OPTIMAL SCHEDULE OF ELECTRICITY GENERATED BY HYDRO, GAS AND STEAM TURBINES

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ABSTRACT: *The energy problem is the most important issue that became a challenge not only for Pakistan but also for many other countries of the world from the political and economic point of view. The countries with sufficient energy resources developed and implemented a number of optimization models to aid in the planning of energy generation. Government of Pakistan has been facing serious problems of providing energy to industries as well as for the domestic use at affordable cost for the last eight years. Reduction in the limited resources and rapid increase in cost led to the idea of optimal power generation planning. In this paper, a mathematical programming model is developed for planning the schedule of electricity generated by three technologies. The demand of electricity of 24 hours is divided in to two load blocks: (i) Peak load (4 hours), (ii) Off-peak load (20 hours). The developed model is implemented on the production and scheduling problem for 24 hours as a case study that reduced the operating cost of electricity by 7.02%.*

Keywords: Optimization, Peak load, Off-peak load, Power Generation Planning, Fuel-mix.

INTRODUCTION

The most widely used form of energy is electricity. It is the basic need of everybody for enhancing the standard of living. It also plays an important role for economic development of any society. With the increase in population and expansion in the economy of any country the demand of electricity multiplies. Because of the living standard improvement the demand for sufficient quantities and satisfactory structures of various energy resources has been increasing all over the world in the past decades. The decision makers and planners are facing too much pressure due to the complexities and uncertainties to resolve effectively a number of issues and conflicts related to the energy sector.

For the stable system operation the generation fuel-mix and the cost of generation of electricity are very important. But fuel-mix can be defined as a configuration of the power generation that gives the maximum benefit while satisfying a specific purpose. Such purpose can be the maximization of profit or minimization of the cost or risk of return of investment from the market participants. For this reason, generation companies as well as sales companies become interested in the optimal fuel mix. The researchers used a range of optimization techniques to implement the idea of minimizing the cost of fuel-mix.

Many organizations of different countries are taking advantage of these techniques for developing various types of optimization models. The implementation of the techniques for the optimum allocation of energy resources, best use of different technologies, and relevant services under one or several administrative objectives gave remarkable economic benefits [1]. Sharma et al. suggested an approach for the optimal plan of compressed air energy systems which reduced the capital and operating cost [2]. Kavrakoğlu proposed dynamic programming model to organize countrywide energy system [3]. Smith recommended an optimization model for scheduling the energy system of New Zealand [4]. Two linear programming models, a global energy system model and an electricity generation system model, were discussed by Samouilidis [5]. Wescouger optimization program was designed by S. R. Erwin [6] using dynamic programming and branch-and-bound techniques and by the implementation of these approaches the fuel costs for Southern Company over the past few years were reduced up to $140 million. Kahane [7] presented the analysis of optimization model for managing different energy systems.

A linear programming model for the economy, a long-term coordination among energy and the environment in Turkey was proposed by Tiris [8]. Arivalagan proposed an optimization model of an industry and the overall cost of energy of fuel mix was which minimized by using mixed integer linear programming approach [9]. Hobbs discussed various optimization techniques to utilize the resources in a best way [10]. MODEST, a linear programming based approach, was developed by Henning to minimize the functional costs of energy distribution [11]. Balachandra and Chandru developed a linear programming model to match the electricity demand changing day by day with lowest cost, and Karnataka electricity system implemented successfully this model [12]. D. G. Choi and Thomas developed a model for the investment and operation plan for the generating capacity of an electric power system of Georgia, and then it was implemented successfully to the energy system [13]. A mixed integer linear programming model of fuel-mix for 2022 was analyzed by Y. B. Jung et al. as a result the cost of power generation was minimized while satisfying the daily load demand [14].

MATERIALS AND METHODS

Formulation of Optimization Model

Mathematical functions of a number of variables to be maximized or minimized, subject to certain constraints, fall in the field of optimization. Many theoretical and real-world problems relating almost too every field of life can be modeled in this area of study. The general term used to maximize or minimize is to optimize.

The general mathematically form of optimization problem is written as

$Maximize\ or\ Minimize \quad f(\underline{\boldsymbol{x}})$
$Subject\ to$
$g_i(\underline{x}) \le 0 \qquad (i = 1,2,3, \dots . I)$
$h_j(\underline{x}) = 0 \qquad (j = 1,2,3, \dots, J)$
$l_k \le x_k \le u_k \qquad (k = 1,2,3, \dots . n)$
where, $\underline{x} = (x_1, x_2, x_3, \dots \dots, x_n)^T \in R^n$

An optimization model to fulfill the demand of electricity at minimum cost with the operational constraints (plant capacity factor, demand satisfactions) is formulated. Notations and decision variables which used in the model are:

Notations

K_i : Installed capacity in MW of type *i*

t_p : Duration of load block *p* in hours

c_i : Production cost (fuel cost + operating cost + maintenance cost) in *Rs.* for plant *i*

A_{ip} : Minimum percentage of capacity factor for plant *i* in load block *p*

B_{ip} : Maximum percentage of capacity factor for plant *i* in load block *p*

Index

i: Plant type, $i = 1,2,3, \dots, I$

p: Load block, $p = 1,2,3, \dots, P$

Variables

x_{ip} : Power generated in MW by plant *i* in load block *p*

Objective Function

The objective is to minimize the total power generation cost of I number of plants with P load blocks in 24 hours. Thus using the above defined notations and variables, the objective function is

$$Minimize \qquad f(\underline{x}) = \sum_{p=1}^{P} t_p \sum_{i=1}^{I} c_i x_{ip}$$

Constraints

a) Plant Capacity Factor

The constraints related to minimum and maximum capacity factor for the power plant are

$$A_{ip} \le \frac{x_{ip}}{K_i} \le B_{ip}$$

b) Power Demand

The power demand in any period and at each load block must be satisfied by the power generation of plants.

$$\sum_{i=1}^{I} x_{ip} \ge d_p$$

The complete optimization model is

$$Minimize \qquad f(\underline{x}) = \sum_{p=1}^{P} t_p \sum_{i=1}^{I} c_i x_{ip}$$

Subject to

$$A_{ip} \le \frac{x_{ip}}{K_i} \le B_{ip}$$

$$\sum_{i=1}^{I} x_{ip} \ge d_p$$

$$x_{ip} \ge 0$$

CASE STUDY

Pakistan has multiple resources for power generation which include hydro, gas, oil, nuclear, coal, and diesel. It is a proven fact that the cost of energy produced by thermal power plant is higher than any other type of plant. A huge amount of imported oil of worth Rs: 14.50 billion is used to generate electricity by thermal power plants.

It can be seen from the following table that Pakistan reserves larger share of oil in the production of electricity [15].

Table-1: Comparison of Generation of Electricity by Sources

	Gas	**Oil**	**Coal**	**Hydel**
Pakistan	29.0%	35.0%	0.1%	35.7%
India	9.2%	0.8%	71.0%	19.0%
Bangladesh	73.0%	20.4%	3.4%	3.2%

Thus, there is immediate need of fuel mix for the generation of electricity. To achieve this goal an appropriate technique of optimization is used which can minimize the overall production cost of electricity.

The above developed optimization model was implemented on the power generation cost in Pakistan. In this paper, we considered three types of generation technologies (i) Hydro (ii) Gas Turbine (iii) Steam Turbine.

The information for the cost problem is taken from Power System Statistics, Pakistan [16]. The following table shows the installed capacity and operating cost of three technologies.

Table-2: Power Plant Data

S. No.	Plant Type	Installed Capacity (MW)	Cost (RS in Million)
1	Steam Turbine	6087.2	12447
2	Gas Turbine + Combined Cycle	5606.8	10334
3	Hydro	6626	2335

We have planned the generation schedule for the electricity for 1 day. In Pakistan, demand of electricity is divided into two load blocks: (i) peak hours (ii) off-peak hours [17]. The demands of electricity during peak hours and off-peak hours are shown in the following table.

Table-3: Detail of Time Block

Demand Block	Duration (Hours)	Maximum Demand
1	4 (peak)	14,830
2	20 (off-peak)	9268.75

We assumed the minimum and maximum capacity factor of each power plant in two blocks is given as:

Table-4: Capacity Factors of Power Plants

Hydro				Steam Turbine				Gas Turbine + Combined Cycle			
Peak		Off-Peak		Peak		Off-Peak		Peak		Off-Peak	
Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
75%	95%	70%	85%	65%	80%	25%	65%	70%	85%	55%	70%

NUMERICAL RESULTS AND DISCUSSION

The above developed model was formulated for the optimal fuel mix of generation for the electricity. Since the above problem was formulated as a linear programming model of 24 variables, so we solved it by using built-in solver in Microsoft Excel. The optimal generation of electricity by three different types of power plants is presented in the following table 5(a) & 5(b).

Table-5(a): Optimal Fuel Mix of Generation

Hydro	Steam Turbine	Gas Turbine + Combined Cycle
48%	19%	33%

Table-5(b): Optimal Fuel Mix of Generation in Demand Blocks

Hydro (MW)		Steam Turbine (MW)		Gas Turbine + Combined Cycle (MW)	
Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak
6294.7	4663.21	3956.68	1521.8	4578.62	3083.74

The above table 5(a) shows an optimal fuel mix for the generation of electricity which highly depend on Hydro and Combined Cycle with 48% and 33%, respectively. The table 5(b) shows the production of power 6294.7 MW by Hydro, 3956.68 by Steam Turbine and 4578.62 by Combined Cycle in the peak hours and 4663.21 by Hydro, 1521.8 by Steam Turbine and 3083.74 by Combined Cycle in the off peak hours which fulfill the maximum and minimum demands respectively.

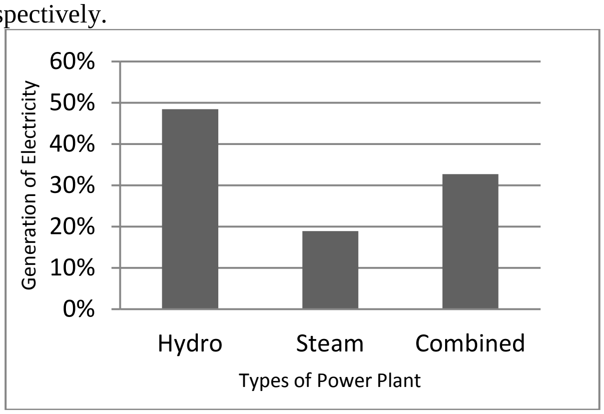

Fig. 1(a): Optimal Fuel Mix for the Power Generation

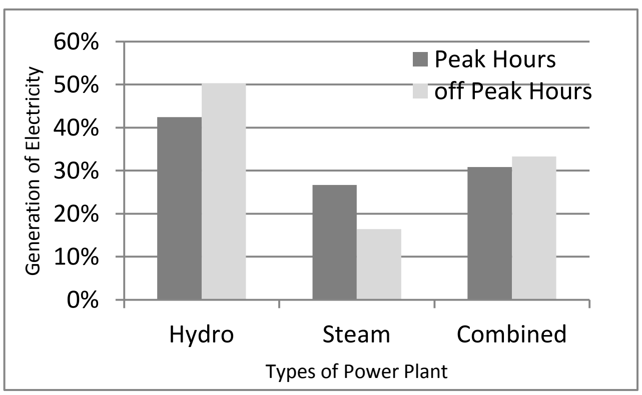

Fig-1(b): Optimal Fuel Mix for the Power Generation in the Peak and off Peak Hours

Fig.1(a) shows the optimal generation of electricity by three different types of fuel mix. This figure also shows that in the total generation of power in Pakistan during peak and off peak hours are contributed by Hydro, Steam and combined cycle by 48%, 19% and 33%, respectively. Fig. 1(b) shows that the contribution of Hydro, Steam and Combined Cycle in the generation of electricity is 42%, 27%, 31% during peak hours and 50%, 16%, 33% during off-peak hours, respectively.

Table-6: Comparison of Electricity Generation Cost

Generation Cost /KWh	
Non-optimal	Optimal
Rs. 7.38	Rs. 6.86
Cost reduced by 7.02 % /KWh	

Table 6 shows the comparison of electricity generation cost before and after optimization.

CONCLUSION

In this paper a useful model for minimum cost has been developed considering three types of technologies for power generation. We have employed a linear programming approach for developing and calculating the plan of optimal cost for the model. The numerical results have proved the suitability of the model for investigation of issues concerning the utility planning involving plant deterioration due to aging and the plant non-availability as a result of outage and compulsory maintenance. In the optimization model, on every individual plant, the production distribution decisions were taken so as to present the information regarding the plant operations that the engineers need to make their decisions. The proposed model is capable of minimizing the generation cost of electricity by making a schedule of fuel-mix of three types of generation technologies while satisfying the demand of electricity. The result presented in table 6 shows 7.02% reduction in operating cost of electricity which can affect significantly the total cost of production. Consequently, the optimization model of our study can help the system planners to carry out more flexible and effective decision making related to the power generation.

REFERENCES

[1] Zeng, Y., Y. Cai, G. Huang & J. Dai. A Review on Optimization Modeling of Energy Systems Planning and GHG Emission Mitigation under Uncertainty. *Energies* **4**(10): 1624-1656 (2011).

[2] Sharma, A. H., H. Chiu, F. W. Ahrens, R. K. Ahluwalia & K. M. Ragsdell. Design of Optimum Compressed Air Energy-Storage Systems. *Energy* **4**(2): 201–216 (1979).

[3] Kavrakoğlu, I. Decision Analysis in the Energy Sector. *Applied Mathematical Modelling* **4**(6): 456–462 (1980).

[4] Smith, B. R. Modelling New Zealand's Energy System. *European Journal of Operational Research* **4**(3): 173–184 (1980).

[5] Samouilidis, J. E., J. Psarras & D. V. Papaconstantinou. Electricity Planning vs. Energy Planning: A Modelling Approach. *Omega* **12**(4): 341–346 (1984).

[6] Erwin, S. R., J. S. Griffith, J. T. Wood, K. D. Le, J. T. Day & C. K. Yin. Using an Optimization Software to Lower Overall Electric Production Costs for Southern Company. *Interfaces* **21**(1): 27-41 (1991).

[7] Kahane, A. New Perspectives for Energy Efficiency and System Optimization. *Energy Policy* **19**(3): 199–201 (1991).

[8] Tiris, M., G. Atagunduz & I. Dincer. Energy, Economy and Environment Modelling: Applications for Turkey. *Energy* **19**(9): 1005–1009 (1994).

[9] Arivalagan, A., B. G. Raghavendra & A. R. K. Rao. Integrated Energy Optimization Model for a

Cogeneration Based Energy Supply System in the Process Industry. *International Journal of Electrical Power & Energy Systems* **17**(4): 227–233 (1995).

[10] Hobbs, B. F. Optimization Methods for Electric Utility Resource Planning. *European Journal of Operational Research* **83**(1): 1–20 (1995).

[11] Henning, D. MODEST-An Energy-System Optimization Model Applicable to Local Utilities and Countries. *Energy* **22**(12): 1135–1150 (1997).

[12] Balachandra, P. & V. Chandru. Supply Demand Matching in Resource Constrained Electricity Systems. *Energy Conversion and Management* **44**(3): 411–437 (2003).

[13] Choi, D. G. & V. M. Thomas. An Electricity Generation Planning Model Incorporating Demand Response. *Energy Policy* **42**:429–441 (2012).

[14] Jung, Y. B. A Study of Optimization Modeling to the Generation Cost under the Stable Operation of Power System. *Journal of International Council on Electrical Engineering* **2**(2): 208-214 (2012).

[15] www. finance. gov. pk

[16] Durrani, Z. H. K. *Electricity Marketing Data, 37th Edition. Pakistan*. Planning (Power), Department (NTDC) WAPDA House, Lahore, (2010).

[17] http://www.lesco.gov.pk/customerservices/3000063.asp