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COST EFFECTIVE GENERATION MIX FOR BANGLADESH POWER SUPPLY SYSTEM

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Abstract The per capita consumption of electricity is a yardstick in measuring the progress report of a country in a given year. In this respect, Bangladesh, as a developing country, lags far behind. It is yet to go a long way to reach the standards of exploitation and consumption of electricity already achieved by the developed countries. In order to accelerate the electrification rate and offset the power deficit in the face of growing power demand over supply, a substantially large amount of new capacity has to be created. At present many plants are derated due to old age, some have even crossed retirement age and many more have become obsolete, yet they are kept in operation. Such a situation always advocates for the expansion and overhauling of the existing plant facilities. In this exercise, a linear programming model has been applied to develop an expansion program based on the optimal generation-mix of various costs attendant therein. The results of the model present future capacity expansion programme, optimal operating schedules showing the generation-mix of various power plants at various loads (peak, day-peak, offpeak and base load) throughout the year and also the optimum generating costs in the fature projection periods

List of Notations

Subscript	Meaning	Range
i	Plant type	i=1,....I
t	Time period	t=1,....T
p	Load duration curve Demand block	p=1,....P
v	plant vintage	v=1,....T

Variables & Symbols:	Meaning
t_1	First feature time period ($1 \le t_1 \le T$)
A_{itv}	Discounted annuitiesed capital cost ($/KW)
G_{iv}	Capacity constructed (KW)
DF_t	Discount factor
r	Discount rate per year (%)
FP_{it}	Fuel price ($/KJ)
μ_{iv}	Heat rate of power plant ((KJ/Kcal)
θ_p	Width of load duration curve (LDC) demand block (hrs.)
$Z_{itp'v}$	Z-substitute to replace U's (power output) (KW)
M_{itv}	Fixed operation and maintenance cost ($/KW/h)
R_{itv}	Remaining capacity in the system (KW)
PP_{tp}	Hight of the demand block of the LDC (KW)
θ_{itv}	Availability of the power plant (%)
Giv	Amount of capacity actually constructed (KW)
m	Planning margin (%)
$G_{max\ iv}$	Limit on future plant construction (KW)

1. INTRODUCTION

The purpose of electricity generating capacity expansion planning is to obtain the best evolution of its future generation system. Linear programming is the most widely used global optimisation technique in electricity supply industries[1]. The linear programming model adopted from the one presented by Turvey & Anderson [2] and applied here is versatile in nature in the sense that with little modifications, this can be used for any capacity expansion planning of any system. In this exercise, the model has been applied vis-a-vis power supply scenario of Bangladesh Power Development Board (BPDB) with a number of parameters to be incorporated in the model. The model minimises the total cost of the system discounted to a base year subject to a number of constraints. The output of the model includes capacity expansion programme, optimal operating schedule and optimum generating costs in the future projection periods.

2. MODEL DESCRIPTION AND MATHEMATICALFORMULATION

The objective of the model is to minimise the total system cost subject to a number of constraints. During the application of the model, a balance and uniformity of the system has to be maintained which calls for following the historical trend of the respective industry. Therefore, to determine an optimal future generation mix, the past and present behavior of the system has to be taken into account. In this exercise of determining the cost-effectiveness of the optimal generation-mix for the future expansion programme of the power supply system in Bangladesh, the model has been run considering a forty year time period (1971-2010) which includes a fifteen year optimisation period from 1996-2010. The time period is divided into discrete time intervals each of five years duration.

If the demand situation of a year is arranged in descending order, it produces a monotonically decreasing curve. This is termed as load duration curve. Using discrete approximation, the load duration curve is divided into a finite number of demand blocks of width θp[3]; as shown in the figure- 1, there are four demand blocks and θ_1 = 910 hrs., θ_2 = 1280 hrs., θ_3 = 3650 hrs. & θ_4 = 2920 hrs. The values of the p-subscript 1, 2, 3, and 4 refer to the peak, day-peak, off-peak and base load demand block.

2.1 Objective Function:

The costs associated in the model are *capital, fuel, and operation & maintenance[4]*. All these costs are discounted back to a base year. The objective function can be written as:

Minimize Z

$$Z = \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{v=1}^{t} A_{itv}G_{iv} + \sum_{i=1}^{I}\sum_{t=t_1}^{T}\sum_{p=1}^{P}\sum_{p=p}^{P}\sum_{v=1}^{t} DF_t FP_{it}\mu_{iv}\theta_p Z_{itpv} + \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{v=1}^{t} DF_t\, M_{itv}R_{itv} \qquad \text{.........(1)}$$

The first term in the objective function is the discounted capital cost per year where, G_{iv} is the capacity of the plant type i, commissioned during vintage v ; A_{itv} is defined as the aggregated present value of capital costs per unit capacity in the base year of plant type i, vintage v and in time period t.

Mathematically,

$$A_{itv} = K_{iv}\left[\frac{(1+r)^4 + ((1+r)^3 + (1+r)^2 + (1+r) + 1}{(1+r)^{n-b}}\right] \qquad \text{........(2)}$$

where, r is the discount rate, b is the base year and n is the last year of the five year time period and K_{iv} is the capital cost of a plant per unit capacity per year and is given by:

$$K_{iv} = \frac{W_{iv}}{1-(1+r)^{-L}}\frac{r}{(1+r)} \qquad \text{.........(3)}$$

where, W_{iv} is the initial capital cost per unit capacity of plant type i, having a vintage V and L being the economic life of the power plant.

The term in the square brackets in eqn-(2) is actually the discount factor DF_t. In general, the expression for A_{itv} can be written as follows:

$A_{itv} = DF_t K_{iv}$ for $v \geq t+l-L/5$ & $v \leq t$ .... (4)

= 0 for $V < t + 1 - L/5$ or $V > t$

It is, however, worth noting that in any time period, capital payments have to be made on a range of plants constructed in earlier periods in addition to those constructed during the period itself.

The second term in the objective function (eqn- 1) is the discounted fuel cost per year. The fuel consumption in a power plant depends upon the level of the power output, the duration of power generation and the efficiency of the power plant. The fuel cost for a particular plant in a particular time period is given by the product of the above factors and the price of fuel at that time period. It is then discounted back to a base year. The duration and level of power output of a plant depend on the load duration curve, which is a monotonically decreasing function of time. Using the discrete approximation, the load duration curve can be represented by a finite number of discrete demand blocks of width θ_p with p=1, ------- P, as shown in figure-l.

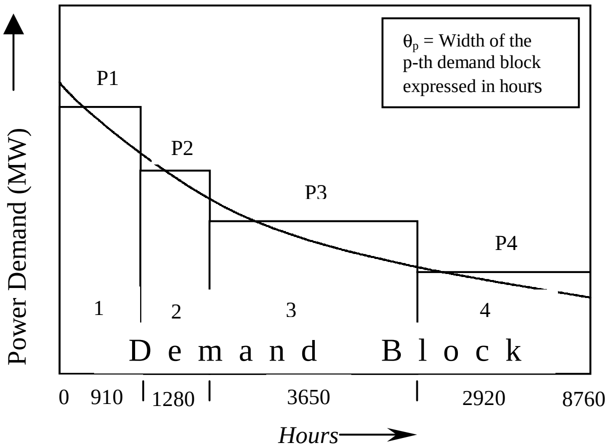

Fig. 1: A typial load duration curve and its discretised form

If the power output in time interval t and demand block p of plant type i and vintage v is U_{itpv}, which varies from 0 to plant type capacity at that vintage period [$0 \leq U_{itpv} \leq Giv$], the fuel cost component in the objective function can be mathematically expressed as:

$$\sum_{i=1}^{I}\sum_{t=t_1}^{T}\sum_{p=1}^{P}\sum_{v=1}^{t} DF_t FP_{it}\mu_{iv}\theta_p U_{itpv} \qquad \text{......... (5)}$$

Replacing U's by the Z-substitutes of Anderson [**1], the fuel cost term can be written as

$$\sum_{i=1}^{I}\sum_{t=t_1}^{T}\sum_{p=1}^{P}\sum_{p'=p}^{P}\sum_{v=1}^{t} DF_t FP_{it}\mu_{iv}\theta_p Z_{itp'v} \qquad \text{... (6)}$$

where,

$$Z_{itpv} = U_{itpv} - U_{it(p+1)v} \geq 0, \text{ p =1, ..., P-1} \qquad \text{......... (7)}$$

With

Zitpv = Uitpv ≥ 0 p=P

From which it follows that

$$\text{Uitpv} = \sum_{p'=P}^{p} Zitp'v \qquad \ldots\ldots (8)$$

[**] Z-substitute popularly known as Z-substitutes of Anderson has been used for the ease of calculation; this will help in calculating the area under the load duration curve for the demand of each block.

The third term in the objective function is the discounted operation & maintenance (O&M) cost per year which are the non-fuel running costs including costs for research and maintenance. The operation & maintenance cost in the objective function is given as the product of operation and maintenance cost per unit capacity per year and the ramaining capacity in the system. To ensure that a plant is retired at the end of its technical life, a very high penalty factor is to be included in the O&M cost term for that plant after the expiry of the technical life-time.

2.2 Constraints:

The objective function described above is minimized subject to the following constraints:

(1) Power Demand:

The instantaneous power demand must be met at all points on the load duration curve (LDC) for all times. That is,

$$\sum_{i=1}^{1} \sum_{v=1}^{t} \sum_{p'=p}^{p} Zitp'v \geq PPtp \quad t=t_1,\ldots\ldots\ldots T; \; p=1,\ldots,P \qquad \ldots\ldots (9)$$

where, PP_{tp} is the height of the p-th demand block in time period t.

(2) Plant Availability:

In a deterministic formulation like this, it is necessary to derate the actual capacity of a plant by multiplying this by its availability in order to account for non-availability due to preventive maintenance and forced outages. This ensures that no plant can generate more than its available capacity. That is,

$$\sum_{p=1}^{p} Z_{itpv} \leq \alpha_{itv} R_{itv} \qquad I=1,\ldots\ldots\ldots I; \quad t=t_1,\ldots..T; \quad V=1,\ldots...,t \qquad \ldots\ldots (10)$$

where, α_{itpv} is the availability of plant type i, vintage v, in time period t.

(3) Historic Profile of Plant Vintage:

It is necessary to provide data on the system's existing capacity at the start of the first future time period at which optimisation begins.

$$G_{iv} = \hat{G}_{iv} \quad 1=1,\ldots I; \quad V = 1, \ldots,(t_1 - I) \qquad \ldots\ldots (11)$$

Where, $\hat{G}_{iv}$ is the capacity of plant type i and vintage V which has been actually constructed.

(4) System Security:

The total capacity remaining in the system should always be greater than the anticipated peak demand by some fraction m, which may be termed as reserve or planning margin. This may be expressed as:

$$\sum_{i=1}^{I} \sum_{v=1}^{t} R_{itv} \geq PP(1+m) \quad t=t_1,\ldots\ldots, T; \; p=1 \; \ldots (12)$$

(5) Remaining Capacity:

At any time period t, the capacity remaining in the system for plant type i, vintage V cannot be greater than the capacity of the same type of plant , vintage V that was actually constructed. This may be expressed as

$$R_{itv} \leq G_{iv} \quad \forall i \,;\, t=t_1,\ldots T \,;\, v = 1, \ldots, (t-2) \qquad \ldots (13)$$

$$R_{itv} \leq G_{iv} \quad \forall i \,;\, t=t_1,\ldots.,T \,;\, v = (t-1), t \qquad \ldots (14)$$

The strict equality in the above equation ensures that plants less than ten years old cannot be retired. Also, once a plant is retired, it is not available for use at some future time. This is ensured by the following statement:

$$R_{i\,(t+1)\,v} \leq R_{iv} \quad \forall i \,;\, t=t_1,\ldots, (T-1) \,;\, v = 1, \ldots,t \; \ldots (15)$$

(6) Fuel Diversification

In order to take in account the uncertainty in fuel price and fuel availability, it is necessary to constrain the amount of capacity constructed of plant type i the future projection periods. This may be expressed as:

$$Giv \leq Gmaxiv \quad \forall i \,;\, t = t, \ldots,T \,; \qquad \ldots (16)$$

(7) Non-negativity of Decision Variables:

The last set of constraints requires that all decision variables G's, Z's, and R's must be non-negative. That is

$$Giv \geq 0 \quad \forall i \,;\, v = t_1, \ldots, T \qquad \ldots. (17)$$

$$Zitpv \geq 0 \quad \forall i \,;\, t = t_1, \ldots., T \,;\, v = 1, \ldots, t \qquad \ldots (18)$$

$$Ritv \geq \quad \forall i \,;\, t = t_1, \ldots.,T \,;\, v = 1, ., t \qquad \ldots. (19)$$

3. RESULTS AND DISCUSSIONS

The model was run on an IBM computer using LINDO programme developed by Linus Schrage, Graduate School of Business, University of Chicago. The model contains 301 rows including the objective function row and 353 structural variables with 607 iterations to reach the optimality condition.

The model takes into account eight time periods (1971-2010), each of five years. Five five-year periods have been taken to define the existing system and plant vintages. Optimisation has been performed in other three periods (1996-2000, 2001-2005, 2006-2010). In this model, five types of plants, namely,- steam turbine, gas turbine, hydro, combined cycle and diesel- have been considered. The model was run with three annual demand growth rates of 7%, 9.5% & 11%.

The output of the model[5] includes plant capacity expansion programme for the future projection periods, optimum operating schedules for the load distribution for the different types of plants and the optimum operating costs as well.

Plant Capacity Expansion Programme:

The plant capacity expansion programme given by the model in each of the three projection periods are for three demand growth rates are shown in table-(1):

Table 1: Plant capacity expansion programme in the future projection periods

Period (t)	Demand Growth (%)	Construction programme by different types of plants (MW)				
		Steam	Gas	Hydro	Combined Cycle	Diesel
t=6 (1996-2000)	7 9.5 11	480 480 480	600 600 600	- - -	82 82 500	- - -
t=7 (2001-2005)	7 9.5 11	570 570 570	600 600 600	- - -	265 1589 1800	- - 33.428
t=8 (2006-2010)	7 9.5 11	715 715 715	750 750 750	- - -	- - -	- - -

It has been found that when the model was run with a 12% demand growth rate, the solution becomes infeasible. This is because with the stipulated limit for future plant construction programme (Table-I), the demand would exceed the installed capacity taking into account the planning margin).

Optimal Operating Schedule:

The operating schedule for the load distribution for the different types of plants constructed at different periods gives the optimum planning programme. As an illustration, the operating schedule for the first projection period (1996-2000) at the 9.5% demand growth rate has been shown here[5]. For this purpose, first the non-zero values of Z_{itpv} has been summarised and arranged for various load periods (table-2) and finally graphically set (Figure-2) to carry out optimal operating schedule as shown below:

Table 2: Non-zero values of Z_{itpv} (power output) for various load periods: (6th period)

Variable Z_{itpv}	Value (MW)	Peak period load
Z_{2612} Z_{2613} Z_{2614} (Gas Turbine) Z_{2615} Z_{2616}	107.1 18.0 276.45 60.36 390.00	851.9
Z_{4613} (Combined Cycle)	51.27	51.27
Z_{5612} (Diesel) Z_{56114}	15.0 5.1	20.1
		Day peak load
Z_{1621} Z_{1626} (Steam turbine) Z_{1622}	74.75 59.64 38.50	172.89
Z_{4623} (Combined Cycle) Z_{4625}	23.43 67.50	90.93
		Off-peak load
Z_{1633} (Steam Turbine) Z_{1633}	127.50 136.32	268.82
		Base load = 1187.19
Z_{1644} Z_{1645} (Steam Turbine) Z_{1646}	696.0 294.0 92.04	1082.04
Z_{3643} (Hydro) Z_{3644}	20.0 40.0	60.0
Z_{4646} (Combined Cycle)	45.15	5.15

Here, during peak period, out of 851.9 MW, only 390 MW (Z_{2616}) gas turbine power plant has to be constructed in the first projection period. For day peak, off-peak and base load period, 59.64 MW (Z_{1626}), 136.32 MW (Z_{1636}) and 92.04MW (Z_{1646}) steam turbine power plant respectively in addition to 45.15 MW

(Z_{4646}) combined cycle power plant have to be constructed for the first future time period.

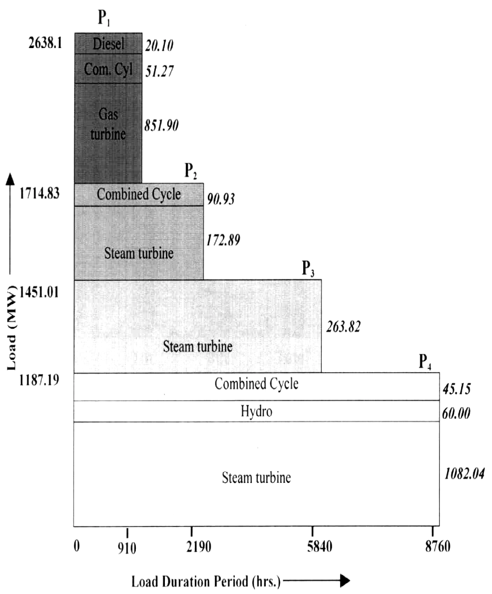

Fig. 2 : Optimal operating schedule for the 1st future projection period (1996-2000)

Optimal Generating Costs:

Considering annual growth rate of 9.5%, the total electricity generating cost for the whole projection period (1996-2000), as the model output shows, will stand at $7.489 billion. The percentage shares for three projection periods are as follows [5]:

	Period	**Percentage**
1^{st}	(1996-2000)	19.49
2^{nd}	(2001-2005)	36.58
3^{rd}	(2006-2010)	43.93

The breakdown of capital, fuel and operation &maintenance cost for individual projection periods in percentage are summarised in the table-(3) below:

Table 3: Breakdown of electricity generation costs (capital, fuel and opearation & maintenance):

Period (t)	**Cost (%)**		
	Capital	**Fuel**	**Operation & Maintenance (O & M)**
6^{th}	43.01	55.32	1.67
7^{th}	60.08	38.17	1.75
8^{th}	48.23	50.13	1.64
Total for three periods	51.12	47.45	1.43

The cost figures given in the table-(3) and the above figure reveal that for the total projection period, capital and fuel cost dominate and carry the bulk of the total cost involved in the system. It is noticed that in the seventh period (2001-2005), capital cost stands higher than the fuel cost because of the fact that the major construction programme of power plants will take place during that period which entails a huge investment programme.

4. CONCLUSIONS

Some of the major conclusions [5] are presented below:

- The model prefers the construction of steam turbine, gas turbine and combined cycle power plants to the total exclusion of hydro and very little amount of diesel plants in the expansion planning period.
- Steam turbine, combined cycle and hydro electric power plant will operate as the base load plants for all the projection periods.
- The model output contrasts sharply with the current practice as it suggests that due to the low cost of operation, it is economical to run the hydro power plant at part load capacity in the base load period throughout the year thereby implying that the current practice of running the hydro at full capacity in peak period only is not cost-effective.
- In all the projection periods, in addition to the limited use of the small type diesel plants, gas turbine plants figure prominently during the peak period. Since a considerable amount of additional capacity must be retained in the system at any time to ensure security of supply, gas tubine plants become the obvious choice because of their low capital and high availability.
- In all future periods, steam turbine and combined cycle power plant will operate during day-peak and off-peak perjods.

5. REFERENCES

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