AN FORMULATION OF THE ENERGY MODEL FOR THE KOREAN ENERGY INDUSTRY

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ABSTRACT

The main contribution of this research is the development of methodology which is capable of solving problems associated with the capacity expansion and operating schedule of energy industries. The principal concern of such industries is the proper allocation of primary energy which are required for the production of sufficient supply of electricity and petroleum products for the Korea's energy needs.

Nonlinear programming models are developed for the power generation expansion planning and for the oil refinery industry. In order to deal with uncertainties about future demands for final energy, chance-constrained programming is used to formulate appropriate constraints. The methodology of the model can be used to evaluate Korean energy policy and expansion planning in the energy industry, especially the electric power generation industry and the refinery industry.

1. INTRODUCTION

The Korean energy issues, though not fundamentally different from that of many other countries, have their own peculiarities. These are mainly due to the development strategy of the nation's economy, which is somewhere between a developing country and an industrialized country.

The income elasticity of energy demand has increased in the last twenty years, due to the rapid industrialization process. The high energy intensity industries are expected to be the leading growth sectors of the economy. The recent low oil price fostered the growth of oil consumption which can last for a long time in the future. The proportion of imported energy is increasing in spite of the government anti-oil policy.

Expansion planning of the nuclear power plants has reached a stage which could cause some safety problems. Many people have started to raise questions about safety in nuclear power plants even though they respect the opinion that uranium is the last fossil fuel which can replace oil and coal for electricity generation. Coal is an extremely abundant energy resource, but a number of programs exist, including environmental problems related to both production and consumption, and the difficulty of securing experienced technicians and miners.

Recognizing the situations mentioned above, a modelling effort has been conducted to give a better understanding of the interrelationship among the important factors which are shaping the energy system. The model has been structured with the aim of finding the optimal capacity expansion plan based on the optimization approach. The model consists of two submodels; namely, the electric power generation model and the oil refinery model. Major specifications and considerations are explained under restrictions of energy sources and environment as well as the necessary conditions for a desirable energy system.

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2. METHODOLOGY

As the principal purpose of this research is to develop a tool which can be used to establish a capacity expansion plan in the Korean energy system, there can be two main methods to model energy system. One is the *econometric method* and the other is the mathematical programming method.

The econometric method, based on economic theory and estimates using historical data, reflect the overall aggregate characteristics of energy supply and consumption and are oriented towards forecasting. As described by Theil(1), econometrics is concerned with the empirical determination of economic laws. The typical analysis process which constitutes the construction of an econometric method is composed of several steps as follows:

- Specification of the model in mathematical form;
- Collection of the appropriate and relevant data from the economy;
- Estimation of the parameters of the model;
- Testing of the model to judge whether it constitutes a realistic picture of the system.

Therefore, this method is used to get a reasonable forecast of the future energy demand which is not explained in detail in this research.

The modelling process in this research is developed by mathematical programming. Mathematical programming is suitable for solving expansion problems in the energy system, the main reason being that it is mainly concerned with supply. The basic forms of mathematical programming are linear, nonlinear and integer programming. Linear programming(LP) models have been used, since the early 1950's, in determining the optimum operation of petroleum refineries considering changing product prices and qualities of crude oil inputs. It was not until the mid-1970's, however, with the construction of the supply side of the PIES model(2), that a large scale LP framework was used to model the entire energy supply system of a country. LP models are relatively simple but frequently the solution of the problem considered requires the imposition of too many constratints to obtain solutions in a reasonable length of computing time.
However, an advanced package names GAMS/MINOS(3) can handle complex and large LP problems effectively. For the purpose of modelling the oil refining sector, linear programming can be used and the solution of the model used for sesitivity studies. To simplify and aggregate the refinery system, a relatively compact model is constructed.

Generation expansion planning can cover a rich diversity of techniques for addressing unit expansion, load management, production costing, and dispersed technology. The capabilities needed to keep track of various changes in the economic environment, production cost and reliability are the main concerns of a long-term planning process. Efficient optimization techniques based on linear programming formulations are inadequate because they are incapable of properly modelling nonlinear production costing and reliability considerations. Thus, nonlinear programming which include production costing and probabilistic reliability capabilities is used to construct a model for electricity generation expansion planning.

Existing models using the least-cost approach are mainly concerned with supply. This means that the demand for electricity is assumed to be exogenous, and therefore electricity consumption is assumed also to be unaffected by variations in the prices of primary energy. In this research, the effects of price changes of primary energy on capacity expansion are observed and analyzed.

3. CHANCE—CONSTRAINED PROGRAMMING

Chance-constrained programming is one of the three approaches to probabilistic programming, chance-constrained programming and stochastic programming with recourse. It was originated in the latter part of 1953 by Charnes, Cooper and Symonds(4) in the context of developing a planning and operations model for Standard Oil of New Jersey for the scheduling of heating oil manufacture, storage and distribution with weather dependent demand.

In the chance-constrained programming framework a very interesting line of development has been the decision rule approach to dynamic planning under risk and uncertainty. Its emphasis and extension in capital budgeting and other problems of operations research, is due to Byrne(5), Hillier(6) and Naslund(7). Two main points may be mentioned about this approach. Firstly, it seeks through decision rules of different orders such as zero, first and second order in terms of the number of previous time periods of history considered in the current decision to allow approximate, and yet simple and at times flexible, decision-making which can allow updating and hence suitable revision. Secondly, it allows the constraints of a programming problem to have a stochastic interpretion so that the budget constraint need only be satisfied in a probabilistic sense. The basic idea of chance-constrained programming is to convert the probabilistic nature of the problem into and equivalent deterministic siutation.

Statistical analysis is used to develop a plan and an operationally implementable procedure for "most", but not all, randomly emergent situations. This can be achieved by posing the problem of chanceconstrained programming as determining from a preassigned admissible class a vector of stochastic decision rules which would satisfy the chanc-constraints and optimize the expected value of a preassigned functional. Within this presceiption, chance-constrained programming is a method of tremendous flexibility with innumerable individual possible variations or models. A chance-constrained model is defined generally as follow(8) :

Maximise $Z=\sum_{j=1}^{n} C_jX_j$ (1)

subject to

$P(\sum_{j=1}^{n} a_{ij}x_j<b_i)\geq 1-\alpha_i$ (2)

$i=1, 2, \cdots, m$

$x_j\geq 0$, for all j.

The name 'chance-constrained' is given by constraint such as $\sum_{j=1}^{n} a_{ij}x_j\leq b_i$ being relized with a minimum probability of $1-\alpha_i$, $0<\alpha_i<1$. There are two possible cases to handle constraints according to considerations of coefficients and variables, and it is assumed that the parameters are normally distributed with known means and variance.

In the first case, it is assumed that each coefficient is normally distributed with mean E(coefficients) and variance Var(coefficients). It is further assumed that the covariances exist between coefficients. The analysis is explained as follows : Consider the i th stochastic constraint.

$P(\sum_{j=1}^{n} a_{ij}x_j<b_i)>1-\alpha_i$ (2)

and define

$g_i=\sum_{j=1}^{n} a_{ij}x_j$ (3)

Then g_i is normally distributed with $E(g_i)=\sum_{j=1}^{n} E(a_{ij})x_j$ and $Var(g_i)=X^T D_i X$

where $X=(x_1, \cdots, x_n)^T$

D_i = i th covariance matrix

$Var(a_{i1})\cdots\cdots\cdots Cov(a_{i1}, a_{in})$ (4)

$Cov(a_{in}, a_{i1})\cdots\cdots\cdots Var(a_{in})$

Now,

$$P(g_i\leq b_i)=P(\frac{g_i-E(g_i)}{\sqrt{Var(g_i)}}-\frac{b_i-E(g_i)}{\sqrt{Var(g_i)}})-1-\alpha_i \quad (5)$$

where $(\frac{g_i-E(g_i)}{\sqrt{Var(g_i)}})$ is normally distributed with mean zero and variance one. This means that

$$P(g_i\leq b_i)=\Phi(\frac{b_i-E(g_i)}{\sqrt{Var(g_i)}})$$

where Φ represents the C. D. F. of standard normal distribution. Defining K_{α_i} as the standard normal value such that $\Phi(K_{\alpha_i})=1-\alpha_i$, then the statement.

$P(g_i \leq b_i) \geq 1-\alpha_i$ is realized if and only if

$$\frac{b_i - E(g_i)}{\sqrt{Var(g_i)}} \geq K_{\alpha_i}$$

This yields the following nonlinear constraint

$$(\sum_{j=1}^{n} E(a_{ij})x_j + K_{\alpha_i}\sqrt{X^T D_i X}) \leq b_i \qquad (6)$$

which is equivalent to the doriginal stochastic constraint. For the special case where the normal distributions are independent, than $Cov(a_{ij}, a_i{}^1{}_j{}^1)=0$ and the last constraint reduces to

$$\sum_{j=1}^{n} E(a_{ij})X_j + K_{\alpha_i}\sqrt{\sum_{j=1}^{n} Var(a_{ij})x_j^2} \leq b_i \qquad (7)$$

In the second case, it is assumed that only b_i is a normal random variable with mean $E(b_i)$ and variance $Var(b_i)$. The analysis in this case is very similar to that of the first case above.

$$P(b_i \geq \sum_{j=1}^{n} a_{ij}x_j) \geq \alpha_i \qquad (8)$$

Thus, as in the first case,

$$P(\frac{b_i - E(b_i)}{\sqrt{Var(b_i)}} - \frac{\sum_{j=1}^{n} a_{ij}x_j - E(b_i)}{\sqrt{Var(b_i)}}) \geq \alpha_i \qquad (9)$$

This can only hold if,

$$(\frac{\sum_{j=1}^{n} a_{ij}x_j - E(b_i)}{\sqrt{Var(b_i)}}) \leq K_{\alpha_i} \qquad (10)$$

This means that the stochastic constraint is equivalent to the deterministic linear constraint.

$$E(b_i) + K_{\alpha_i}\sqrt{Var(b_i)} \geq \sum_{j=1}^{n} a_{ij}x_j \qquad (11)$$

Therefore it is shown that the chance-constrained model can be converted into an equivalent linear programming problem, when the distributions are independent.

4. FORMULATION OF THE MODELS

4.1 The Power Generation Model

The model for generation expansion planning is formulated as follows. The objective function represents the total of capital costs, fuel costs and operating costs of all plants over the planning horizon.

Minimize

$$Z = \sum_{t=1}^{I}\sum_{i=1}^{M} C_{it}(X_{it}) + \sum_{t=1}^{I}\sum_{i=1}^{M} F_{it}(Q_{it}) + \sum_{t=1}^{I}\sum_{i=1}^{M} P_{it}(Q_{it}) \qquad (12)$$

where

C_{it} = the capital cost of plant i per unit capacity in period t ($/KW).

X_{it} = the new capacity addition of each type of plant in period t(GW).

F_{it} = the fuel cost of plant i per unit of electricity generated in poeriod t ($/KWH).

Q_{it} = the electricity generated of plant i in period t (GWH).

P_{it} = the operating cost of plant i in period t ($/KWH).

The objective function is minimized subject to the following inequality and equality constraints.

i) The electricity demand constraint :

$$\sum_{i=1}^{M} Q_{it} \geq \sum_{j=1}^{J} D_{jt} \quad i=1,\cdots,M \quad j=1,\cdots,J \quad t=1,\cdots,T \qquad (13)$$

where

Q_{it} = the electricity generated of plant i in period t.

D_{jt}=the demand of consumer j in period t (GWH).

ii) The reliability constraint :

$P(QM_t > \sum_{i=1}^{M} AD_{it}QE_{it}) \leq \alpha_t$, t=1, …, T (14)

where

QM_t=the maximum peak loading in period t.

α_t=the expected loss of load probability.

AD_{it}=the availability of plant i in period t.

QE_{it}=the existing capacity of plant i in period t.

iii) The annual fuel availability :

$Q_{it}/HR_i \leq FA_{it}$ i=1, …, M (15)
t=1, …, T

where

HR_i=the heat rate of fuel for plant i (KWH/ton(TOE)).

FA_{it}=the fuel availability of plant i in period t (TOE).

iv) The hydro reserve constraints :

$Q_{hydro,t} \leq H_t$ t=, …, T (16)

where

H_t=the upper bound for hydro energy (GWH).

v) The balance constraint :

$Q_{it}=AD_{it}QE_{it}H_{it}$ i=1, …, M (17)
t=1, …, T

4.2 The Oil Refinery Model

Nine plant units are considered while assuming that all refinery industries have the same processing techniques in similar plant units. The major decision variables of the oil refinery model are the unit sizes of new added capacities, the operation levels of each existing plant unit, and the time of installation.

The objective function includes purchase costs for crude oil, operating costs and capital costs of refinery industries. The objective criterion is to minimize the total cost of satisfying forecasted demands for specified products. The algebraic form is as follows :

Minimize

$$Z=\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{M} C_{it}X_{ijt}+\sum_{t=1}^{T}\sum_{j=1}^{J} F_tR_{jt}+\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{M} P_{it}Q_{ijt} \quad (18)$$

i=1, …, M

j=1, …, J

t=1, …, T

where

C_{it}=the capital cost of processing unit i per unit capacity (U$/MTSD).

X_{ijt}=the new added capacity for each process unit i of plant j in period t (MTSD).

F_t=the crude oil cost per ton in period t.

R_{jt}=the feed stock of imported crude oil of plant j in period t (MTSD).

P_{it}=the operating cost of process i in period t (U$/MTSD).

Q_{ijt}=the process level of processing unit i of plant j in period t (MTSD).

The objective function is required to be minimized subject to several requirements which contain equality and inequality constraints. The major constraints considered for the oil refinery model are formulated as follows :

i) The petro-chemical products demand constraint

$$\sum_{i=1}^{M} IO_{ki}P_{ijt} \geq F_{kjt} \quad i=1, \cdots, M \quad j=1, \cdots, J \quad k=1, \cdots, K \quad t=1, \cdots, T \qquad (19)$$

where

IO_{ki}=the Input-Output coefficients to products k in process i.

P_{ijt}=the process level of process i from plant j in period t.

F_{kjt}=the quantity of the final petro-chemical products k from plant j in period t.

ii) The reliability constraint

$$P(RC_j TD_{kdt} \geq F_{kjt}) \leq \alpha_t \qquad (20)$$

$t=1, \cdots, T$

where

RC_j=the market share of plant j.

TD_{kdt}=the total demand for product k of demand sector d in period t.

F_{kjt}=the quantity of the final products k from plant j in period t.

α_t=the probability of umet demand.

iii) The material balances

$$\sum_{i=1}^{M} IO_{k'i}P_{ijt}=0.0 \quad k'=1, \cdots, K \quad i=1, \cdots, M \quad t=1, \cdots, T \qquad (21)$$

where

K′=the intermediate commodities.

iv) The raw material availability

$$\sum_{i=1}^{M} IO_{ri}P_{ijt}+R_{rjt}>0.0 \quad r=\text{crude oil} \quad i=1, \cdots, M \quad j=1, \cdots, J \quad t=1, \cdots, T \qquad (22)$$

where

R_{rjt}=the quantity of raw material (crude oil) input for plant j in period t.

v) The capacity constraint

$$\sum_{i=1}^{M} C_{ui}P_{ijt}-QE_{ujt} \quad u=1, \cdots, U \qquad (23)$$

where

C_{ui}=the capacity requirement coefficients for process i of process unit u.

QE_{ujt}=the existing capacity of process unit u for plant j in period t.

In addition to providing useful summary measures, energy models should provide, on the basis of given assumptions, a realistic and accurate assessment of the impact of government action and other change in the energy supply sector. It is known that the methodological approach which aims to make the model a representative of the real world as closely as possible, rests on the implicit acceptance of a number of principles as follows :

1) It is impossible to construct a model that can be claimed to represent the real world in a global sense.
2) The validity of conclusions drawn directly from a model does require a maximum degree of real world representation.
3) It is necessary to make use of a suitable methodology of function specification in order to maximize the degree of real world representation.
4) The macroeconomic responses to changes in an energy subsystem can be more important to the final outcome in the energy model than the direct effects of change.

It is impossible to construct a model which in any true sense can be claimed to represent the actual energy system, simply because the structure of the economic, social and political situations is unstable and contains uncertainties. The best that can be expected from an expansion model, which includes uncertain components such as the potential supply of crude oil, the price mechanism in primary energy markets, and a forecast of demand, is that it can provide useful information from which decision maker(s) can establish expansion policy for energy industries.

4.5 CONCLUSIONS

The development of an effective methodology has been conducted to handle some important issues in the Korean energy system. The model has been formulated to determine the optimal capacity expansion plan.

Mathematical programming is suitable for solving expansion problems in the energy system since it is mainly concerned with supply. The model consists of two sub-models; namely, the electric power generation model and the oil refinery model.

Nonlinear programming which include production costing and probabilistic reliability capabilities is used for the electric power generation model to handle nonlinear constraints and objective functioin. For the purpose of modelling the oil refinery industry system, nonlinear programming is also used to cope with the reliability constraint which can be considered nonlinear, using GAMS/MINOS. To solve probabilistic constraints, chance-constrained programming is used in the modelling process. It is emphasize that the energy model should provide, on the basis of given assumptions, a realistic and accurate assessment of the impact of government action on supply and other changes in it. Therfore, uncertainties affecting future energy systems can be identified easily and some useful moves can be planned against them.

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