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Energy Utility Fuel Allocation Model for Non-Linear Revenue and Regulatory Tariff Implications

by

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Abstract

The primary motivation for this paper is based on the challenge faced by a utility firm that generates its electricity through multiple coal fired thermal power plants. The utility firm operates in a regulated market and faces severe shortages of low priced coals that are critical to its profitability. The regulatory authority prices the electricity generated on the basis of capacity utilization and energy costs. The capacity component of tariff encourages operation of plants at high utilization levels. Hence, the surplus maximization of the firm turns out to be a non-linear problem. Based on the characteristics of the problem, we suggest a heuristic approach to arrive at the solution. The fallout of the tariff pricing is that it is more profitable to shut-down a power plant rather than operate it at low utilization levels. The secondary motivation for this paper is to address this regulatory tariff issue. An alternate tariff model is proposed that encourages consumption of costlier coals also so that the firm operates at a high utilization level while offering electricity to the grid at a reasonable tariff. Determination of the optimal solution is simple is this model which makes it simple to administer.

Keywords: Non-linear Programming, Non-smooth Optimization, Utility Tariff, Fuel Allocation

1. Introduction and Literature

The primary motivation for this paper is based on the challenge faced by a utility firm that produces its electricity through multiple coal fired thermal power plants. These plants were established at different time points and differ somewhat, which has implications on efficient usage of coal. In other words, a particular plant would be better suited than others for burning a particular type of coal. They are also located at different geographic locations, which have an implication from the point of view of transportation cost. Each plant has access to a variety of coal sources that are in the proximity of the plants. The cost of coal varies from source to source and there is a limited availability of same from each source. Requirement of coal beyond the availability of these sources has to be met through imports which is much costlier. The unit tariff entitled to a particular plant of the firm is decided by a regulatory authority and comprises of a capacity component and an energy component. The former is a function of the plant's capital and other fixed costs (including interest expenses). To encourage maximum generation of power, the regulatory authority allows this cost to be fully recovered only from a particular level of plant capacity utilization by having a scaled capacity component of unit tariff till this target level. This implies that any production below this target level would result in the utility firm not recovering fully its capacity cost. As an incentive for production beyond the target utilization, the regulatory authority permits the firm to charge the same capacity component of unit tariff for generation beyond the target level. The energy component of unit tariff is independent of plant utilization or fixed costs and is based on the technology used by the plant and a weighted average coal cost based on a bundle of different coal types. Older plants are allowed to charge a higher energy component to compensate for the higher amount of coal required per unit output of electricity. The total cost incurred by the utility firm is based on the coal, coal freight and variable costs of a bundle of different types of coal and the utility firm could improve its profitability by using a higher proportion of cheaper coal.

The secondary motivation for this paper is to address the regulatory tariff issue and explore whether the tariff proposed by the regulatory authority results in maximum electricity generation at the most reasonable tariff factoring capital and input costs while maximizing the surplus of the energy utility. Based on this we attempt to propose alternate tariff models to tackle availability limitations in low cost domestic coal.

Hobbs (1995) carried out a detailed review of literature on electric utilities. He describes the industry as an early user of optimization methods and one where optimization needs have changed in response to environmental concerns, increased competition and growing uncertainty. Based on the review, the author identifies in the gaps in literature. An important gap identified is that of models that incorporate variable pricing. Pandey (2002) reports that the capability of established energy policy models for enabling a comprehensive policy analysis for developing countries is limited owing to their not having factored issues specific to developing countries. He also reports that most developing countries have been using bottom–up (optimization) energy models that reflect the earlier centralized and government controlled markets rather than increasingly privatized and competitive markets. Balachandra and Chandru (1999) report that large electricity demands in India are unmet due to severe shortages of supply. Supply interruptions and power rationing is a means of tackling supply shortages.

Utility modeling problems are generally considered complex to solve owing to integer variables and non-linear objective functions. Sirikum, Techanitisawad and Kachitvichyanukul (2007) describe the mixed integer non-linear power-generation expansion planning problem as one of the most complex optimization problems. They propose a GA-heuristic based method to solve their problem. Though there is sufficient information in the internet and industry reports (Wikipedia Contributors, n.d.) on utilization based utility tariffs, scholarly articles on same considering fuel shortages in regulated markets appears to be sparse. This paper attempts to contribute to literature in this area.

2. The Utility Firm: Relevant Data and Current Fuel Allocation

The utility firm studied produces its electricity through six coal fired thermal power plants located in five different geographic locations. Let $I = \{i|i = 1, 2,\ldots, I\}$ indicate the set of electricity generation plants. Let $J = \{j|j = 1, 2,\ldots, J\}$ indicate the set of coal sources. The utility firm annually negotiates with coal companies and the railroad company before the beginning of a financial year. Thus, the coal cost, freight charge and coal availability are information available before the start of the year and are not subject to volatility. Let A_j denote the annual availability of coal from source j, c_j denote the unit coal cost for procuring from source j and f_{ij} denote the unit coal freight charge for transporting coal from source j to plant i. The remaining notations are C_i the peak load of plant i; q_{ij} the unit coal requirement at plant i using coal from source j; r_i the unit tariff energy component at plant i; s_i the capacity charge slope at plant i; t_i the target plant output (available for sale after factoring internal consumption) at plant i for realizing peak tariff capacity component; u_i the yield at plant i as a proportion of generation (amount available for sale after factoring internal consumption), $0 \le u_i \le 1$; and v_{ij} the unit other variable cost at plant i using coal from source j. Let the decisions variables be denoted by x_{ij} the optimal electricity generation at plant i using coal from source j and X_i the optimal electricity generation at plant i. The relevant data are shown in the following tables.

Table 1A: Coal freight charges (f_{ij}), Coal Cost (c_j) and Annual Availability (A_j)

Coal Source	Coal freight charges (Rs./MT)						Coal Cost	Availability (mi
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	(Rs./MT)	MTs per year)
A1	350	110	110	100	212	300	2225	4.15
A2	350	110	110	100	212	300	4640	3.00
B	300	190	190	190	300	300	1274	1.30
C	350	110	110	100	250	300	1235	2.53
D	479	517	517	500	300	818	763	9.15
Imports	550	550	550	550	550	550	5000	Unlimited

Table 1B: Coal requirement for unit power generated (q_{ij})

Coal Source	Coal requirement per unit power generated (MT/MWH)					
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
A1	0.70	0.68	0.68	0.65	0.72	0.65
A2	0.65	0.65	0.65	0.63	0.72	0.65
B	0.70	0.70	0.70	0.70	0.72	0.70
C	0.80	0.75	0.75	0.75	0.82	0.76
D	0.90	0.90	0.90	0.85	0.95	0.88
Imports	0.65	0.63	0.63	0.64	0.68	0.63

Table 1C: Other variable cost (v_{ij})

Coal Source	Other variable costs (Rs./MWH)					
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
A1	500	500	500	550	500	500
A2	500	500	500	550	500	500
B	700	700	700	700	700	700
C	550	550	550	580	550	530
D	630	650	650	650	800	650
Imports	500	450	450	500	500	480

Table 1D: Other details

Detail	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
Peak Load, C_i, (MW)	1260	630	420	150	450	600
Energy Charge, r_i, (Rs/MWH)	1784.3	1581.3	1581.3	1581.3	2044.2	1581.3
Capacity charge slope, s_i, (Rs./MW-MWH)	0.68	1.56	1.94	5.49	2.22	1.36
Target, t_i, (MW)	886	487	325	115	279	464
Yeild, u_i	0.893	0.890	0.890	0.883	0.883	0.886

The firm currently allocates coal to the different plants that result in electricity generation as shown in the table below. This allocation enables the firm to operate at 90.66% of its peak load but results in a deficit of Rs. 6,754 million. The weighted average tariff per MWH turns out to be Rs. 2,082.

Table 2: Current Allocation of Coal and Overall Utilization

Coal Source	Electricity Generation (MW)						Coal Required (mi MTs per year)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	
A1	90	100	68	70	190	176	4.15
A2	147	63	42	22	95	148	3.00
B	82	20	13	65	16	16	1.30
C	90	114	76	0	56	38	2.53
D	539	244	163	113	36	71	9.15
Imports	74	55	36	0	0	54	1.22
Total	1022	596	398	270	393	503	Firm Utilization
Peak Load	1260	630	420	150	450	600	90.66%

3. Model and Solution

The optimization model is one of maximizing the surplus of the firm. The surplus function comprises of (i) revenue, (ii) coal cost, (iii) coal freight cost and (iv) other variable cost terms. The decision variable is the amount of electricity that should be generated at a particular plant using coal of a particular coal source. The firm in question operates in a region of electricity shortages and, hence, we assume that it is capable of selling all the electricity that it generates. At plant *i*, the capacity component of unit tariff is $s_i u_i X_i$ up to electricity generation of t_i / u_i and $s_i t_i$ for electricity generation above t_i / u_i. Hence, the hourly revenue can be described as $\{s_i [u_i X_i - (u_i X_i - t_i)^+] + r_i\} u_i X_i$, where $u_i X_i$ is the electricity available for sale after factoring internal consumption. The hourly coal cost, hourly freight cost and hourly other variable cost at plant *i* can be described as, $\sum_j c_j q_{ij} x_{ij}$, $\sum_j f_{ij} q_{ij} x_{ij}$ and $\sum_j v_{ij} x_{ij}$, respectively. In the formulation we convert the hourly revenue and costs to annual figures in million rupees. The surplus maximization non-linear formulation is as follows:

Maximize $\sum_i 0.00876 \left(\{s_i [u_i X_i - (u_i X_i - t_i)^+] + r_i\} u_i X_i - \sum_j \{(c_j + f_{ij}) q_{ij} + v_{ij}\} x_{ij} \right)$ … (1)

Subject to:

$0.00876 \sum_i q_{ij} x_{ij} \le A_j \quad \forall j$ … … … … … … (2)

$\sum_j x_{ij} = X_i \quad \forall i$ … … … … … … (3)

$X_i \le C_i \quad \forall i$ … … … … … … (4)

$x_{ij} \ge 0 \quad \forall i, j$ … … … … … … (5)

As already mentioned the revenue component is a non-linear function up to given plant utilization level. The various cost terms described above are linear. The constraints are linear in nature and indicate the plant capacity and coal availability. The revenue, total cost and surplus for a particular plant with respect to electricity generated using a particular combination of coal sources is as described in Figure 1 below. The dotted lines indicate the costs for the cheapest and costliest coal sources. The actual total cost would be a line between these two extreme cases and its slope would depend on the mix of various coals used. The slopes of revenue, total cost and surplus for a particular plant with respect to electricity generated using a particular combination of coal sources is described in Figure 2. The objective function is not strictly convex with respect to X_i and, hence, there is difficulty in determining the optima. As described in Lemma 1 below, the slope of revenue term increases linearly till $X_i = t_i / u_i$ and peaks at this X_i value. It is constant from there onwards and lesser than the slope in the non-linear phase at $X_i = t_i / u_i$. The non-smooth behavior and negative surplus for X_i values just above zero, results in the the GRG nonlinear solver (Microsoft® Excel) not able to determnine the optimal solution.

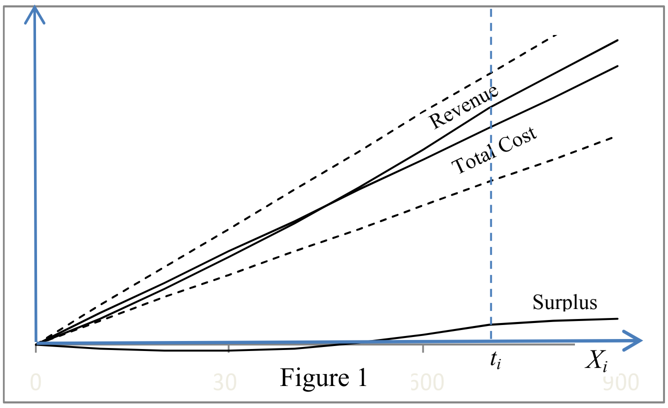

Figure 1

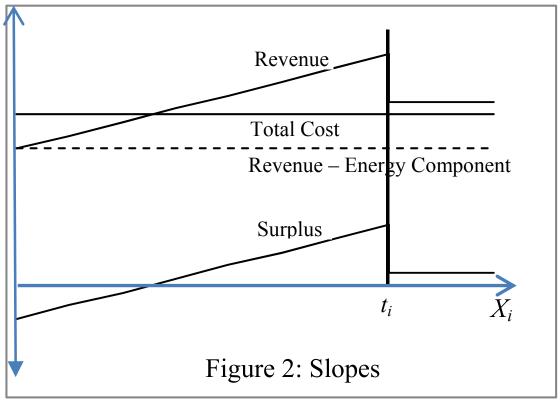

Figure 2: Slopes

From (1) it can be seen that the hourly surplus at plant i for $X_i \le t_i/u_i$ is $\{s_i u_i X_i + r_i\}u_i X_i - \sum_j \{(c_j + f_{ij})q_{ij} + v_{ij}\}x_{ij}$ and $\{s_i t_i + r_i\}u_i X_i - \sum_j \{(c_j + f_{ij})q_{ij} + v_{ij}\}x_{ij}$ for $X_i > t_i/u_i$. Let $w_{ij} = (c_j + f_{ij})q_{ij} + v_{ij}$ denote the total unit cost of electricity generation at plant i for coal procured from source j and $W_i = \sum_j \{(c_j + f_{ij})q_{ij} + v_{ij}\}x_{ij} / \sum_j x_{ij}$ denote the average total unit cost of electricity generation at plant i. The hourly surplus at plant i is then $(\{s_i u_i X_i + r_i\}u_i - W_i)X_i$ and $(\{s_i t_i + r_i\}u_i - W_i)X_i$ for $X_i \le t_i/u_i$ and $X_i > t_i/u_i$, respectively. If plant i is run exclusively on coal from source j then the hourly surplus for $X_i \le t_i/u_i$ and $X_i > t_i/u_i$ are $(\{s_i u_i X_i + r_i\}u_i - w_{ij})X_i$ and $(\{s_i t_i + r_i\}u_i - w_{ij})X_i$, respectively, as $X_i = x_{ij}$.

Lemma 1: Source *j* will qualify to supply coal to plant *i* only if $w_{ij} < u_i(2s_i t_i + r_i)$.

Proof

Using the hourly surplus expressions above, the hourly revenue when plant i is run exclusively on coal from source j can be expressed as $(s_i u_i^2 X_i + r_i u_i)X_i$ and $(s_i t_i + r_i)u_i X_i$ for $X_i \le t_i/u_i$ and $X_i > t_i/u_i$, respectively. The hourly revenue slopes with respect to X_i are $(2s_i u_i X_i + r_i)u_i$ and $(s_i t_i + r_i)u_i$ for $X_i \le t_i/u_i$ and $X_i > t_i/u_i$, respectively. The revenue slope with respect to X_i maximizes at $X_i = t_i/u_i$ and is equal to $(2s_i t_i + r_i)u_i$ at this value of X_i. When plant i is run exclusively on coal from source j then the cost slope is constant at w_{ij} for all values of X_i. Hence, it is obvious that we can exclude sources for which $w_{ij} \geq u_i(2s_i t_i + r_i)$.

Lemma 2: The average total unit cost of electricity generation at plant *i*, W_i, has to be lesser than $u_i(s_i t_i + r_i)$ for a positive surplus.

Proof

From Lemma 1, $w_{ij} < u_i(2s_i t_i + r_i)$. We analyze the hourly surplus at plant *i* for $W_i < u_i(s_i t_i + r_i)$ and $u_i(s_i t_i + r_i) \leq W_i < u_i(2s_i t_i + r_i)$.

For $W_i < u_i(s_i t_i + r_i)$ let $W_i = u_i(s_i t_i + r_i) - \delta$. Then the hourly surplus at plant *i* for $X_i \leq t_i / u_i$ is

= $(u_i\{s_i u_i X_i + r_i\} - u_i(s_i t_i + r_i) + \delta) X_i$

= $(s_i\{u_i X_i - t_i\} + \delta / u_i) u_i X_i$ … … … … … … (6)

From (6), the hourly surplus is $\delta t_i / u_i$ (positive) at $X_i = t_i / u_i$ and increases further at δ for $X_i > t_i / u_i$. In other words, the hourly surplus has become non-negative at $X_i < t_i / u_i$ and will be positive there onwards up to C_i.

For $u_i(s_i t_i + r_i) \leq W_i < u_i(2s_i t_i + r_i)$ let $W_i = u_i(s_i t_i + r_i) + \delta$. Then the hourly surplus at plant *i* for $X_i \leq t_i / u_i$ is

= $(u_i\{s_i u_i X_i + r_i\} - u_i(s_i t_i + r_i) - \delta) X_i$

= $(s_i\{u_i X_i - t_i\} - \delta / u_i) u_i X_i$ … … … … … … (7)

From (7), the hourly surplus is non-positive for $X_i \leq t_i / u_i$ and decreases further at δ for $X_i > t_i / u_i$. Hence, $W_i < u_i(s_i t_i + r_i)$ for achieving a positive surplus at plant *i*.

Lemma 3: The lower bound of X_i are zero and $(w_{ij}^{\min} - r_i u_i) / s_i u_i^2$ for $w_{ij}^{\min} \leq r_i u_i$ and $w_{ij}^{\min} > r_i u_i$, respectively.

Proof

Let j_i^l be the coal source that results in lowest total unit cost of electricity generation at plant *i*. Let $w_{ij}^{\min}$ indicate the w_{ij} value for $j = j_i^l$. From the hourly surplus expressions above, the surplus is zero for X_i = 0. Hence, while determining optimal X_i we can limit our search to X_i values for which the plant surplus is non-negative. The lower bound of X_i, X_i^L, is the X_i value for which surplus is zero and increasing from there onwards. From Lemma 2, the surplus at plant i will be positive only if $W_i < u_i(s_i t_i + r_i)$ and the hourly surplus becomes non-negative at $X_i < t_i / u_i$. As W_i is the average unit cost based on coal sourced from different sources, $w_{ij}^{\min} \le W_i < u_i(s_i t_i + r_i)$. Hence, hourly surplus becomes non-negative at $X_i < t_i / u_i$ when the coal is exclusively supplied from source j_i^l.

For $X_i < t_i / u_i$ while using coal from source j_i^l, the hourly surplus $(\{s_i u_i X_i + r_i\} u_i - w_{ij}^{\min}) X_i$ is zero at $X_i = (w_{ij}^{\min} - r_i u_i) / s_i u_i^2$. Hence, for $w_{ij} \le r_i u_i$ and $w_{ij} > r_i u_i$ the lower bounds of X_i are zero and $(w_{ij}^{\min} - r_i u_i) / s_i u_i^2$, respectively.

Lemma 4: The linear function $\{s_i t_i + r_i\} u_i X_i - \sum_j \{(c_j + f_{ij}) q_{ij} + v_{ij}\} x_{ij}$ is an upper bound for the hourly surplus of plant *i*.

Proof

From (1) hourly surplus at plant i is for $X_i \le t_i / u_i$ is $\{s_i u_i X_i + r_i\} u_i X_i - \sum_j \{(c_j + f_{ij}) q_{ij} + v_{ij}\} x_{ij}$ and for $X_i > t_i / u_i$ is $\{s_i t_i + r_i\} u_i X_i - \sum_j \{(c_j + f_{ij}) q_{ij} + v_{ij}\} x_{ij}$. It is obvious that for a given X_i, the linear expression $\{s_i t_i + r_i\} u_i X_i - \sum_j \{(c_j + f_{ij}) q_{ij} + v_{ij}\} x_{ij}$ dominates the plant i hourly surplus objective function for all values of i.

Using above lemmas we add the following constraint to the original model.

$$x_{ij} \le m_{ij} \qquad \forall\, i, j \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (8)$$

where, $m_{ij} = C_i$ for $w_{ij} < u_i(s_i t_i + r_i)$,

$= t_i / u_i - X_i^L$ for $u_i(s_i t_i + r_i) \le w_{ij} < u_i(2 s_i t_i + r_i)$ and

$= 0$ for $w_{ij} \ge u_i(2 s_i t_i + r_i)$.

The formulation becomes a simple linear programming problem when the non-linear objective function is substituted by $\{s_i t_i + r_i\} u_i X_i - \sum_j \{(c_j + f_{ij}) q_{ij} + v_{ij}\} x_{ij}$. Based on the first three lemmas, we propose below a heuristic solution to solve this non-linear and non-smooth problem. The optimal surplus arrived at using the linear formulation in Lemma 4 is used as benchmark for comparing the heuristic solution.

Heuristic Solution:

Step 1: Determine the X_i^L values for all i as per Lemma 3.

Step 2: Set $x_{ij} = 0$ for all i and j. Determine solution for the model including constraint in (8) using a solver like GRG nonlinear solver in Microsoft® Excel. Let $X_i^/$ indicate optimal X_i determined by this solution.

Step 3: If $X_i^/ > X_i^L$ for all $X_i^L > 0$ and surplus of all plants is non-negative, solver has arrived at an initial solution. Note $X_i^/$ and go to Step 5. Otherwise, go to Step 4.

Step 4: Among all i for which plant surplus is negative determine the i with highest deficit (lowest negative surplus) and set its X_i^L to zero. Go to Step 2.

Step 5: Set $x_{ij} = 0$ for all i and j and alter constraint in (4) to $X_i = X_i^/$. Re-run the solver and determine the optimal x_{ij} and X_i values. Stop heuristic.

The heuristic was tested out using GRG nonlinear solver in Microsoft® Excel. It yielded the same solution in different runs indicating a high level of consistency. The allocation as per above heuristic is shown in the table below. This allocation enables the firm to achieve an overall surplus of Rs. 6,834 million by operating at 59.06% of its peak load. The optimal surplus using the linear formulation in Lemma 4 turned out to be Rs. 6,876 million, which is only Rs. 42 million more than the heuristic solution. The weighted average tariff per MWH turns out to be Rs. 2,432. Only three of the six plants need to be operated as per this allocation. Coal from source A1 was partially used while coal from sources A2 and imports were not used at all. The cheaper coal sources B, C and D were fully utilized. Higher utilization of the firm capacity would require usage of the costlier coal sources.

Table 3: Heuristic Allocation of Coal and Overall Utilization

Coal Source	Electricity Generation (MW)						Coal Required (mi MTs per year)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	
A1	0	245	0	0	85	0	2.00
A2	0	0	0	0	0	0	0.00
B	0	0	0	0	206	0	1.30
C	0	385	0	0	0	0	2.53
D	993	0	0	0	159	0	9.15
Imports	0	0	0	0	0	0	0.00
Total	993	630	0	0	450	0	Firm Utilization
Peak Load	1260	630	420	150	450	600	59.06%

4. Tariff Implications: Simulation Results

It is obvious from the above optimal allocation that it is beneficial only to the utility firm and the regulatory tariff would require alterations to achieve the additional goal of increased generation. We developed a simple alternative tariff plan that does not penalize generation at low utilization and rewards usage of coal from costlier sources. According to this plan the capacity component of unit tariff is constant with respect to electricity generated by the firm. The energy component of unit tariff follows the existing values up to a particular level of total firm peak load capacity that is denoted by a, $0 < a < 1$. Beyond this level of utilization, the energy component of unit tariff will be equal to existing energy component multiplied by a factor b, where $b > 1$. With three values of a (0.7, 0.8, 0.9) and four values of b (2, 3, 4, 5), 12 experiments were carried out and the results are as shown in the table below.

Table 4: Firm Performance for Alternative Tariff

No.	*a*	*b*	Surplus (Rs. mi)	Utilization (%)	Unit Tariff (Rs./MWH)
1	0.70	2	15881	70.2	2863
2	0.70	3	25749	70.2	3376
3	0.70	4	35637	70.5	3889
4	0.70	5	47022	85.9	4402
5	**0.80**	**2**	**9065**	**80.0**	**2692**
6	0.80	3	16550	80.0	3034
7	0.80	4	24036	80.0	3376
8	0.80	5	31521	80.0	3718
9	0.90	2	6075	63.2	2350
10	0.90	3	6075	63.2	2350
11	**0.90**	**4**	**8887**	**90.0**	**2863**
12	0.90	5	13098	90.0	3034

Based on a capacity weighted average of existing data, we use a capacity component of unit tariff of Rs. 640 per MWH and energy component of unit tariff of Rs. 1,710 per MWH uniformly for all the plants. In experiment 1, this implies that the total unit tariff is Rs. 2,350 per MWH upto a firm level capacity utilization of 70%. From firm level capacity utilization of 70% onwards, the total unit tariff would be Rs. 2,863 per MWH (Rs. 640 + 0.7 x Rs. 1,710 + [1 – 0.7] x 2 x Rs. 1,710). The tariff plan is very simple from the perspective of arriving at the optimal solution and, hence, from the view-point of the stakeholders. Based on the experiments, the regulatory authority can arrive the right combination of *a* and *b* values that results in the satisfying the goals of the different stakeholders. Referring to the table below, the unit tariff is least in experiments 9 and 10 at Rs 2,350 per MWH. However, the firm operates only at just 63.2% for maximizing its surplus (Rs. 6,075 million). Compared to the heuristic solution for existing tariff plan, this is only a marginal improvement in power generation, which also results in decline of surplus for the utility firm. However, looking at experiments 5 and 11 it can be seen that the alternative tariff plan succeeds in improving the power generated as well as the surplus of the firm but is accompanied by a moderate increase in unit tariff (10.7% in experiment 5 and 17.7% in experiment 11 compared to Rs. 2,432 for existing tariff plan).

By trial and error it was found that for a = 0.8 and b = 1.70 the firm could generate a surplus of Rs. 6,834 million at a unit tariff of Rs. 2,590 per MWH. For this combination, the surplus is same as the surplus in the heuristic solution for existing tariff plan while the unit tariff is higher by Rs. 158 per MWH (6.5%). Though this combination does not result in any consumption of imported coal (the costliest source) it has resulted in full usage of coal from source A1 and usage of 1.82 million MTs of coal from source A2. The latter was not all utilized in the heuristic solution for existing tariff plan.

Table 5: Allocation of Coal and Overall Utilization for *a* = 0.8 and *b* = 1.70

Coal Source	Electricity Generation (MW)						Coal Required (mi MTs per year)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	
A1	0	123	0	0	0	600	4.15
A2	0	111	208	0	0	0	1.82
B	0	0	212	0	0	0	1.30
C	0	385	0	0	0	0	2.53
D	1019	0	0	150	0	0	9.15
Imports	0	0	0	0	0	0	0.00
Total	1019	619	420	150	0	600	Firm Utilization
Peak Load	1260	630	420	150	450	600	80.00%

Similarly for a = 0.9, the firm could generate a surplus of Rs. 6,834 million at a unit tariff of Rs. 2,780 per MWH for b = 3.51. For this combination, the unit tariff is higher than the unit tariff in the heuristic solution for existing tariff plan by Rs. 348 per MWH (14.3%). This combination resulted in usage of imported coal (the costliest source) and full usage of coal from all the domestic sources.

Table 6: Allocation of Coal and Overall Utilization for *a* = 0.9 and *b* = 3.51

Coal Source	Electricity Generation (MW)						Coal Required (mi MTs per year)
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	
A1	0	0	0	129	0	600	4.15
A2	0	245	272	10	0	0	3.00
B	110	0	0	0	99	0	1.30
C	0	385	0	0	0	0	2.53
D	1150	0	0	11	0	0	9.15
Imports	0	0	148	0	0	0	0.82
Total	1260	630	420	150	99	600	Firm Utilization
Peak Load	1260	630	420	150	450	600	90.00%

5. Conclusions

The heuristic solution arrived at improves the functioning of the firm significantly. The current allocation of coal followed by the firm results in a deficit of Rs. 6754 million. Our heuristic solution enables the firm to have a surplus of Rs. 6834 million though it would operate only at 59.06% of its peak load capacity. This is owing to regulatory tariff pricing that makes it more profitable to shut-down a power plant rather than operate it at low utilization levels when the firm is faced with shortage of coal from cheaper sources.

We suggest an alternative tariff plan that would enable the firm to generate much higher level of electricity by using coal from costlier sources while protecting its surplus. This plan would entail a tariff increase of 6.5% and 14.3% for firm level power generation of 80% and 90% of the peak load capacity, respectively, without reducing the surplus of the firm. Though providing electricity at a reasonable tariff was a stated objective of the alternative tariff plan, it may be noted that the tariff levels as per existing regulation results in electricity being sold at a low price in India compared to many other parts of the world. As coal based energy contributes to huge emission of carbon dioxide and other gases, this increase may be looked at as serving the purpose of charging a more reasonable tariff considering carbon emissions, which would reduce the gap in tariff between electricity generated from coal fired plants and electricity generated from renewable sources. In addition, the alternative tariff plan sets targets at a firm level instead of at a plant level and would be much simpler to administer.

6. References

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