Developing a Multi-objective Mathematical Model for Power Generation Expansion Planning in Iran

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INTRODUCTION

Although there are several types of energy which are consumed by countries, electronic energy plays an important role in economic and technological development and the improvement of the level of public welfare. It is the main effective factor to be considered in demands for electronic energy which leads to the development of new power stations for expanding the capacity of power generation. Unlike other energies, power cannot be saved at macro level. In other words, it is not possible to save power through storage systems. Moreover, with respect to the basic nature of the power industry, the lack of timely electronic energy supplies results in many problems such as power outage. It can be said that the cost of inappropriate power supply is more than the cost of other energies. This is the reason why it is necessary to adapt the capacity of power generation to demands by using precise planning. On the other hand, the power industry is an important industry which has huge investments. It is known as the capital intensity. Such characteristics make precise planning an inevitable tool for the plans to expand power generation. Power generation is the main part of power...
industry. With respect to the high costs of power generation departments and the role that these departments play in power generation, it is necessary to establish new power stations and maintain the existing ones in the best manner (Knizley & Mago, 2013). On the other hand, the shortage of power stations capacity in Iran has different unfavorable effects on economic and sociopolitical aspects such as power outage. This is why it is necessary to develop the most appropriate plans in this area.

Generation expansion planning, which refers to investment in energy generation, attracts the attention of many investors and researcher to itself. Indeed, planning for investment in generation expansion plans should consider different aspects of the issue such as optimum volume, appropriate time, appropriate technologies, investment return, risks, and uncertainty so that the goals of the generation expansion planning can be achieved. According to Kothari and Kroese (2009), generation expansion planning is a process which attempts to respond to power demand through the following functions:

1. Defining technology type and new resources which should be added to the existing power generation system.
2. Defining the best geographic location for establishing new power generation systems.
3. Defining the best time for establishing new power generation systems.

It can be said that the purpose of generation expansion planning is to develop the existing power generation systems in order to satisfy the ever-increasing demands through considering reliability criteria (Hemmati et al., 2013: 955). In fact, generation expansion planning attempts to define the optimal size, location, and time for establishing new power stations in order to satisfy the predicted demand based on the reliability criteria. This is the reason why the present study aims to develop a multi-objective model of power generation expansion planning in Iran. For this purpose, two objective functions and several constraints were considered. In this regard, minimizing the production costs (both operational and investments costs) and the environmental effects (e.g., CO₂, SO₂, and NOₓ) are considered. As mentioned earlier, the constraints of this model are reserve margin constraints, demand constraints, constraints of the production concentration in special technologies, and non-negative constraints.

**REVIEW OF LITERATURE**

When power supplies are higher than demands, it is necessary to add new generation units. Generation expansion planning is a systematic effort to answer the question concerning “what, where, and when power stations should be established?” Indeed, the purpose of the generation expansion planning is to define the location, time, and size of the power stations to satisfy the reliability criteria. Generation expansion planning encounters different challenges from the past and present. The first challenge can be the uncertainty of the parameters and the input data which is caused by the long-term nature of the issue. In this regard, the uncertainties about the future demands, the fuel price, the technical and economic characteristics of the new power generation technologies, the time scale for establishing the power stations, and ecological rules and regulations are the main challenges. The first challenges in this area are simultaneous (and sometimes unadoptable) objectives. Such objectives can indicate the need to minimize the total cost and the effects of ecological pollutants and maximize the system reliability. There are other parameters and costs which are considered as the constraints of the problem (Meza, 2006). All of these challenges make generation expansion planning very complex and cause the emergence of different models, methods, ideas, and constraints (Sharma, Chandel, Delebarre, & Alappat, 2013).

From the mathematical perspective, generation expansion planning is a large-scale optimization problem with non-linear, discounted, dynamic, and conditional nature (Nakamura, 1984: 231-240), (Wang and McDonald, 1994).

Generally, generation expansion planning includes the two processes of calculating the generation costs and finding the best development plan. With respect to the existence of random factors such as
demand, the generation costs cannot be calculated very precisely. On the other hand, these expenses are a significant part of the system costs (Yamamoto et al., 2013). This is why different methods were suggested for calculating them such as probability cost simulation in which the generation costs are calculated through considering these random factors (Wang, 1994). In this respect, different optimization methods are employed such as linear programing, non-linear programing, dynamic programing, integer linear programing, and so on.

With respect to the different factors like the market growth, the fuel price, and other factors which are not certain, generation expansion planning can be done through the following methods:

1. Stochastic methods

In the first method, the factors are uncertain and in the deterministic method, system performances are investigated for different scenarios that can possibly happen. As a result, a method of rapid optimization is necessary in this method for the number of simulations in different scenarios. Most of the problems in generation expansion planning are viewed as single-objective problems in which there is a singular objective function. Since the beginning of the 1980s, the application of multi-objective models has been prevalent in solving the problems of generation expansion planning. In the multi-objective models, optimum response is replaced with uncertainty solutions for single-objective problems (Coello et al., 2002).

In general terms, a mathematical multi-objective model can be presented in the following form (Yakov and Warres, 1974: 615-624).

\[
\min_x \{f_1(x), f_2(x), \ldots, f_n(x)\}
\]

subject to:

\[
g_k(x) \leq 0 \quad k = 1, 2, \ldots, m
\]

In the model, “x” is a vector with “n” decision variables, “n” objective functions, and “m” constraints. If there is not any other “x” variable, then “x” will be a non-dominant answer as following.

\[
f_i(x) \leq f_i(x^*) \quad , \quad i = 1, 2, \ldots, n
\]

**RESEARCH METHODOLOGY**

So far as the research purpose is concerned, the current study is an example of applied research and, respecting the research methodology, it is a descriptive study. The statistical population consists of all the fossil power stations in Iran. In order to collect the research data, the reports provided by the Iranian power industry were used. In this regard, authors have used different reports. Generally, there are two types of multi-objective functions including different methods for solving models based on the information from the decision-maker and other methods (Mehregan, 2007: 31-245). Each method has its own strengths and weaknesses. In the present study, the goal programming and the comprehensive criteria methods have been used.

**RESEARCH MODEL**

The target functions and constraints of this model are described in the following section.

The first function of the goal: as indicated previously, the first goal of generation expansion planning is minimizing the total production costs (both investment and operational costs). The primary goal of generation expansion planning is minimizing the cost. According to Shiina (2011), such a cost may include the investment and operational costs (Speight, 2013b). Generation expansion planning models attempt to reduce the power expense through reducing both operational and investment costs. As a result, customer satisfaction will be secured. The formula for this function is presented in the following section.

\[
f_1 = \min \sum_{n=1}^{3} \sum_{t=1}^{20} l_n G_{nt} + \sum_{n=1}^{3} \sum_{j=1}^{20} F_{nj} \times 8760 \times C_{njt} \times G_{nt}
\]

The second function of the goal: minimizing the ecological pollutants (including \(CO_2\), \(SO_2\), and \(NO_x\)) is the second target function of our generation expansion planning. Around 50% of global power energy is generated through nonrenewable resources (Bossavy, Girard, & Kariniotakis, 2013). The use of nonrenewable resources for generating
power can create many ecological pollutants such as CO$_2$, SO$_2$, and NO$_x$. As a result, many irrecoverable damages may emerge. Some authors assert that some developed countries like the US have expanded several policies for reducing nonrenewable resources consumption (Menz, 2005: 2399). On the other hand, it should be noted that achieving renewable resources face different problems and difficulties. This is why that nonrenewable resource is used for generating power energy. Therefore, using renewable resources in power generation is inevitable. The formula for this goal function is presented below.

$$f_2 = \min \sum_{n=1}^{3} \sum_{j=1}^{2} \sum_{t=1}^{20} F_{n,j} \times a_n \times 8760 \times E_{n,j} \times G_{nt}$$

**Constraints**

The first constraint: reserve margin constraint refers to the probability of outage for the lack of power demand dissatisfaction. It is considered to be one of the main constraints which are addressed in many studies such as the present study. Indeed, the constraint indicates that the existing power generation units along with the new ones should generate power much more than the demands so that power demand can be satisfied perfectly. The formula for this constraint is presented in the following section.

1) $$(1 + R) \cdot q_{peak} \leq \sum_{n=1}^{3} a_n \cdot G_{nt}$$

The second constraint: this constraint states that the generation of both the existing and new generation units should be up to a degree that satisfies power demand perfectly. For this purpose, demand constraint is the second constraint which is considered in our study.

2) $$\sum_{n=1}^{3} G_{nt} \times a_n \times 8760 \geq d_t$$

The third constraint: the constraint of production concentration in special technologies is the third constraint of our study. This constraint states that power generation should not be focused completely on special technologies. The formula for this constraint is presented in the following section.

3) $$\sum_{t=1}^{20} G_{nt} \leq l_n \sum_{n=1}^{3} G_{nt}$$

The fourth constraint: this constraint refers to non-negative variables. In other words, the constraint states that none of the variables should be negative.

The formula of this constraint is presented in the following section.

4) $$G_{nt} \geq 0$$

The overall model of this study is presented in the following section.

1) $$f_1 = \min \sum_{n=1}^{3} \sum_{t=1}^{20} l_n G_{nt} + \sum_{n=1}^{3} \sum_{j=1}^{2} \sum_{t=1}^{20} F_{n,j} \times a_n \times 8760 \times C_{n,j,t} \times G_{nt}$$

2) $$f_2 = \min \sum_{n=1}^{3} \sum_{j=1}^{2} \sum_{t=1}^{20} F_{n,j} \times a_n \times 8760 \times E_{n,j} \times G_{nt}$$

s.t:

1) $$(1 + R) \cdot q_{peak} \leq \sum_{n=1}^{3} a_n \cdot G_{nt}$$

2) $$\sum_{n=1}^{3} G_{nt} \times a_n \times 8760 \geq d_t$$

3) $$\sum_{t=1}^{20} G_{nt} \leq l_n \sum_{n=1}^{3} G_{nt}$$

4) $$G_{nt} \geq 0$$

**Introducing decision variables**

$G_{nt}$ refers to capacity of unit “$n$” in time scale “$t$” (MW). “$t$” refers to time period ($t=1, 2, \ldots, 20$). “$n$” refers to the type of technology ($n=1$ (steamy), 2 (gas), and 3 (combined cycle)). “$j$” refers to the type of fuel (1 (gas) and 2 (gasoline)). All of the parameters of the research model are presented and introduced in table 1.

**DATA ANALYSIS**

In order to encode and solve the model, GAMS was used. In this regard, the goal programming and the comprehensive criteria methods were both used for solving the model. In order to solve the model through the comprehensive criteria methods, it is necessary to calculate all the target functions and constraints. They are presented in the following section.

$$f_1^* = 1.35 \times 10^{12} \quad \text{gram}$$

$$f_2^* = 9.374 \times 10^{15} \quad \text{gram}$$

In the second step, each target function should be calculated using the software. Indeed, the target function of the comprehensive criteria method refers to the deviation of optimum amount of the goal of the target function which should be
minimized as much as possible. This is presented in the following section.

\[ z^* = 0.107 \]

In the third step, we can calculate the optimum value of the decision variables through placing optimum values of decision variables in each target function. These values are presented below.

\[ f_1^* = 1.701 \times 10^{12} \]  
\[ f_2^* = 9.379 \times 10^{15} \text{ gram} \]

In addition, the target function of the goal programming is \( z^* = -9.37 \times 10^{14} \). It is possible to calculate optimum values through placing the optimum values of the decision variables in each target function. They are presented below.

\[ f_1^* = 1.701 \times 10^{12} \]  
\[ f_2^* = 9.374 \times 10^{15} \text{ gram} \]

Because optimum values of the target functions are similar in both methods, it can be said that the two methods confirm each other.

The output of GAMS is presented in table 2.

INSERT TABLE 2 HERE

Based on the results of comprehensive criteria, capacity of gas for 2015 is 62598.556 M.W.

Figures for the findings are presented in the following parts.

INSERT FIGURE 1, 2 & 3 HERE

CONCLUSION AND SUGGESTIONS

The study aimed to develop a multi-objective mathematical model for power generation expansion planning in Iran. The study is an applied and descriptive research seeking to develop a linear mathematical model for the generation expansion planning using mathematical programming techniques. The target functions are minimizing the total production costs (both investment and operational costs) and ecological pollutants (e.g., CO₂, SO₂, and NOₓ). The constraints of the model are demand constraints, constraints of the production concentration in special technologies, reserve margin constraints and non-negative constraints. The present study attempts to prepare the generation expansion planning for the time period from 2015 to 2034. The proposed model was encoded in GAMS and was approached by both the Goal Programming and the Comprehensive Criteria methods.

Based on the limitations of this study, the following suggestions can be followed by future authors.

• Considering Loss of Load Probability (LOLP) as one of the main limitations of system reliability which makes the model in probability conditions.
• Considering other goal functions such as minimizing energy import and minimizing risks of energy price changes
• Considering modern renewable technologies in generation expansion planning
• Considering uncertain variables in the model
• Considering social issues in the goal function of generation expansion planning model
• Using other forecasting methods in predicting model data such as energy prices.

REFERENCES


Mehregan, Mohamad Reza, (2007), multi-objective decision making models, Faculty of management press, university of Tehran, pp. 81-83.


APPENDIX

Table 1: Parameters of research model

<table>
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<tr>
<th>Parameters</th>
<th>Description</th>
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<tr>
<td>$I_n$</td>
<td>Investment cost of powerhouse “n” (MW/dollar)</td>
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<tr>
<td>$F_{nj}$</td>
<td>Percentage of fuel “j” usage in technology “n”</td>
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<td>$C_{njt}$</td>
<td>Generation costs (both operational and maintenance costs) of unit “nj” in time period t</td>
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<tr>
<td>$E_{nj}$</td>
<td>Amount of pollutants (gram) for every MW-H generated power by unit “nj”</td>
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<td>$q_{peakt}$</td>
<td>Maximum point of power demand in time period “t” (MW)</td>
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<tr>
<td>$a_n$</td>
<td>Coefficient of exploitation of unit “n”</td>
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<td>$R$</td>
<td>Reserve margin</td>
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<td>$l_n$</td>
<td>Coefficient of production reliant on technology “n”</td>
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<td>$d_t$</td>
<td>Demand of power in the time period “t” (MW/H)</td>
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Table 2:

The summary of GAMS output

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<th>Years</th>
<th>Combined cycle</th>
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Figure 1: The necessary capacity of steamy

Figure 2: The necessary capacity of gas
Figure 3: The necessary capacity of combined cycle