MULTI-OBJECTIVE OPTIMIZATION OF PLANNING ELECTRICITY GENERATION AND CO_2 MITIGATION STRATEGIES INCLUDING ECONOMIC AND FINANCIAL RISK

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Abstract

In this paper, we present a mathematical programming model in planning electricity generation and CO_2 mitigation (EGCM) infrastructure, including financial risk management under uncertainty. The objective of our study is to determine the optimal design of the EGCM infrastructure, which is composed of available technologies to produce electricity and treat CO_2, capable of fulfilling electricity demands and CO_2 mitigation standards. In addition, the model presented allows controlling the variation of the economic performance of the EGCM infrastructure in the space of uncertain parameters (i.e. CO_2 mitigation operating costs, carbon credit prices and electricity prices etc.). This is accomplished by using the weighted-sum method that imposes a penalty for risk to the objective function. The capability of the proposed modeling framework is illustrated and applied to a real case study based on Korea, for which valuable insights are obtained.

Keywords

Electricity generation, CO_2 mitigation, infrastructure, uncertainty, financial risk management

Introduction

Currently, a large amount of electricity relies primarily on fossil fuels combustion power plants. These plants have emitted a great deal of greenhouse gas (GHG) which is known as a primary accelerating factor of global warming. There has been concern about whether energy supplies can meet increasing electricity demands with the reduction of GHG emissions.

Several research works were undertaken for the planning of electricity generation and CO_2 mitigation (EGCM) strategies under meeting the GHG mitigation standards. Several mathematical programming models have been proposed that address the design of the EGCM infrastructure (Nasiri and Huang 2008; Han and Lee 2011; Han and Lee 2011). These studies address deterministic approaches assuming that all problem parameters are invariant over a given planning horizon. Uncertainties may exist in various impact factors such as GHG emission inventory, GHG reduction costs, electricity prices and emission reduction credits. Hence, several research efforts were conducted for dealing with various uncertainties in the EGCM infrastructure. For example, interval mathematical programming (IMP) and stochastic mathematical programming (SMP) was proposed to the design of the EGCM infrastructure under uncertainties (Chen, Li et al. 2010; Li, Huang et al. 2011). These approaches allow assessing the performance of the problem under study in the space of uncertain parameters by optimizing the expected value of the objective function.

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However, this strategy does not allow controlling the variability of the objective function in the uncertain space. The introduction of a financial risk metric enable to control the variability of the objective function in the space of uncertain parameters (Barbaro and Bagajewicz 2004). In the context of designing the EGCM infrastructure under uncertainties, few research works have adopted financial risk management techniques.

Therefore, this study aims to address the financial risk management associated with the planning of the EGCM infrastructure under uncertainty in prices (i.e. the electricity price and carbon credit price) and operating costs (i.e. the carbon capture and sequestration cost). A multi-objective optimization problem which consists of the expected total profit of the infrastructure and a specific metric for financial risk is generated to consider this problem. Hence, the weighted-sum method is also presented to expedite the search for the Pareto solutions of the model. Finally, the capability of the proposed model is illustrated through its application to a real case study based on Korea.

Problem statement

The key objective of this paper is to construct a mathematical optimization model that determines the configuration of the EGCM infrastructure with the goal of maximizing the expected total profit and minimizing financial risk. The superstructure of the EGCM infrastructure in this work is depicted in Figure 1. This infrastructure model includes three main components such as an environmental management system, the power plants themselves, and an energy management system.

The decision-making problem of the EGCM infrastructure model is to determine where and how to generate electricity and treat CO_2 under the given conditions, which include electricity demand, CO_2 reduction target, capacity limitations of electricity generation technologies and CO_2 mitigation technologies, uncertain parameters (i.e. prices and operating costs); in order to simultaneously maximize the expected total profit and minimize the associated financial risk of the EGCM infrastructure.

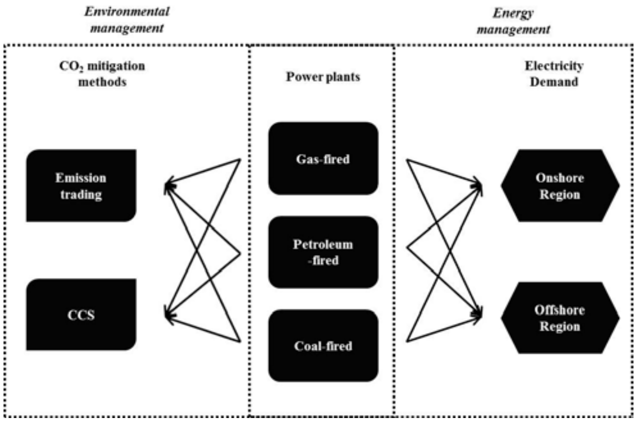

Figure 1. The superstructure of the EGCM infrastructure.

Mathematical model

The model presented is motivated by previous formulations (Han and Lee 2011). Specifically, the model considers the uncertainty of the coefficients (e.g. prices and operating costs) of the objective function via a multiscenario stochastic programming approach. The EGCM system whose model has been described previously must meet two target requirements; a) maximizing the expected total net profit of the network, b) minimizing the total financial risk of the network.

Expected total net profit

The expected total net profit is given by the mean value of the profit distribution:

$$E[TNP] = \sum_r prob_r TNP_r \quad , \tag{1}$$

where r is the number of scenarios implemented to represent the uncertain parameters space, and $prob_r$ is the probability of occurrence associated to each scenario.

The total net profit (TNP_r) in each particular scenario r is calculated by the difference between total net benefit (TNB_r) and total net cost (TNC_r):

$$TNP_r = TNB_r - TNC_r \qquad \forall r. \tag{2}$$

In Equation (2), the total net benefit (TNB_r) in each particular scenario r is the income from selling electricity generated by power plants and the total net cost (TNC_r) is the sum of emission trading cost and CCS facility cost:

$$TNB_r = \sum_e \sum_p \sum_f \sum_g UNB_{p,g,r} G_{e,p,f,g} \qquad \forall r, \tag{3}$$

$$TNC_r = \sum_i \left(\begin{array}{l} \left(\sum_p \sum_f \sum_g Cprice_r AEP_{i,p,f,g} \right) \\ + \left(CCSCC_i + CCSOC_{i,r} \right) \end{array} \right) \qquad \forall r \ , \tag{4}$$

where the capital cost (eg, $CCSCC_i$) can be regarded as non-scenario-dependent variables, whereas the prices and operating costs (eg, $UNB_{p,g,r}$, $Cprice_r$ *and* $CCSOC_{i,r}$) will in general depend on the specific scenario realization.

The detailed explanations for the first objective and its constraints were described by Han and Lee (Han and Lee 2011).

Expected total financial risk

In the previous work (Barbaro and Bagajewicz 2004), the financial risk associated with a design x and target profit Ω can be expressed as follows:

$$Risk(x,\Omega_k) = P[TNP(x) < \Omega_k] = \sum_r prob_r z_{r,k}(x,\Omega_k) \ \forall k \tag{5}$$

where z_r is a binary variable defined for each scenario and $prob_r$ is probability of occurrence of scenario *s*.

Multiobjective problem

The EGCM infrastructure design in this study is mathematically formulated as follows:

$$\begin{aligned}
&Maximize\ \ E[TNP](x, y_r);\\
&Minimize\ \ Risk(x, \Omega_k)\\
&Subject\ \ to:\\
&h(x, y_r) = 0\,\{\text{Overall mass balance}\}\\
&g(x, y_r) \le 0\,\{\text{Capacity limitations}\}\\
&x \in \mathrm{N}, y_r \in \Re.
\end{aligned} \tag{6}$$

where *x* and y_r denote the integer and continuous variables of the problem, respectively. The aforementioned multi-objective problem can be solved by the weighted-sum method (Ehrgott and Gandibleux 2000), as presented next.

$$\begin{aligned}
&Maximize\ \ E[TAP](x, y_r)\\
&\qquad\qquad -\sum_{r\in R}\sum_{k\in K} prob_r \rho_k \left(1 - z_{r,k}\right)\\
&Subject\ \ to:\\
&h(x, y_r) = 0\ \{\text{Overall mass balance}\}\\
&g(x, y_r) \le 0\,\{\text{Capacity limitations}\}\\
&x \in \mathrm{N}, y_r \in \Re\\
&prob_r TNP_r \le \Omega_k + U_r\left(1 - z_{r,k}\right)\\
&\qquad\qquad \forall k = 1, \ldots, NK, r = 1, \ldots, NR,\\
&prob_r TNP_r \ge \Omega_k - U_r z_{r,k}\\
&\qquad\qquad \forall k = 1, \ldots, NK, r = 1, \ldots, NR.
\end{aligned} \tag{7}$$

where ρ_k is goal programming weight for financial risk formations.

Results and Discussion

To verify the proposed model, it is applied to the case study in paper (Han and Lee 2011) adopted as a benchmark. The model contains 16 regions representing the self-governing communities of Korea, whose electricity demand fulfilled (EDF) by combustion power plants is supposed to cover 58% of the total demand. Electricity can be obtained from three different generation technologies, including gas-fired, petroleum-fired and coal-fired electricity generation. Also, the CO_2 reduction target is assumed to 30% of total CO_2 emissions. CO_2 can be disposed from two different mitigation technologies such as carbon capture and storage (CCS) and carbon emission trading (CET). The uncertainty is represented by fifty scenarios, generated using Monte Carlo sampling on a set of normal distributions that characterize the uncertain prices and operating costs. Specifically, in this particular example we aim to analyze the impact that the large variability in the carbon credit price and petroleum price has on the EGCM infrastructure design.

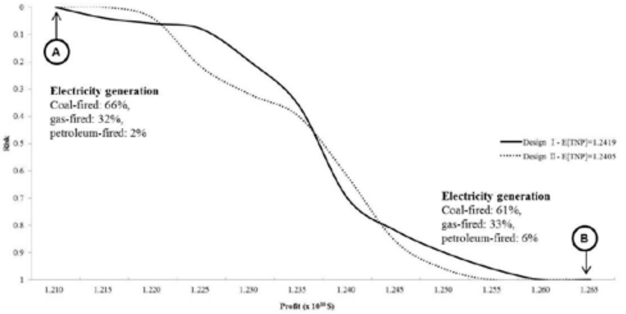

Figure 2. Pareto optimal solution curve

Figure 2 presents the Pareto frontier of the multi-objective problem. The results obtained show that in order to minimize the financial risk, the model resolves to reduce a petroleum-fired generation. This is because the petroleum price shows higher variability than the coal and natural gas. Let us note that electricity generation plants utilize CCS or CET for reducing the GHG emissions (Figure 3 and 4). The minimum financial risk solution, which corresponds to point A of Figure 2 and to results depicted in Figure 3 and 4, entails that CCS is utilized and CET is reduced overall in the entire power system. This is because the price variability of carbon credit had direct effect on the configuration of CO_2 mitigation.

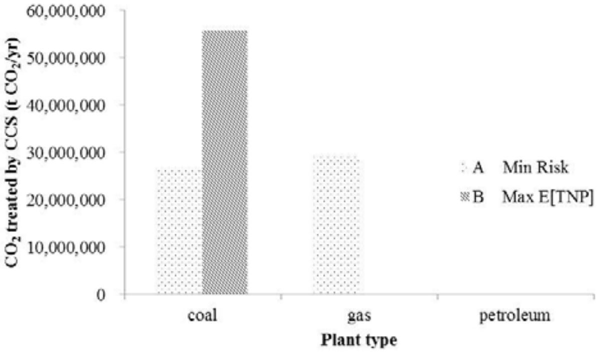

Figure 3. CO_2 treated by CCS facilities in each plant type associated with the extreme solutions.

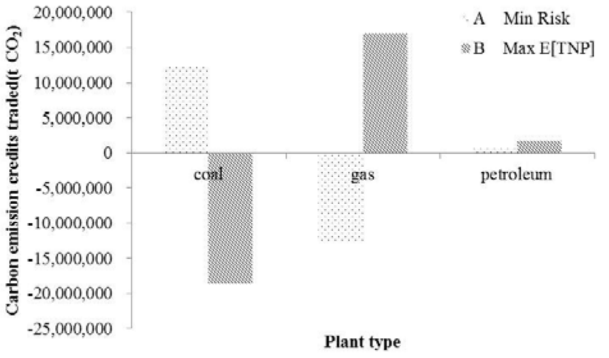

Figure 4. Carbon emission credit traded in each plant type associated with the extreme solutions.

Figure 5 illustrates a hypothetical example with three risk curves responding to these different risk attitudes. The figure reveals that for high target profits (higher than $1.240 \cdot 10^{10}$ \$), the solution shows a level of risk lower than the one for low target profits.

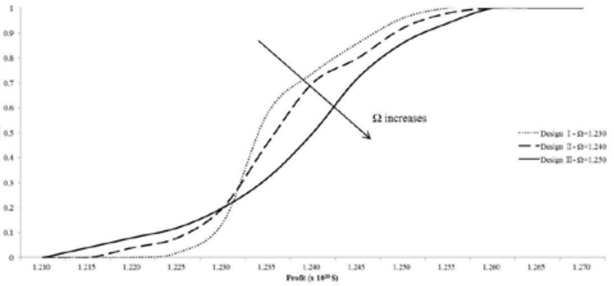

Figure 5. Different kinds of financial risk curves.

A risk-averse decision maker will prefer to lower the target profit, whereas a risk taker will prefer to higher the target profit. The trade-off lies in between these extreme solutions, which reflect different possible attitudes towards.

Conclusions

This work has introduced a mathematical model for risk management in the strategic design and planning of the EGCM infrastructure under uncertainty in prices and operating costs. The problem has been considered as a multi-objective stochastic MILP that simultaneously accounts for the maximization of the expected total profit and minimization of the financial risk. The weighed-sum method has also been employed in order to expedite the solution of such model. Simulation results have shown that the petroleum-fired electricity generation should be replaced by coal-fired one to reduce the variability of the profit distribution. We can propose the optimal operation of each power plant under uncertainty.

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Notation

Indices
e, Product form of electricity
f, Facility name for electricity generation
g, Geographical region
i, Physical form of CO_2
p, Type of power plant
r, Scenarios

Sets
x, Feasibility set for first-stage decision variables
y_r, Feasibility set for second-stage decision variables in scenario *r*
k, Set of profit targets

Parameters
$prob_r$, Probability of occurrence of scenario *r*
$UNB_{p,g,r}$, Unit net benefit of selling electricity generated from type of power plant *p* into region *g* in scenario *r*
$Cprice_r$, Price of carbon emission credits in scenario *r*
Ω, Target profit
ρ_k, Goal programming weight for financial risk formations

Variables
E[TNP], Expected total net profit
TNP_r, Total net profit in scenario *r*
TNB_r, Total net benefit in scenario *r*
TNC_r, Total net cost in scenario *r*
$CCSCC_i$, Capital cost of CCS facilities for CO_2
$CCSOC_{i,r}$, Operating cost of CCS facilities for CO_2 in scenario *r*
$G_{e,p,f,g}$, Amount of electricity generated by electricity facility *f* of plant type *p* in region *g*
$AEP_{i,p,f,g}$ CO_2 emission permit reallocated to electricity facility *f* of plant type *p* in region *g*
Risk(x,Ω), Financial risk of solution *x* at a profit target Ω
$Z_{r,k}$, Binary variable equal 1 if the profit of scenario *r* is smaller than the profit target Ω_k

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