more qualitatively and did not seek to draw a single optimal portfolio. Instead, the expected cost and risk characteristics of each portfolio were reviewed, and the preferred portfolio was selected subjectively based on that review. Idaho Power and PSCo relied on a scenario analysis to manage the cost/risk tradeoff. Idaho Power did not make a tradeoff at all, but portfolio selection was based purely on a scenario-weighted assessment of expected costs, with no apparent consideration given to the expected variability of those costs. PSCo did not assign probabilities to its scenarios and therefore evaluated the cost/risk tradeoff qualitatively.

Table 62. Summary of Cost/Risk Trade off

	Utility	Cost/Risk Weighting
Stochastic	Avista	50%/50%
	North-Western	70%/30%
	Pacific-Corp	Qualitative
Scenarios	Idaho power	None
	PSco	Qualitative

Source: Bolinger & Wiser (2005)

In contrast, this study clearly suggested on which area of the efficient frontier the portfolio should exist in order to have the optimal cost-risk portfolio by using the result of the least-cost optimization model. By doing so, we made a rational suggestion about how to constitute the energy portfolio to achieve sustainable growth.

In addition, an analysis method, which applied both the least-cost optimization model and cost-risk optimization model, can be applied to various external environments and policy conditions. As we have seen from the scenario analysis, this study also has implications proposing a realistic portfolio, which optimized an energy portfolio which applied a different carbon price and RPS obligation rate.

Therefore, this research could be applied to various situations in which price change is incurred by time like energy, so this research is expected to be applied to transportation, construction, and various industries in addition to the electricity industry.

6.4 Further Research

The result of the cost-risk optimization model analyzed in this study has a significant implication in that it considered both socio-economic impacts and stable supply of energy to achieve sustainable growth. Nevertheless, the method to specifically decide the range of an optimal portfolio on the efficient frontier suggested in this study is required. For example, future studies should focus on the standards with which the decision for an optimal portfolio will be made through policy agreements and discussion with experts.

The current levelized generation cost internalizes only carbon price. According to this, the actual effects of energy sources cannot be fully reflected in the current generation cost. This point is understood by Japan's calculated social cost of nuclear power after the Fukushima nuclear power accident. This research forms a portfolio to reflect the research results of external cost classified by IEA (1995) and pollution cost. However, different works of research draw different results and different specific standards of these studies draw inconsistent results, so some cost-risk optimization models show unrealistic results. However, socially influential elements like carbon cost should be internalized in generation cost. For this purpose, studies that internalize cost elements like environment cost or inconvenience cost into generation cost for reflecting realistic situation are needed in the future.

LCOE reflecting carbon cost is used in this research. Carbon cost, which has been applied in current research about the energy portfolio, is formed in the carbon trade market. Therefore, carbon price tends to be changed by market circumstance. However, there is a question regarding whether it is right to apply the changed carbon price according to the market situation. So, further in-depth study about the changed carbon price by market situation is needed, because carbon price is an important cost factor for forming an energy portfolio.

This problem was raised from the start of external cost research. Previous research applied carbon cost as an additional cost for developing technology or facilities reducing carbon, but ExternE started research about effects on the environment or human body from carbon emissions, and this kind of research has been done actively. Then the environmental effect caused by carbon emissions was calculated and internalized in generation cost, and as carbon trade was implemented, carbon price has been decided by the market. Therefore, the approach to carbon price considering both technological factors and environmental factors together is needed.

The power transmission cost is also an important issue in the electricity industry. It is not reflected in generation cost, but it considers a big part of the total generation cost. If transmission cost is reflected in generation cost, it is expected that the importance of conventional energy, like thermal and nuclear power generation, will be decreased in the energy portfolio. Therefore, it is considered that further research about transmission cost and internalization of this cost in generation cost is needed.

Additionally, electricity demand was assumed to increase yearly by 3% according to the electricity demand-supply plan, but this should be reformed in consideration of the recent electricity shortage situation. A more realistic energy portfolio could be established by reflecting electricity demand forecast, which reflects the real situation well to forecast the demand of the main components of electricity demand.

Bibliography

Abdullah, S., & Jeanty, P.W. (2011). Willingness to pay for renewable energy: Evidence from a contingent valuation survey in Kenya. *Renewable and Sustainable Energy Reviews, 15*(6), 2974-2983.

Agnew, RA. (1971). Counter-examples to an assertion concerning the normal distribution and a new stochastic price fluctuation model. *The Review of Economic Studies*, 381-383.

Aguilar, F.X. (2009). Investment preferences for wood-based energy initiatives in the US. *Energy Policy, 37*(6), 2292-2299.

Álvarez-Farizo, B., & Hanley, N. (2002). Using conjoint analysis to quantify public preferences over the environmental impacts of wind farms. An example from Spain. *Energy policy, 30*(2), 107-116.

Arnesano, M., Carlucci, AP, & Laforgia, D. (2012). Extension of portfolio theory application to energy planning problem–The Italian case. *Energy, 39*(1), 112-124.

Arrow, K.J. (1971). *Essays in the theory of risk-bearing* (Vol. 1): Markham Publishing Company Chicago.

Asif, M., & Muneer, T. (2007). Energy supply, its demand and security issues for developed and emerging economies. Renewable and Sustainable *Energy Reviews, 11*(7), 1388-1413.

Association, European Wind Energy. (2011). *Pure Power-wind energy targets for 2020 and 2030*: Ewea.

Awerbuch, S. (1993). The surprising role of risk in utility integrated resource planning. *The Electricity Journal, 6*(3), 20-33.

Awerbuch, S. (1995a). Market-based IRP: It's easy!!! *The Electricity Journal, 8*(3), 50-67.

Awerbuch, S. (1995b). New economic cost perspectives for valuing solar technologies. *Advances in solar energy, 10*.

Awerbuch, S. (2000a). Getting It Right: The real cost impacts of a renewables portfolio standard. *Public Utilities Fortnightly, 138*(4), 44-55.

Awerbuch, S. (2000b). Investing in photovoltaics: risk, accounting and the value of new technology. *Energy Policy, 28*(14), 1023-1035.

Awerbuch, S. (2002). *Energy Diversity and Security in the EU: Mean-Variance Portfolio Analysis, of Electricity Generating Mixes, and the Implications for Renewables.* Paper presented at the EURELECTRIC Twin Conf. on DG, Brussels.

Awerbuch, S. (2004). Restructuring our electricity networks to promote decarbonisation. *Tyndall Centre for Climate Change Research Working Paper*, 49.

Awerbuch, S. (2006). Portfolio-based electricity generation planning: policy implications for renewables and energy security. *Mitigation and adaptation strategies for Global Change, 11*(3), 693-710.

Awerbuch, S., & Berger, M. (2003a). Energy security and diversity in the EU: A mean-variance portfolio approach. *IEA Research Paper*.

Awerbuch, S., & Berger, M. (2003b). Applying portfolio theory to EU electricity planning and policy-making. *IEA/EET working paper*, 72.

Awerbuch, S., & Deehan, W. (1995). Do consumers discount the future correctly?: A market-based valuation of residential fuel switching. *Energy Policy, 23*(1), 57-69.

Awerbuch, S., Jansen, J., Buerskens, L., & Drennen, T. (2005). The Cost of geothermal energy in the western US region: A portfolio-based approach. *Sandia National Laboratories*.

Awerbuch, S., & Yang, S. (2007). Efficient electricity generating portfolios for Europe: maximising energy security and climate change mitigation. *EIB papers, 12*(2), 8-37.

Bacon, R.H., Besant-Jones, J.F., and Heidurian, J. (1996). Estimating construction costs and schedules: Experience with power generation projects in developing countries. *World Bank Technical Paper No*. 325.

Bae, J.H., & Cho, G.L. (2010). A dynamic general equilibrium analysis on fostering a hydrogen economy in Korea. *Energy Economics, 32*, S57-S66.

Baer, P., Athanasiou, T., Kartha, S., & Kemp-Benedict, E. (2008). The greenhouse development rights framework. *The Right to Development in a Climate Constrained World. 2a edición. Berlín: Heinrich Böll Stiftung/Christian Aid/EcoEquity/Stockholm Environment Institute.*

Baños, R., Manzano-Agugliaro, F., Montoya, FG, Gil, C., Alcayde, A., & Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy: A review. *Renewable and Sustainable Energy Reviews, 15*(4), 1753-1766.

Bar-Lev, D., & Katz, S. (2012). A portfolio approach to fossil fuel procurement in the electric utility industry. *The Journal of Finance, 31*(3), 933-947.

Batley, S.L., Colbourne, D., Fleming, PD, & Urwin, P. (2001). Citizen versus consumer: challenges in the UK green power market. *Energy Policy, 29*(6), 479-487.

Beard, L.M., Cardell, J.B., Dobson, I., Galvan, F., Hawkins, D., Jewell, W., Kezunovic, M., Overbye, T.J., Sen, PK., Tylavsky, D.J. (2010). Key technical challenges for the electric power industry and climate change. *Energy Conversion, IEEE Transactions on, 25*(2), 465-473.

Bernow, S., Biewald, B., & Marron, D. (1991). Full-cost dispatch: incorporating environmental externalities in electric system operation. *The Electricity Journal, 4*(2), 20-33.

Bernow, S.S., & Marron, D.B. (1990). *Valuation of Environmental Externalities for*

Energy Planning and Operations: May 1990 Update: Tellus Institute.

Bhattacharyya, S.C. (1997). An estimation of environmental costs of coal-based thermal power generation in India. *International journal of energy research, 21*(3), 289-298.

Bird, L., & Sumner, J. (2010). Green power marketing in the United States: A status report (2009 data).

Bisset, R., & Hagbrink, I. (2009). World bank: 10 years of carbon finance experience: World Bank Group, DC Washington.

BlueNext Statistics. (http://www.bluenext.eu)

Bolinger, M., & Wiser, R. (2005). Balancing cost and risk: The treatment of renewable energy in western utility resource plans. *Lawrence Berkeley National Laboratory: LBNL-58450, August.*

Bolinger, M., Wiser, R., & Golove, W. (2002). *Quantifying the value that wind power provides as a hedge against volatile natural gas prices*. Paper presented at the Proceedings of the American Wind Power Conference.

Borch, K. (1969). A note on uncertainty and indifference curves. *The Review of Economic Studies, 36*(1), 1-4.

Buonanno, P., Carraro, C., & Galeotti, M. (2003). Endogenous induced technical change and the costs of Kyoto. *Resource and Energy economics, 25*(1), 11-34.

Cai, YP, Huang, GH, Yang, ZF, Lin, QG, & Tan, Q. (2009). Community-scale renewable energy systems planning under uncertainty—An interval chance-constrained programming approach. *Renewable and Sustainable Energy Reviews, 13*(4), 721-735.

Cao, L., Bala, G., Caldeira, K., Nemani, R., & Ban-Weiss, G. (2010). Importance of carbon dioxide physiological forcing to future climate change. *Proceedings of the National Academy of Sciences, 107*(21), 9513.

Cass, D., & Stiglitz, J.E. (1970). The structure of investor preferences and asset returns, and separability in portfolio allocation: A contribution to the pure theory of mutual funds. *Journal of Economic Theory, 2*, 122-160.

Chernick, P., & Caverhill, E. (1989). The Valuation of Externalities from Energy

Production, Delivery and Use, Fall 1989 Update. *Chernick and Caverhill Inc., Boston.*

Cifuentes, L.A., & Lave, L.B. (1993). Economic valuation of air pollution abatement: Benefits from health effects. *Annual Review of Energy and the Environment, 18*(1), 319-342.

Cormio, C., Dicorato, M., Minoia, A., & Trovato, M. (2003). A regional energy planning methodology including renewable energy sources and environmental constraints. *Renewable and Sustainable Energy Reviews, 7*(2), 99-130.

Couture, T., & Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy, 38*(2), 955-965.

Dantzig, G.B. (1949). Programming of interdependent activities: II mathematical model. Econometrica, *Journal of the Econometric Society*, 200-211.

DeLaquil, P., Awerbuch, S., & Stroup, K. (2005). A portfolio risk analysis of electricity supply options in the Commonwealth of Virginia. *Chesapeake Climate Action Network Report*.

Delarue, E., De Jonghe, C., Belmans, R., & D'haeseleer, W. (2011). Applying portfolio theory to the electricity sector: Energy versus power. *Energy Economics, 33*(1), 12-23.

Delmas, M., Russo, M.V., & Montes-Sancho, M.J. (2006). Deregulation and environmental differentiation in the electric utility industry. *Strategic Management Journal*, *28*(2), 189-209.

Dixit, A.K., & Stiglitz, J.E. (1977). Monopolistic competition and optimum product diversity. *The American Economic Review*, 297-308.

Doherty, R., Outhred, H., & O'Malley, M. (2006). Establishing the role that wind generation may have in future generation portfolios. *Power Systems, IEEE Transactions on, 21*(3), 1415-1422.

Douglas, J.M. (1988). *Conceptual design of chemical processes*: McGraw-Hill New York.

Engle, R. (2004). Risk and volatility: Econometric models and financial practice. *American Economic Review*, 405-420.

EIA, US. (2012). Annual Energy Outlook 2012.

Elliott, D. (2000). Renewable energy and sustainable futures. *Futures, 32*(3), 261-274.

EPSIS (Electric Power Statistics Information System: http://epsis.kpx.or.kr)

European Commission (EC). (1995). ExternE: Externalities of Energy, *Office for Official Publications of the European Communities,* 1–6.

European Commission (EC). (1999). ExternE: Externalities of Energy, *Office for Official Publications of the European Communities,* 7–10.

Faaij, A., Meuleman, B., Turkenburg, W., van Wijk, A., Bauen, A., Rosillo-Calle, F., & Hall, D. (1998). Externalities of biomass based electricity production compared with power generation from coal in the Netherlands. *Biomass and Bioenergy, 14*(2), 125-147.

Feldstein, M.S. (1969). Mean-variance analysis in the theory of liquidity preference and portfolio selection. *The Review of Economic Studies, 36*(1), 5-12.

Fishburn, P.C. (1977). Mean-risk analysis with risk associated with below-target returns. *The American Economic Review,* 116-126.

FInkenrath, M.I. (2011). Cost and performance of carbon dioxide capture from power generation: OECD Publishing.

Fishbone, L.G., & Abilock, H. (1981). Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version. *International journal of Energy research*, *5*(4), 353-375.

Friedrich, R., & Voss, A. (1993). External costs of electricity generation. *Energy policy*, *21*(2), 114-122.

Gerlagh, R., & Van der Zwaan, B. (2003). Gross world product and consumption in a global warming model with endogenous technological change. *Resource and Energy Economics*, *25*(1), 35-57.

Glover, F. (1977). Heuristics for integer programming using surrogate constraints. *Decision Sciences*, *8*(1), 156-166.

Glover, F. (1996). Tabu search and adaptive memory programming-advances, applications and challenges. *Interfaces in computer science and operations research*, *1*.

Glover, F., Laguna, M., & Martí, R. (2003). Scatter search. *Advances in evolutionary computing*, 519-537.

Gotham, D., Muthuraman, K., Preckel, P., Rardin, R., & Ruangpattana, S. (2009). A load factor based mean–variance analysis for fuel diversification. *Energy Economics, 31*(2), 249-256.

Goulder, L.H., & Schneider, S.H. (1999). Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics, 21*(3), 211-253.

Green, R. (2006). Carbon tax or carbon permits: the impact on generators' risks. *Institute for Energy Research and Policy, University of Birmingham.*

Hall, D.C. (1990). Preliminary estimates of cumulative private and external costs of energy. *Contemporary Economic Policy, 8*(3), 283-307.

Hart, E.K., & Jacobson, M.Z. (2011). A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables. *Renewable Energy, 36*(8), 2278-2286.

Helby, P. (1998). Renewable energy projects in Sweden: An overview of subsidies, taxation, ownership and finance: *Department of Environmental and Energy System Studies.*

Herzog, A.V., Lipman, T.E., Edwards, J.L., & Kammen, D.M. (2001). Renewable energy: a viable choice. *Environment: Science and Policy for Sustainable Development, 43*(10), 8-20.

Herzog, H.J. (2001). Peer reviewed: What future for carbon capture and sequestration? *Environmental science & technology, 35*(7), 148-153.

Hill, D., Sailor, V.L., & Fishbone, L.G. (1981). Future US energy technologies: Cost and oil-import tradeoffs. *Energy, 6*(12), 1405-1431.

Hitchcock, F.L. (1941). The distribution of a product from several sources to numerous localities. *J. Math. Phys, 20*(2), 224-230.

Hohmeyer, O., Ottinger, R.L., & Rennings, K. (1997). *Social costs and sustainability: valuation and implementation in the energy and transport sector: proceedings of an international conference, held at Ladenburg, Germany, May 27-30, 1995.*

Paper presented at the Social Costs and Sustainability-International Conference, 1995, Ladenburg, Germany.

Hohmeyer, O. (1988). *Social costs of energy consumption*: Springer.

Hohmeyer, O. (1992). The social costs of electricity-renewables versus fossil and nuclear energy. *International journal of solar energy, 11*(3-4), 231-250.

Holland, M., & Watkiss, P. (2002). Benefits table database: Estimates of the marginal external costs of air pollution in Europe. *Database Prepared for European Commission DG Environment.*

Huang, Y.H., & Wu, J.H. (2008). A portfolio risk analysis on electricity supply planning. *Energy Policy, 36*(2), 627-641.

Huisman, R., Mahieu, R., & Schlichter, F. (2009). Electricity portfolio management: Optimal peak/off-peak allocations. *Energy Economics, 31*(1), 169-174.

IEA, D.R. (2008). Principles for effective policies. *International Energy Agency (IEA), Paris*.

IEA. (1995). Global warming damage and the benefits of mitigation. Cheltenham. IEA Greenhouse gas R&D programme

IEA. (2010). Projected Cost of Generating Electricity. *IEA, Paris.*

IEA. (2011). World Energy Outlook. *IEA, Paris.*

Jafferali, M., Venkateshwaran, J., & Son, Y.J. (2005). Performance comparison of search-based simulation optimisation algorithms for operations scheduling. *International Journal of Simulation and Process Modelling, 1*(1), 58-71.

Jain, S., Creasey, R. R., Himmelspach, J., White, K. P., & Fu, M. (2011). Performance analysis of commercial simulation-based optimization packages: OptQuest and Witness optimizer. *Proceedings of the 2011 Winter Simulation Conference*

Jansen, JC, Beurskens, LWM, & Van Tilburg, X. (2006). Application of portfolio analysis to the Dutch generating mix. *Energy research Center at the Netherlands (ECN) report C-05-100*.

Jegarl, S., Baek, J.I., Jang, D.S., & Ryu, C.K. (2009). Impact assessment of CO2 mitigation options in Korea using energy system analysis model. *Energy*

Procedia, 1(1), 3747-3754.

Jeong, S.J., Kim, K.S., Park, J.W., Lim, D., & Lee, S. (2008). Economic comparison between coal-fired and liquefied natural gas combined cycle power plants considering carbon tax: Korean case. *Energy, 33*(8), 1320-1330.

Kanudia, A., & Loulou, R. (1998). Robust responses to climate change via stochastic MARKAL: The case of Quebec. *European Journal of Operational Research, 106*(1), 15-30.

Kara, M., Syri, S., Lehtilä, A., Helynen, S., Kekkonen, V., Ruska, M., & Forsström, J. (2008). The impacts of EU CO2 emissions trading on electricity markets and electricity consumers in Finland. *Energy Economics*, *30*(2), 193-211.

Kartha, S., & Erickson, P. (2011). Comparison of Annex 1 and non-Annex 1 pledges under the Cancun Agreements. *Stockholm Environment Institute.*

KEPCO. (2010). Financial effect analysis and counterplan establishment of RPS

Kim, H.S., Ko, K.H., Ahn, N.S., & Cho, B.O. (2006). The System dynamics model development for forecasting the capacity of renewables. *Korea System Dynamics* *research, 7*(2), 35-56

Kim, J.O & Cho, K.Y. (2002). Promotion strategy of renewable energy in competitive electricity market. *Korea Energy Economics Institute. 2*(9), 1-141.

Kim, J., Park, J., Kim, H., & Heo, E. (2011). Assessment of Korean customers' willingness to pay with RPS. *Renewable and sustainable energy reviews*.

Kim, S., Koo, J., Lee, C.J., & Yoon, E.S. (2012). Optimization of Korean energy planning for sustainability considering uncertainties in learning rates and external factors. *Energy*.

Kirat, D., & Ahamada, I. (2011). The impact of the European Union emission trading scheme on the electricity-generation sector. *Energy Economics, 33*(5), 995-1003.

Kobos, P.H., Erickson, J.D., & Drennen, T.E. (2006). Technological learning and renewable energy costs: implications for US renewable energy policy. *Energy policy, 34*(13), 1645-1658.

Koo, J., Han, K., & Yoon, E.S. (2011). Integration of CCS, emissions trading and volatilities of fuel prices into sustainable energy planning, and its robust optimization. Renewable and Sustainable *Energy Reviews*, *15*(1), 665-672.

Koo, J., Park, K., Shin, D., & Yoon, E.S. (2011). Economic evaluation of renewable energy systems under varying scenarios and its implications to Korea's renewable energy plan. *Applied Energy, 88*(6), 2254-2260.

Korea Energy Management Corporation. (2010). 2010 Renewable energy whitepaper.

Korea Energy Management Corporation. (2012). Renewable Portfolio Standard Guidebook.

Krenker, A., Bešter, J., & Kos, A., (2011). Introduction to the Artificial Neural Networks, *Artificial Neural Networks - Methodological Advances and Biomedical Applications,* Prof. Kenji Suzuki (Ed.).

Krey, B., & Zweifel, P. (2006). Efficient electricity portfolios for Switzerland and the United States. *University of Zurich, Working Paper No, 602.*

Krukanont, P., & Tezuka, T. (2007). Implications of capacity expansion under uncertainty and value of information: The near-term energy planning of Japan. *Energy, 32*(10), 1809-1824.

Ku, S.J., & Yoo, S.H. (2010). Willingness to pay for renewable energy investment in Korea: A choice experiment study. Renewable and Sustainable *Energy Reviews, 14*(8), 2196-2201.

Kydes, AS, & Rabinowitz, J. (1979). Time-stepped energy system optimization model (TESOM): overview and special features: Brookhaven National Lab., Upton, NY (USA). National Center for Analysis of Energy Systems.

Kydes, A.S., & Rabinowitz, J. (1981). Overview and special features of the time-stepped energy system optimization model (TESOM). *Resources and Energy, 3*(1), 65-92.

Law, A.M., Kelton, W.D., & Kelton, W.D. (1991). *Simulation modeling and analysis* (Vol. 2): McGraw-Hill New York.

Lee, K.D,. Boo K.J., & Lee C.H. (2007). Policy options to promote renewable-powered electricity generation through green pricing and grid-connection. *Korea Energy Economics Institute.5*(11), 1-254.

Lee, M.S. (2009). Comparing between FIT and RPS, and implication: focused on Solar energy. *Korea Industry Bank Economy Institute*.

Lee, W.W., Rho, D.S., & Cho, SH. (2004). A study of influences that reconstruction of electricity business have on choosing electricity generating fuel. . *Korea Energy Economics Institute. 4*(5), 1-200

Levy, H., & Markowitz, H.M. (1979). Approximating expected utility by a function of mean and variance. *The American Economic Review,* 308-317.

Levy, H., & Sarnat, M. (1970). International diversification of investment portfolios. The *American Economic Review*, 668-675.

Lior, N. (2010). Sustainable energy development: the present (2009) situation and possible paths to the future. *Energy, 35*(10), 3976-3994.

Lintner, J. (1965). The valuation of risk assets and the selection of risky investments in stock portfolios and capital budgets. *The review of economics and statistics, 47*(1), 13-37.

Lüdeke-Freund, F., & Loock, M. (2011). What Kinds of Photovoltaic Projects Do Lenders Prefer to Finance? *Marcus, A*, 107-124.

Lüthi, S., & Prässler, T. (2011). Analyzing policy support instruments and regulatory risk factors for wind energy deployment—A developers' perspective. *Energy Policy, 39*(9), 4876-4892.

Maddison, D. (1999). The plausibility of the ExternE estimates of the external effects of electricity production. *CSERGE GEC WORKING PAPER*.

Markandya, A. (1998). Poverty, income distribution and policy making. *Environmental and Resource Economics*, *11*(3), 459-472.

Markowitz, H. (1952). Portfolio Selection. *The journal of finance, 7*(1), 77-91.

Masini, A., & Menichetti, E. (2012). The impact of behavioral factors in the renewable energy investment decision making process: Conceptual framework and empirical findings. *Energy Policy, 40,* 28-38.

McDonald, A., & Schrattenholzer, L. (2001). Learning rates for energy technologies. *Energy policy, 29*(4), 255-261.

Merton, R.C. (1973). Theory of rational option pricing. *The Bell Journal of Economics and Management Science,* 141-183.

Ministry of Knowledge Economy. (2010). The 5th basic plan of long-term electricity supply and demand.

Mondal, M.A.H., & Islam, A. (2011). Potential and viability of grid-connected solar PV system in Bangladesh. *Renewable energy, 36*(6), 1869-1874.

Mozumder, P., Flugman, E., & Randhir, T. (2011). Adaptation behavior in the face of global climate change: Survey responses from experts and decision makers serving the Florida Keys. *Ocean & Coastal Management, 54*(1), 37-44.

Muis, ZA, Hashim, H., Manan, ZA, Taha, FM, & Douglas, PL. (2010). Optimal planning of renewable energy-integrated electricity generation schemes with CO2 reduction target. *Renewable energy, 35*(11), 2562-2570.

Mulder, P., De Groot, H.L.F., & Hofkes, M.W. (2003). Explaining slow diffusion of energy-saving technologies; a vintage model with returns to diversity and learning-by-using. *Resource and Energy Economics, 25*(1), 105-126.

National Energy Committee of Korea. (2008). Korean national energy plan, 2008-2030.

Newcomer, A., & Apt, J. (2008). Implications of generator siting for CO2 pipeline infrastructure. *Energy Policy, 36*(5), 1776-1787.

Nomura, N., & Akai, M. (2004). Willingness to pay for green electricity in Japan as estimated through contingent valuation method. *Applied Energy, 78*(4), 453-463.

ORNL/RFF (Oak Ridge National Laboratory and Resource for the Future). 1994. Fuel cycle externalities. Report prepared for the US Department of Energy and European Commission. Oak Ridge, Tennessee. Washington, DC

Ott, W., Hohmeyer, O., Ottinger, RL, & Rennings, K. (1997). External costs and external price addings in the Swiss energy sector. *Social costs and sustainability: Valuation and implementation in the energy and transport sector. Berlin: Springer*.

Ottinger, R.L., Wooley, D., Robinson, N., Hodas, D., & Babb, S. (1990). Environmental costs of electricity.

Parfomak, P.W. (1997). Falling generation costs, environmental externalities and the economics of electricity conservation. *Energy policy, 25*(10), 845-860.

Park , J.I & Park, R. (2009). Improvement of the using condition for domestic new and renewable. *Korea Society of Geothermal Energy Engineers, 5*(2), 7-12

Painuly, J.P. (2001). Barriers to renewable energy penetration; a framework for analysis. *Renewable Energy, 24*(1), 73-89.

Pearce, DW. (1994). Costing the environmental damage from energy production. *CSERGE, University College London y University of East Anglia*.

Pearce, D., Bann, C., & Georgiou, S. (1992). The social cost of fuel cycles. *report to the UK Department of Trade and Industry by the Centre for Social and Economic Research on the Global Environment, HMSO*.

Petroleum, B. (2008). BP statistical review of world energy. *Retrieved September, 9,* 2008.

Porter, R.B., & Gaumnitz, J.E. (1972). Stochastic dominance vs. mean-variance portfolio analysis: an empirical evaluation. *The American Economic Review, 62*(3), 438-446.

Pratt, J.W. (1964). Risk Aversion in the Small and in the Large. *Econometrica: Journal* *of the Econometric Society*, 122-136.

Putta, S.N. (1991). Methods for valuing and incorporating environmental costs in electric resource planning and acquisition. *External Environmental Costs of Electric Power: Analysis and Internalization, Berlin: Springer-Verlag*, 371-389.

Ragwitz, M., & Huber, C. (2005). Feed-In Systems in Germany and Spain and a comparison. *Fraunhofer Institute for Systems and Innovation research*.

Resch, G., Held, A., Faber, T., Panzer, C., Toro, F., & Haas, R. (2008). Potentials and prospects for renewable energies at global scale. *Energy Policy, 36*(11), 4048-4056.

Roe, B., Teisl, M.F., Levy, A., & Russell, M. (2001). US consumers' willingness to pay for green electricity. *Energy policy, 29*(11), 917-925.

Roques, F.A., Newbery, D.M., & Nuttall, W.J. (2008). Fuel mix diversification incentives in liberalized electricity markets: A Mean–Variance Portfolio theory approach. *Energy Economics, 30*(4), 1831-1849.

Roques, F., Nuttall, W., Newberry, D., de Neuville, R., & Connors, S. (2006) Nuclear

Power: A Hedge against Uncertain Gas and Carbon Prices?. *The Energy Journal 27* (4), 1-24.

Rowe, R.D., Lang, C.M., Chestnut, L.G., Latimer, D.A., Rae, D.A., Bernow, S.M., & White, D.E. (1995). New York State environmental externalities cost study. *Oceana, NY: Empire State Electric Energy Research Corporation*.

Rubin, E.S., Taylor, M.R., Yeh, S., & Hounshell, D.A. (2004). Learning curves for environmental technology and their importance for climate policy analysis. *Energy, 29*(9), 1551-1559.

Samuelson, P.A. (1967). General proof that diversification pays. *Journal of Financial and Quantitative Analysis, 2*(1), 1-13.

Savvanidou, E., Zervas, E., & Tsagarakis, K.P. (2010). Public acceptance of biofuels. *Energy Policy, 38*(7), 3482-3488.

Scarpa, R., & Willis, K. (2010). Willingness-to-pay for renewable energy: Primary and discretionary choice of British households' for micro-generation technologies. *Energy Economics, 32*(1), 129-136.

Schuman, M., & Cavanagh, R. (1982). A model conservation and electric power plan for the Pacific Northwest. *Seattle: NCAC*.

Sharpe, W.F. (1964). Capital asset prices: A theory of market equilibrium under conditions of risk. *The Journal of Finance, 19*(3), 425-442.

Showalter, S., Wood, F. & Vimmerstedt, L. (2010). Energy efficiency and renewable energy research, development, and deployment in meeting greenhouse gas mitigation goals: The case of the lieberman-warner climate security Act of 2007, *National Renewable Energy Laboratory*.

Sims, REH. (2004). Renewable energy: a response to climate change. *Solar Energy, 76*(1), 9-17.

Sims, R.E.H., Rogner, H.H., & Gregory, K. (2003). Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy, 31*(13), 1315-1326.

Söderholm, K., & Söderholm, P. (2002). *Scientific controversies as a source of environmental information: the case of sulphate odour from a Swedish paper mill in the early 20th century*: Luleå University of Technology, Economics.

Soderholm, P., Ek, K., & Pettersson, M. (2007). Wind power development in Sweden: Global policies and local obstacles. *Renewable & Sustainable Energy Reviews, 11*(3), 365-400.

Söderholm, P., & Sundqvist, T. (2007). Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies. *Renewable energy, 32*(15), 2559-2578.

Spinney, P.J., & Watkins, G.C. (1996). Monte Carlo simulation techniques and electric utility resource decisions. *Energy Policy, 24*(2), 155-163.

Stern, N.H., & Britain, G. (2006). *Stern Review: The economics of climate change* (Vol. 30): HM treasury London.

Stirling, A. (1994). Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. *Energy Policy, 22*(3), 195-216.

Stirling, A. (1998). Risk at a turning point? *Journal of Risk Research, 1*(2), 97-109.

Stirling, A., & Mayer, S. (2001). A novel approach to the appraisal of technological risk.

Environ Plann C Gov Policy, 19, 529-555.

Strand, J., & Wenst0p, F. (1993). Implicit environmental costs in hydroelectric development: An analysis of the Norwegian master plan for water resources. *Journal of Environmental Economics and Management, 25*, 201-221.

Sundqvist, T. (2004). What causes the disparity of electricity externality estimates? *Energy Policy, 32*(15), 1753-1766.

Swisher, J.R., Hyden, P.D., Jacobson, S.H., & Schruben, L.W. (2000). *A survey of simulation optimization techniques and procedures.* Paper presented at the Simulation Conference, 2000. Proceedings. Winter.

Tavakkoli-Moghaddam, R., Javadian, N., Khorrami, A., & Gholipour-Kanani, Y. (2010). Design of a scatter search method for a novel multi-criteria group scheduling problem in a cellular manufacturing system. *Expert Systems with Applications, 37*(3), 2661-2669.

Thayer, MA, Sebold, FD, Murdoch, JC, Mayer, TA, Murray, DR, & Tracy, SR. (1994). The Air Quality Valuation Model. *Regional Economic Research Inc. and TRC Environmental Consultants.*

Tobin, J. (1958). Liquidity preference as behavior towards risk. *The Review of Economic Studies*, 65-86.

Turner, J.A. (1999). A realizable renewable energy future. *Science, 285*(5428), 687-689.

UNEP. (2010). Waste and Climate Change: Global Trends and Strategy Framework.

Van Horen, C. (1996). *Counting the social costs: Electricity and externalities in South Africa*: University of Cape Town Press: Elan Press.

Van Zon, A., & Fuss, S. (2005). Investing in Energy Conversion Technologies: An Optimum Vintage Portfolio Selection Approach: MERIT, *Maastricht Economic Research Institute on Innovation and Technology*.

Vita, A., Coninck, H., McLaren, J., & Cochran, J. (2009). A climate for collaboration: analysis of US and EU lessons and opportunities in energy and climate policy. *A climate for collaboration: analysis of US and EU lessons and opportunities in energy and climate policy.*

Vithayasrichareon, P., MacGill, I., & Wen, F. (2009). Monte Carlo optimization framework for assessing electricity generation portfolios. *Paper presented at the Power Engineering Conference, 2009*. AUPEC 2009. Australasian Universities.

White, B. (2007). A mean-variance portfolio optimization of California's generation mix to 2020: Achieving California's 33 percent renewable portfolio standard goal. Report CEC-300-2007-009-D.

Wiser, R., Hamrin, J., & Wingate, M. (2002). Renewable energy policy options for China: A comparison of renewable portfolio standards, feed-in tariffs, and tendering policies. *Center for Resource Solutions, 16*.

Xie, YL, Li, YP, Huang, GH, & Li, YF. (2010). An interval fixed-mix stochastic programming method for greenhouse gas mitigation in energy systems under uncertainty. *Energy*.

Yoo, S.H., & Kwak, S.Y. (2009). Willingness to pay for green electricity in Korea: A contingent valuation study. *Energy Policy, 37*(12), 5408-5416.

Yoon, S.J. (2002). Sustainable development and energy policy in the 21st century: The need for energy system transformation and desirable directions for energy policy change. *Korea Academy of Policy, 36*(3), 147-166.

Yun, W.C. (2009). Selection of new generation option using portfolio approach. *Korean Energy Economic Review, 8*(1), 59-90

Yun, W.C. & Sonn Y.H. (2008). Optimal fiscal budget allocation of oil crisis strategies using portfolio approach. *Korean Resource Economics Association, 17*(4), 719-750

Zarnikau, J. (2003). Consumer demand for 'green power'and energy efficiency. *Energy Policy, 31*(15), 1661-1672.

Zhang, C.Y., Li, P.G., Guan, Z.L., & Rao, Y.Q. (2007). A tabu search algorithm with a new neighborhood structure for the job shop scheduling problem. *Computers & Operations Research, 34*(11), 3229-3242.

Zografakis, N., Sifaki, E., Pagalou, M., Nikitaki, G., Psarakis, V., & Tsagarakis, K.P. (2010). Assessment of public acceptance and willingness to pay for renewable energy sources in Crete. *Renewable and sustainable energy reviews, 14*(3), 1088-1095.

Zon, A., & Fuss, S. (2005). Investing in energy conversion technologies-An optimum

vintage portfolio selection approach.

Appendix 1: Overview of External Cost Studies

Study	Country	Fuel	External Cost (US Cents/kWh)	Approach
Schuman & Cavanagh (1982)	US	Coal	0.06-44.07	Abatement cost
	US	Nuclear	0.11–64.45	
	US	Solar	0–0.25	
	US	Wind	0–0.25	
Hohmeyer (1988)	DE	Nuclear	7.17–14.89	Damage cost (top-down)
	DE	Wind	0.18–0.36	
	DE	Solar	0.68–1.03	
Chernick & Caverhill (1989)	US	Coal	4.37–7.74	Abatement cost
	US	Oil	4.87–7.86	
	US	Gas	1.75–2.62	
Bernow & Marron (1990) Bernow et al. (1991)	US	Coal	5.57–12.45	Abatement cost
	US	Oil	4.40–12.89	
	US	Gas	2.10–7.98	
Hall (1990)	US	Nuclear	2.37–3.37	Abatement cost
Putta (1991)	US	Coal	1.75	Abatement cost
Ottinger et al. (1991)	US	Coal	3.62–8.86	Damage cost (top-down)
	US	Oil	3.87–10.36	
	US	Gas	1.00–1.62	
	US	Nuclear	3.81	
	US	Hydro	1.43–1.62	
	US	Wind	0–0.12	
	US	Solar	0–0.50	
	US	Biomass	0–0.87	

Study	Country	Fuel	External Cost (US Cents/kWh)	Approach
Hohmeyer (1992)	DE	Nuclear	7.01–48.86	Damage cost (top-down)
	DE	Wind	0.12–0.24	
	DE	Solar	0.54–0.76	
Friedrich & Voss (1993)	DE	Coal	0.36–0.86	Damage cost (top-down)
	DE	Nuclear	0.03–0.56	
	DE	Wind	0.02–0.33	
	DE	Solar	0.05–1.11	
Pearce et al. (1992)	UK	Coal	2.67–14.43	Damage cost (top-down)
	UK	Oil	13.14	
	UK	Gas	1.05	
	UK	Nuclear	0.81	
	UK	Hydro	0.09	
	UK	Wind	0.09	
	UK	Solar	0.15	
Strand & Wenst0p (1993)	NO	Hydro	2.68–26.26	Abatement cost
Thayer et al. (1994)	US	Oil	0.03–5.81	Damage cost (bottom-up)
	US	Gas	0.003–0.48	
ORNL & RfF (1994-1998)	US	Coal	0.11–0.48	Damage cost (bottom-up)
	US	Oil	0.04–0.32	
	US	Gas	0.01–0.03	
	US	Nuclear	0.02–0.12	
	US	Hydro	0.02	
	US	Biomass	0.2	
EC (1995)	UK/DE	Coal	0.98/2.39	Damage cost (bottom-up)
	DE	Oil	3	
	UK	Gas	0.1	
	FR	Nuclear	0.0003–0.01	
	NO	Hydro	0.32	
	UK	Wind	0.11–0.32	

Study	Country	Fuel	External Cost (US Cents/kWh)	Approach
Pearce (1994)	UK	Coal	3.02	Damage cost (top-down)
	UK	Gas	0.49	
	UK	Nuclear	0.07–0.55	
Rowe et al. (1995)	US	Coal	0.31	Damage cost (bottom-up)
	US	Oil	0.73	
	US	Gas	0.22	
	US	Nuclear	0.01	
	US	Wind	0.001	
	US	Biomass	0.35	
Cifuentes & Lave (1993)	US	Coal	2.17–20.67	Abatement cost
Parfomak (1997)	US	Gas	0.03–0.04	
van Horen (1996)	ZA	Coal	0.90–5.01	Damage cost (bottom-up)
	ZA	Nuclear	1.34–4.54	
Bhattacharyya (1997)	IN	Coal	1.36	Damage cost (bottom-up)
Ott (1997)	CH	Oil	12.97–20.57	Damage cost (top-down)
	CH	Gas	8.85–13.22	
	CH	Nuclear	0.62–1.50	
	CH	Hydro	0.25–1.50	
Faaij et al. (1998)	NL	Coal	3.98	Damage cost (top-down)
	NL	Coal	3.84	Damage cost (bottom-up)
	NL	Biomass	8.1	

Study	Country	Fuel	External Cost (US Cents/kWh)	Approach
EC (1999)	BE, FI, FR, DE, IE, NL, PT, ES, SE, UK	Coal	0.84–72.42	Damage cost (bottom-up)
	FR, DE, GR, IT, UK	Oil	2.07–39.93	
	AT, BE, DK, FR, DE, GR, IT, NL, NO, PT, ES, UK	Gas	0.26–11.78	
	BE, DE, NL	Nuclear	0.02–1.45	
	AT, GR, IT, PT, SE	Hydro	0.02–18.54	
	DK, DE, GR, NO, ES, UK	Wind	0.05–0.80	
	DE	Solar	0.05–1.69	
	AT, DK, FI, FR, DE, GR, NL, NO, PT, ES, SE, UK	Biomass	0.14–22.09	
Maddison (1999)	UK/DE	Coal	0.31/0.71	Damage cost (bottom-up)
	DE	Oil	0.78	
	UK	Gas	0.13	

Appendix 2: Data description

1. Production Cost

① Investment cost

Data regarding investment costs, which are used in this study, are as follows. First of all, investment costs include overnight costs and the implied interest during construction (IDC). The overnight cost is the base cost, in other words. To examine the data for analysis, in the case of conventional energy, Korean power plant's data in the IEA (2010) report are used, and in the case of renewable energy, data from KEPCO (2010) are used in this research. First of all, explanation about data f conventional energy is as follows.

In the case of nuclear energy generation, data from Table 3.7a on page 61 in IEA (2010) are reorganized. The Korean nuclear energy plant is divided into Optimized Power Reactor (OPR) and Advanced Power Reactor (APR) according to generation technology type. Currently, APR-type plants are in operation, and the APR-type plant is planned to be newly built in the future. Moreover, after 2013, APR-type plants are expected to increase, so this research used an average of APR-type plant data. Therefore, overnight costs (2098$/kW, 1751$/kW) of each plant plus the interest during construction is applied at a 5% discount rate.

In the case of coal generation, data from Table 3.7b on page 62 in IEA (2010) is reorganized. In the report, coal plants are classified into two types of plant according to the net capacity like gas plant, and to the overnight cost (895$/kW, 807$/kW) of each plant is applied the interest rate (5%) to calculate investment cost. In this research, the average investment cost of two types of plant is applied.

In the case of gas generation, data from Table 3.7b on page 62 in IEA (2010) are reorganized. In the IEA (2010) data, two types of investment cost according to net capacity are suggested. For calculating investment cost, the interest rate (5%) is applied to overnight cost (643$/kW, 635$/kW). In this research, the average investment costs of two types of plant are applied. Data (Table 3.7 a, b, c) for calculating investment costs of three energy sources stated above are as follows.

Table 63. Investment Costs of Conventional Energy

Energy	Technology	Net capacity (MW)	Overnight costs (USD/kW)	Investment costs[13] (USD/kW)
Gas	LNG CCGT	495	643	678
	LNG CCGT	692	635	669
Coal	Black PCC	767	895	978
	Black PCC	961	807	881
Nuclear	OPR-1000	954	1876	2098
	APR-1400	1343	1556	1751

Source: Data was reorganized by using IEA (2010)

In the case of renewable energy, data from KEPCO (2010) are used for calculating

[13] 5% discount rate

costs by applying the levelized cost of electricity. In KEPCO (2010), a 7% discount rate was used. Moreover, energy resources which electricity generation companies currently have or which are planned to be built in the future are analyzed. First of all, in the case of solar generation, financial indexes[14] which were applied for drawing the base price of 2009 FIT are used, and these data are applied to energy resources commonly. Technology indexes[15] are calculated based on the SamRangJin Solar generation plant case. Pyung-Chang wind generation data are used for technology indexes of wind power. In the case of hydroelectric power, indexes are calculated based on the Young-Heung hydro power plant. In the case of biomass, construction cost and generation efficiency among technology indexes are referenced to Dong-Suh 30MW generation plant's construction plan. Common indexes and technology indexes for calculating investment cost and O&M cost of renewable energy are as follows.

Table 64. Common Financial Indexes regarding Renewable Energy

Classification	Value	Note
Discount rate (%)	5.0	Application index of feed in tariff-standard price establishment
Borrowing rate (%)	5.0	
Loan capital (%)	70.0	
Redemption period (years)	10	
제세율 (%)	22.0	
Investment tax credit rate (%)	20	Investment tax amount deduction law intended for energy-saving establishment
Investment tax credit period (years)	5	

[14] Financial indexes are used commonly for all energy sources.
[15] Technology indexes include construction cost, running maintenance ratio, capacity factor, economic life, and depreciation period.

SMP (KRW/kWh)	95.03	Average of ’06, 07, 08 SMPs

Table 65. Technology Indexes regarding Renewable Energy

Classification	Hydro	Wind	Solar PV	Biomass
Average construction period (years)	2	2	3	4
Construction unit price (10^4 KRW/kW)	430	500	430	472
Operation and maintenance rate (%)	2.0	1.0	1.57	6
Capacity factor (%)	53	34	25	83
Generating efficiency (%)	-	-	-	31
Caloric value (kcal/kg)	-	-	-	3,500
Fuel price (KRW/kg)	-	-	-	45
Fuel price rate of rise(%)	-	-	-	2
Plant-on consumption rate (%)	-	-	-	9.44
Economic life (years)	20	20	30	30
Depreciation period(years)	20	20	30	30

We can calculate investment cost from the levelized cost of electricity equation by using the above values. Then, by changing KRW into USD (1USD=1100KRW), investment cost of renewable energy is obtained from Table 4.

② O&M cost

Data for calculating O&M cost is the same as investment cost, explained previously. In the case of conventional energy, the IEA (2010) data were used, and in the case of renewable energy, KEPCO (2010) data were used. First of all, the case of conventional energy is as follows.

In the case of nuclear energy generation, data from Table 3.7a on page 61 of IEA (2010) were reorganized, such as investment cost as previously stated. Like previously explained, this research used the average value of data of electricity generation plants that used APR and OPR technology. Therefore, the average O&M cost (10.42$/MWh, 8.95$/MWh) of each plant is used.

In the case of coal, Table 3.7b on page 62 of IEA (2010) report was reorganized. This report used two types of each plant's average value, divided by net capacity. Therefore, the O&M cost of coal is calculated to use the average of O&M cost (4.25$/MWh, 3.84$/MWh) of each plant.

In the case of gas, Table 3.7c on page 63 of IEA (2010) report was reorganized. The data from IEA (2010) suggested two types of O&M cost divided by net capacity. Therefore, the O&M cost of gas is calculated to use the average O&M cost (4.79$/MWh, 4.12$/MWh) of each plant.

Table 66. O&M Costs of Conventional Energy

Energy	**Technology**	**Net capacity (MW)**	**O&M costs (USD/MWh)**
Gas	LNG CCGT	495	4.79
	LNG CCGT	692	4.12
Coal	Black PCC	767	4.25
	Black PCC	961	3.84
Nuclear	OPR-1000	954	10.42
	APR-1400	1343	8.95

Source: Data was reorganized by using IEA (2010)

In the case of renewable energy, common financial indexes and technology indexes of each energy sources are used to calculate O&M cost as in the case of investment cost previously explained.

③ CO_2 emission rate

The value of CO_2 emission rate, which is used in this study, comes from the data from Table 6 of Kim et al., (2012) which analyzed the recent Korean energy industry.

④ Capacity factor

The capacity factor used in this research is applied from the data of the Energy Information Agency (EIA, 2012). The figure below describes the capacity factor of EIA (2012). Coal and gas's capacity factor is the average value of these plants' without CCS. Table 69 organized this is as follows.

Table 67. Capacity Factors by Plant Types

[%]	Coal	Gas	Nuclear	Hydro	Wind	Solar PV	Biomass
Capacity Factor	85	87	90	53	34	25	83

Source: Data was reorganized by using EIA (2012)

The value in Table 4 is calculated when multiplying the capacity factor by operation time during one year (8,760 hrs.: 365 days Ｘ 24 hrs.).

Plant type	Capacity Factor (%)
Dispatchable Technologies	
Conventional Coal	85
Advanced Coal	85
Advanced Coal with CCS	85
Natural Gas-fired	
Conventional Combined Cycle	87
Advanced Combined Cycle	87
Advances CC with CCS	87
Conventional Combustion Turbine	30
Advanced Combustion Turbine	30
Advanced Nuclear	90
Geothermal	92
Biomass	83
Non-Dispatchable Technologies	
Wind	34
Wind-Offshore	27
Solar PV[1]	25
Solar Thermal	20
Hydro [2]	53

Source: EIA (2012)

Figure 42. Capacity Factors by Plant Types

⑤ Initial capacity

Initial capacity used data from EPSIS (http://epsis.kpx.or.kr), which is the sum of all capacity value of each energy source plants built up to December 2012.

⑥ Fuel price

Fuel price used for the least-cost optimization analysis in this research is the fuel price data of EPSIS (http://epsis.kpx.or.kr) from January 2010 to August 2012 and is used to calculate figures in the case of conventional energy[16]. In the case of hydro power, wind power, and solar power (renewable energy sources), fuel prices are assumed to be 0. Lastly, the fuel price of biomass is drawn from the data of Kim et al. (2012).

Table 68. Mean and Standard Deviation of Fuel cost

[$/MWh]	Coal	Gas	Nuclear	Hydro	Wind	Solar	Biomass†
Mean	40	110	4	0[17]	0[12]	0[12]	24
Std.	3	5	1	0	0	0	5

Source: EPSIS (Electric Power Statistics Information System, http://epsis.kpx.or.kr), †: Kim et al (2012)

⑦ CO2 target and Price

The emission target for CO2 reduction by 2030 is obtained in reports prepared by the National Energy Committee of Korea (2008). It is assumed that the value for each year is calculated with linear interpolation. Furthermore, CO2 price shows a continuous decline in the long term. Therefore, in this study, we expected that CO2 price is continuously decreasing and used recent (from January 2012 to October 2012) CO2 price data (BlueNext Statistics, http://www.bluenext.eu).

⑧ Learning rate of energy

16 1USD=1,100KRW

17 In case of hydro, wind, solar, fuel price for electricity generation is assumed to be zero.

The learning rate of Kim et al. (2012) is applied to the investment cost in this study. They suppose that although the learning rates of each region may be different from the global learning rate, Korean trends can reflect the global movement because Korea is one of the countries in which many researches have been conducted in various energy systems. Thus, they assume that the learning rate of each region is the same as the global learning rate (Kim et al., 2012). Therefore, by using equation (7) in Koo et al. (2011), learning rates according to each energy source are applied to the investment cost. The learning rates of Kim et al. (2012) are used for this study.

Table 69. Learning Rate of Energy

	Coal	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Mean	6.3	10.6	5.9	3.8	13.1	28.2	15
Std.	2.4	9.2	0.1	1.9	5.2	6.6	0.3

Source: Kim et al., (2012)

2. Generation Limits of Renewable Energy

As explained previously, the cases of renewable energy and nuclear energy could be set up according to economic or environmental needs, but this is difficult to achieve realistically. Therefore, to estimate the generation limits of nuclear energy and renewable energy from 2012 to 2030, the expert’s survey is used to consider the current Korean generation plant construction environment and intent. The survey was conducted among 40 experts who work for the electricity generation industry in Korea and suggested the technology potential and previous generation capacity trend of each renewable energy source and then asked the experts about the ratio of Korean renewable energy supply potential in the future. The survey result of each energy source is organized as follows.

Table 70. Generation Limits of Nuclear and Renewable Energy

Energy Sources	Generation Limit [MW] 2015	2020	2025	2030
Nuclear	23953	30532	37278	43926
Hydro	2319	3138	3439	3513
Wind	1882	6053	11468	15257
Solar	2304	5609	10717	17865
Biomass	817	1423	2062	2809

The nuclear energy and renewable energy generation limits from 2012 to 2030 are estimated by applying the technology diffusion model explained above as with the IEA (2008) figure, and this is applied as constraints in the analysis of this research.

3. Technology Risk Estimates

This research applied risk regarding investment cost, fuel cost, O&M cost, and CO2 cost to calculate the energy portfolio risk. To get the portfolio risk, in the case of applying factors which affect electricity generation, previous research focused only on conventional energy. However, as the importance of renewable energy grows, the energy portfolio considering renewable energy with conventional energy is becoming more important. Therefore, this research applied gas, coal, and nuclear energy, which are the most-used conventional energy of Korea, and applied previous research which has been referenced a lot (e.g., Awerbuch & Yang, 2007; White, 2007) to apply the risk of hydro, wind, solar, and biomass energy. The cost of risks presented in the report by White (2007) in Table 1 on page 19 is as follows.

Generating Resource	Investment	Fuel	Total O&M	CO_2
Coal	0.35	0.049	0.054	0.260
Biomass	0.20	0.133	0.108	-
Natural Gas	0.20	0.291	0.105	0.260
Nuclear	0.40	0.346	0.055	-
Hydro - Large	0.35	0.000	0.153	-
Hydro - Small	0.20	0.000	0.153	-
Wind	0.20	0.000	0.080	-
Solar Thermal	0.10	0.000	0.080	-
Biogas	0.20	0.133	0.108	-
Solar PV	0.10	0.000	0.034	-
Geothermal	0.20	0.000	0.153	-

Source: White (2007)

Figure 43. Technology Risk Estimates

This research used data regarding energy resources which are applied in this research from the above data, and the characteristics of each item’s cost is as follows. Investment cost risks are different from technology types and construction period. For this, White used the calculated risk from Bacon et al. (1996), which calculated risk regarding thermal plants and large hydro plant projects. Furthermore, investment cost risks for wind, gas, geothermal, and solar energy were determined from developer interviews as mentioned above (Awerbuch et al., 2005). Fuel cost risks have been estimated on the basis of historical (1980-2005) California (biomass and natural gas), NUEXCO (uranium), and EIA (coal) prices. Since renewable energy does not need fuel costs, they have no fuel cost risk, with the exception of biomass (White, 2007). In the case of O&M cost risk, the EIA and Federal Energy Regulatory Commission (FERC) databases were used in White (2007). White (2007) used these data to estimate the holding-period-return (HPR) standard deviations (SD) for O&M costs. The last risk cost category is the cost of CO2 emissions. The future cost of CO2 emissions is relevant for fossil fuel technologies (White, 2007). In 2007, because CO2 is not traded in the U.S., White (2007) used EU prices. However, the EU data are short, because CO2 has only been traded there for about 18 months beginning in 2007. Therefore, to infer the behavior of annual CO2 HPRs from the limited historical data, White (2007) used an analytical approach and MCS. The analytical approach was developed by Green (2006).

4. Correlation coefficient

As mentioned above, in the study of White (2007), the estimates of the standard deviations and correlations of CO2 prices are derived by analytic approach and MCS. The figures below are correlation coefficients.

Generating Resource	Coal	Biomass	Natural Gas	Uranium	CO_2
Coal	**1.00**	0.39	0.53	-0.25	-0.49
Biomass	0.39	**1.00**	0.30	-0.27	0.00
Natural Gas	0.53	0.30	**1.00**	-0.16	0.68
Uranium	-0.25	-0.27	-0.16	**1.00**	0.00
CO_2	-0.49	0.00	0.68	0.00	**1.00**

Source: White (2007)

Figure 44. Fuel and CO2 HPR Correlation Factors

Generating Resource	Coal	Gas	Nuclear	Hydro	Wind	Geo	Solar	Bio
Coal	**1.00**	0.25	0.00	0.03	-0.22	0.14	-0.39	0.18
Gas	0.25	**1.00**	0.24	-0.04	0.00	-0.18	0.05	0.32
Nuclear	0.00	0.24	**1.00**	-0.41	-0.07	0.12	0.35	0.65
Hydro	0.03	-0.04	-0.41	**1.00**	0.29	-0.08	0.30	-0.18
Wind	-0.22	0.00	-0.07	0.29	**1.00**	-0.28	0.05	-0.18
Geo	0.14	-0.18	0.12	-0.08	-0.28	**1.00**	-0.48	-0.70
Solar	-0.39	0.05	0.35	0.30	0.05	-0.48	**1.00**	0.25
Bio	0.18	0.32	0.65	-0.18	-0.18	-0.70	0.25	**1.00**

Source: White (2007)

Figure 45. O&M Correlation Coefficients

Abstract (Korean)

인류는 에너지가 없이는 생활 할 수 없다. 에너지는 인간의 삶에 필수적인 요소이다. 특히, 산업혁명 이후의 에너지의 생산과 소비증가는 경제성장을 위한 필수조건이 되었다. 즉, 충분한 양의 에너지 서비스를 적정한 가격으로 공급하는 것이 안정적인 경제발전과 쾌적한 삶을 영위하기 위한 필요조건인 것이다. 하지만, 에너지 생산과 소비 증가가 높은 단계의 문명사회인지를 결정하는 기준이 되면서 과거 많은 국가들은 풍부하고 값싼 에너지의 안정적인 공급을 위한 에너지 정책을 유지해 왔다. 그 결과, 인류는 에너지 고갈과 다양한 형태의 환경문제와 맞닥뜨리게 되었으며, 이로 인한 국가간, 사회계층간의 갈등이 중요한 사안으로 나타나고 있다.

오늘날과 같이 인류가 화석에너지를 주 에너지원으로 계속 의존하게 된다면, 인류의 복지는 심각한 위기를 맞게 될 것이다. 화석연료의 생산과 소비는 태생적으로 대기 오염과 수질오염을 초래하게 된다. 뿐만 아니라, 방대한 경제적 투자와 안정적인 에너지 공급을 확보하기 위한 국가간의 노력으로 인해 국제적 분쟁을 발생시키기도 한다. 이와 함께 온실가스의 대기방출이 인류에게 엄청난 재앙을 초래할 것이라는 주장은 더 이상 주장에서 그치는 것이 아니라 지구 곳곳에서 조금씩 실현되고 있는 실정이다. 에너지 문제는 한 나라만의 문제가 아닌 국제사회의 문제가 되었으며, 국제사회가 이에 적절히 대응하지 않는다면, 우리 인류는 환경재해, 에너지안보, 경제개발의 3대 위기에 직

면하게 될 것이다.

이에 따라 지구온난화로 인한 전 세계적인 기후변화의 심각성을 인지하고 대응하기 위해 다양한 기후변화 관련 정책들이 국내외에서 추진되고 있다. 특히, 선진국들은 신재생에너지 보급 확대를 통해 환경오염을 줄이고 있으며, 신재생에너지 산업 경쟁력 강화를 위해 신재생에너지 관련 각종 정책을 지원하고 있으며, 한국도 전 세계적인 기후변화 대응노력에 부응하기 위해, 2008년 저탄소 녹색성장을 선언하고 녹색기술을 신성장 동력으로 삼는 에너지 기조를 나타내고 있다.

또한, 1987년 세계환경발전위원회의 (WCED)의 보고서 이후 전 세계적으로 확산된 지속 가능한 발전에 대한 관심과 노력은 21세기 인류가 지향해야 할 가치이자 새로운 발전의 패러다임으로 여겨지고 있는 실정이다. 지속 가능한 발전은 ‘자연자원에 대한 현명한 사용’과 이를 바탕으로 한 ‘지속적 경제성장’에 그 핵심이 있다. 따라서, 에너지의 사용이 자연의 부양능력 한계 안에서 이루어 질 수 있도록, 즉 에너지 사용으로 인한 사회/환경적 영향이 최소화되게 하여야 한다. 뿐만 아니라, 에너지의 안정적인 공급을 통하여 차등 없는 필요 충족이 이루어 져야 한다. 지속 가능한 발전이라는 과제를 풀어나가기 위해서는 현재 에너지 체계가 지속 가능한 발전을 이뤄내기에 적합한지, 지금의 에너지 정책 하에서는 지속 가능한 에너지 체제를 위한 어떠한 노력을 수행해야 하는지 알아보아야 한다. 따라서, 본 연구는 우리나라의 현실 상황을 반영하여 지속 가능한 발전을 위한 에너지 자원의 효율적인 분배에 대한 연구를 수행하였다. 특히 전력산업을 분석 대상으로 하여, 물리적, 정책적 제약하

에서 최적의 전력 공급을 위한 에너지원들의 포트폴리오 구성에 대해서 연구하였다. 이를 위해, 본 연구는 두 가지 관점에서 분석을 수행하였다. 첫째, 최소 비용 관점에서 전력 공급을 위한 포트폴리오를 구성하였다. 이는 앞서 언급한 지속 가능한 발전을 위한 사회/환경적 영향이 최소화 관점의 분석이다. 물리적, 정책적 제약하에서 최소 비용으로 구성되는 전력 공급원들에 대하여 살펴봄으로써 신재생에너지 보급목표 및 최적의 전력공급을 위한 정책방안과 시사점을 제공하였다. 둘째, 비용-위험 관점에서 최적 전력 구성을 위한 분석을 수행하였다. 이는 지속 가능한 발전을 위한 안정적인 에너지 공급 관점의 분석이다. 앞서 수행한 최저 비용 관점의 연구는 에너지원들의 연료, 운영유지, 탄소비용에 대한 위험요인이 반영되어 있지 않음으로 에너지원들 간의 상관관계를 나타낼 수 없다. 하지만, 비용-위험 관점의 연구는 에너지원 및 비용 항목간의 상대적인 영향력이 반영된다. 따라서, 더 이상 위험은 감수하지 않으면서, 즉 임의의 위험 수준에서 최소의 비용을 지불하는 가장 효율적인 포트폴리오를 구성할 수 있다. 뿐만 아니라, 본 연구에서는 최소 비용 관점으로 분석한 포트폴리오를 비용-위험 최적 분석 관점에 반영하여 해당 포트폴리오의 비용과 위험 수준을 분석하였다. 기존 연구에서는 최소 비용 관점에서만 분석하거나, 임의의 발전용량 비율을 가정한 비용-위험 분석을 개별적으로 수행하였지만, 본 연구에서는 각기 다른 관점의 연구를 접목하여 분석하였다는 측면에서 의미가 크다고 할 수 있다.

본 연구는 총 전력 발전 비용에 대한 3가지 시나리오를 설정하여 분석하였다. 먼저, 원자력에너지의 사회적 비용만이 반영된 기본 상황, 기본 상황에서

에너지원 별 외부 비용이 반영된 상황, 마지막으로 기본 상황에서 에너지원 별 대기오염 비용이 반영된 상황이다.

본 연구를 통해 도출된 정량적 결과들은 전략적 주요 결정요인 도출과정에서 중요한 기초자료로 활용될 수 있을 것으로 기대된다. 이와 함께 감축목표 달성 및 비용최소화를 위한 배출권 거래제에 전략적으로 활용할 수 있을 것으로 기대된다. 뿐만 아니라, 주요 국가 및 전력회사의 CER 및 탄소 배출권 거래사례와 운영전략을 분석하여, 해외 CER 거래시장 참여가능성 검토, 수익성 분석 및 참여전략 수립에 활용할 수 있을 것이다. 또한, 본 연구의 결과를 바탕으로 전력산업 의무감축 할당에 따른 전력시장 영향 및 대응전략을 도출하였다. 최종적으로 본 연구를 통해 한국의 여건에 맞는 전력 시장의 대응 전략을 제시하였다. 또한 본 연구에서 새롭게 제시하는 체계적 전략 연구 프로세스는 향후 전력에너지 산업뿐 아니라 다른 에너지 관련 신사업 분야에도 널리 활용될 수 있어 그 의의가 더욱 크다고 할 수 있다.

주요어 : 지속 가능한 발전, 전력 믹스, 외부 비용, 최소 비용 모형, 비용-위험 최적 모형

학 번 : 2007-23110