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TIME OF DAY PRICING SCHEMES FOR ELECTRICITY UTILITIES IN DEVELOPING COUNTRIES

by Babu Ram

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Short Summary

This paper discusses 'Time of Day' pricing (TOD) models for planning demand management by electricity utilities in developing countries. Load forecasting and its management through pricing are presented. Load decomposition analysis which, using coincidence factors over the demand cycle, quantifies the behaviour dynamics of consumers in residential, commercial and industrial categories, has been applied to split the annual system peak, registered by Delhi Electric Supply Undertaking (DESU) in 1987, into different load components. Exploratory TOD pricing schemes under constant own price and cross price elasticity assumptions are developed and applied to the domestic load curve. The results obtained indicate the scope for demand management by change of price regime from single price to differential prices during peak and off-peak periods of the load cycle. The implications of TOD pricing for the utility's revenue have also been presented.

INTRODUCTION

TOD pricing models have become widely used for planning demand management by utilities. Due to the simultaneous occurrence of loads peak time demand often exceeds the capacity of the energy and transport systems. This is seen for example in the peak time capacity shortages encountered in the operation of transport utilities and gas utilities and the thermal capacity shortages or limited energy availability in many hydro-thermal electricity utilities. It has been suggested [1] that developing countries will continue to have capacity shortages during peak periods of the load cycle. Electricity boards or utilities can choose either of the following policy alternatives or a mix of these as components of a strategy for mitigating the effects of capacity shortages on the reliability of electricity supply during peak periods:

1. continue building peaking station
2. reduce peak period demand with interruptible loads;
3. through a system of discriminating prices, induce consumers to increase their use of electricity during off-peak periods and reduce their use during peak periods.

This paper discusses the results of TOD research and the development of a model for managing electricity demand in a developing country context. Electricity pricing policies and load management are discussed in part II. Part III of the paper presents load decomposition analysis which quantifies the time pattern of electricity consumption for residential, commercial and industrial consumers using coincidence factors over the demand cycle. This technique has been applied to analyse different components of loads of the annual system peak of DESU recorded on the peak day in 1987. Part IV of the paper discusses the application of TOD pricing models in the developing country context. Part V presents a numerical example of a TOD pricing scheme applied to DESU. The example relates to the residential load curve obtained by load decomposition analysis. The Results indicate the potential scope for demand management using a TOD pricing scheme. The possible implications of TOD pricing for the utility's revenue have also been presented.

I LITERATURE SURVEY

The building of peaking stations requires fresh investments and costly energy resources - mainly natural gas or diesel are needed for their operation. Utilities in the industrialised countries have been introducing pricing policies [2] and load management technologies [3] as an alternative to enable them to defer investment in new capacity.

In the United Kingdom [4] the Bulk Supply Tariff of the former CEGB provided signals to distributors to design a retail tariff (Economy 7) to increase the consumption of off-peak electricity. The distributors simultaneously adopted a marketing strategy to sell high capacity storage radiators, floor warming systems, etc. to be operated during off-peak periods. Electricit'e de France (EDF) [5] has consistently used marginal cost tariff systems, beginning with Green tariffs for high voltage customers, followed by Universal tariffs, Yellow tariffs for low voltage customers, etc. TOD tariffs of the type in use in France and the United Kingdom and consumers' responses to these tariffs have been applied to assess the potential for shifting industrial electricity loads away from peak hours in California's utilities [6]. In the United States several TOD experiments have been conducted: Arizona [7-12]; Wisconsin [13-14]; Los Angeles Dept. of Power [15-16]; Southern California Edison Company [17-18], etc.

The USA's Pacific Gas and Electric Company has reported on their evaluation of TOD rate schedule A23 which was applied to consumers with contracted demand of more than 500 KW. A weekly average load duration curve, after introduction of TOD prices, indicated a significant shift in load from peak period to off-peak period. As a further example, based upon their demand forecast, marginal capacity and energy costs, the Korea Electric Power Corporation [20] introduced differential pricing during different periods and further estimated that load curves could be flattened by fifteen percent by this strategy. In the case of India, in view of current and possible future peaking shortages, the establishment of peaking stations based upon natural gas [21] was advocated during the Seventh Plan. The Introduction of TOD rates and load management technologies needs to be considered along with the alternative of establishing peaking stations using natural gas during the Eighth Plan. This kind of approach appears necessary as peaking stations impose a cost on the system and remain idle during off-peak periods and therefore a question of economic efficiency is involved.

II LOAD FORECASTING AND MANAGEMENT

In the traditional approach to power system planning load forecasting is extensively used [22-23]. Optimal long term development programmes are designed on the basis of load forecasts using the approach of cost minimisation. In order to achieve economic efficiency Long Run Marginal Costs (LRMC) derived from the capital and operating costs of the long term development programme, are 'prescribed' to be charged to consumers.

LRMC-based tariffs provide accurate signals to consumers about the relative value and scarcity of the fuel they use. Tariff structure and pricing policies can play an indirect role of great significance in managing the load [6]. By the introduction of Time of Day / week / season / year pricing the utilities provide strong incentives to consumers to increase off-peak electricity consumption and decrease peak period electricity use. The consumers then implement these decisions in a decentralised manner. Extensions to the LRMC pricing approach include 'Dynamic Pricing'. This includes several concepts evolved in the pricing literature such as 'spot pricing (real time pricing)' [24-25], 'responsive pricing' [26] , 'state preference pricing' [27], etc.

In the privatised U.K. Electricity Supply Industry, under the 'pooling and settlement arrangements', the market clearing price for trading electricity will be determined every half hour by equating demand and supply. The pool could be considered as a spot market as it will operate in real time. However, implementation of spot pricing at the consumer end entails the introduction of sophisticated metering and communication networks for signalling to the consumers in an effective manner in real time. The 'Energy Management Unit' (EMU) which accepts signals from gas, water and electricity usage has been developed to provide instantaneous feedback on multi-rate tariffs [28]. Spot pricing takes load management a step further in that all items of consumer equipment are implicitly under load control [24]. However, under 'spot pricing' all final decisions are vested in the consumers' hands and continuity of supply is guaranteed to the consumer if he is willing to pay a 'quality of supply premium' during peak periods. The modulatable tariffs under experimentation in EDF for high voltage customers are similar to the peak day withdrawal option. They offer four tariff periods of fixed duration but with a flexible timing defined in real time by EDF. The modulatable option may be treated as a step in the implementation of spot pricing.

Gas utilities are also prone to encounter shortages of transmission capacity due to severe cold weather. British Gas encountered a similar problem during the 1970s which it solved by investing in capacity to store Liquefied Natural Gas (LNG). British Gas thereafter followed a policy to supply large industrial consumers on interruptible terms which corresponds to non-price rationing. The cost and benefits of peak load pricing for different load management strategies for self rationing, as opposed to non-price rationing, have been analysed in the case of large industrial consumers of gas. The results suggests [27] that a change from a uniform price structure might offer net benefits to some consumers, equivalent to permanent reductions in energy bills of as much as three percent.

III LOAD DECOMPOSITION ANALYSIS

In order to manipulate demand through prices, it is necessary to know the hourly variation of demand for each category of consumers. For this it is required to have load research facilities as the available time series data are inappropriate for demand management. In addition, cross section surveys are required to acquire information on consumer characteristics such as appliance ownership, perception of tariff and the extent to which consumers adjust to tariffs, etc. for designing marketing and pricing policies.

Load research provides detailed information on consumers' electricity use for different consumer categories (by half hour in the day, day of week, and period in the day). In the U.K. [28], demand data at half hourly intervals are acquired using dedicated instrumentation. Due to the amount of data required and the need to contain the cost of instrumentation and monitoring, statistically designed samples of electricity usage of 3000 consumers are recorded throughout the year. The following information for any consumer group may be generated:

(i) load curves for representative days;
(ii) key parameters such as system peak demand, maximum demand and load factor;
(iii) effect of temperature.

In the majority of developing countries the utilities do not have facilities to conduct load research of the type mentioned above and due to this their approach to consumers' loads is passive, that is, they accept the existing pattern of electricity use. However, utilities in the industrialised countries have reduced system costs by modifying the pattern of electricity consumed[4,5]. Load decomposition analysis as reported in this paper is therefore useful from a load management point of view in the situations where facilities for load research are not available. The load curve for the peak day is split into components of load applied by domestic, commercial and industrial consumers. While estimating the components of load during peak periods connected loads for domestic, commercial and industrial categories have been aggregated due to similarities in end uses and time of use. At any instant of time coincident maximum demand put by all categories of consumers is less than the sum of the power ratings of their end uses, due to the diverse nature of their operation. The coincidence factors for various group of consumers can be correlated to load factors during use periods (F) by the relationship (F^n) where n is an index indicative of the simultaneous operation of end uses. In the analysis reported here coincidence factors for an infinite number of similar loads during peak periods have been calculated using the method presented in reference [29]. The time at which a coincident peak occurs can be correlated with load factors using a Gauss normal probability relationship which approximates the load duration curve; thus coincidence factors have been assumed to vary similar to Gauss' normal probability curve. Using the model and the sample data, coincidence factors during the peak periods have been estimated for the DESU system and are presented in Table I. Using the method described above and the data given in Table I coincident peak demand during peak time (6 P.M.to 10 P.M.)has been calculated as the sum of the individual sector loads multiplied by their coincidence factors during peak periods, in this case as 846.4 MW. After incorporation of transmission and distribution losses along with auxiliary losses the coincident peak demand comes to 1044.32 MW. Estimated load curves for domestic, commercial and industrial consumers are given in Figure 1. It may be observed from this figure that domestic loads are predominant during peak periods due to large scale penetration of electricity-operated end-uses in the capital city. Commercial loads are the second most important component, despite restrictions on their operation during peak periods. Industrial loads do not contribute significantly during the peak periods as their operation time is limited.

IV TIME OF DAY PRICING MODELS FOR DEVELOPING COUNTRIES

In the developing countries, the relationship between electricity demand and price is not that obvious. For example, on an all India basis connected load

Table I Data in respect of DESU system during 1987

category of load	consumption (million units per day)	likely peak load	use period (hours per day)	aggregate coincidence factors	estimated coincidence factors during peak periods
(1)	(2)	(3)	(4)	(5)	(6)
domestic	4.4311	963	16	0.1917	0.4582
commercial	3.5500	648	12	0.2285	0.4551
industrial	3.4800	605	18	0.2396	0.1822

Source: Central Electricity Authority

TableII Characteristics of Domestic Loads on the DESU System

year	connected load per consumer (Watts)	consumption per consumer(kwh)	consumption per unit of connected load	real price (paise per kwh)
(1)	(2)	(3)	(4)	(5)
1985	752.00	1306.07	1.736	45.03
1986	770.78	1322.90	1.716	45.75
1987	797.00	1339.75	1.68	46.87

Source: DESU and Central Electricity Authority

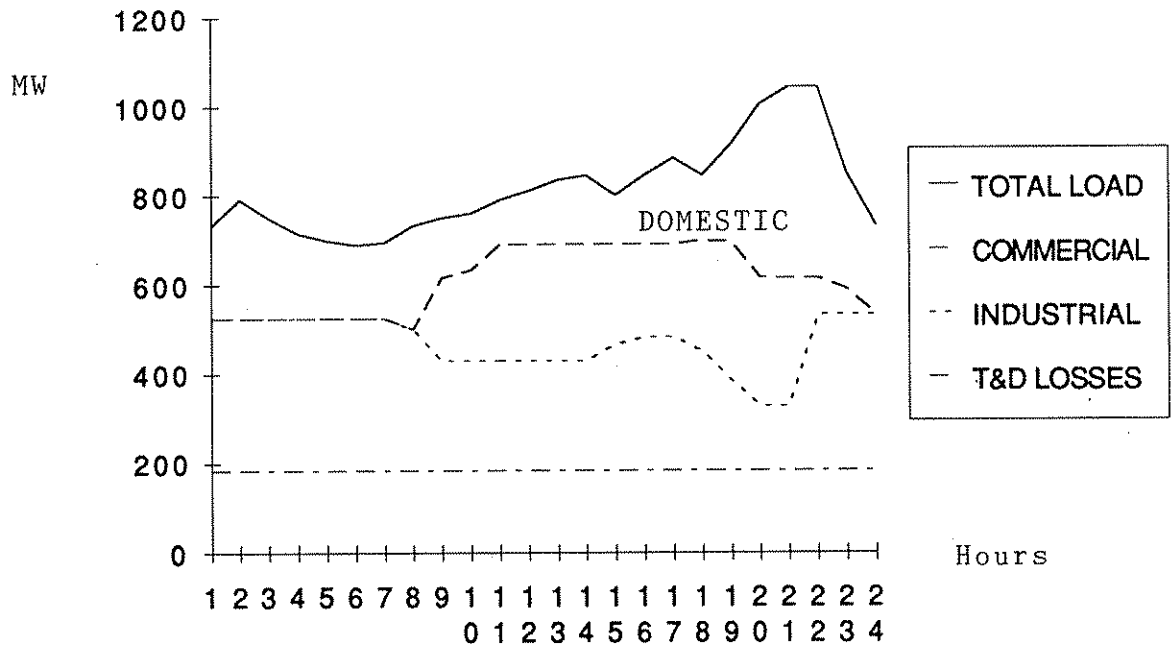

Figure 1 COMPONENTS OF TOTAL LOAD ON THE DAY OF 1987 ANNUAL DESU SYSTEM PEAK(2-8-87)

per consumer and consumption per consumer continue to grow but consumption per unit of connected load has declined each decade with the increase in the real price of electricity. Although electricity demand is growing with the increase in price, the registered decline in electricity consumption per unit of connected load is indicative of the response of consumers to higher electricity prices [30].

Recent trends in the case of the DESU system for domestic consumption per consumer, connected load per consumer and consumption per unit of connected load are given in Table II. Similar trends, in respect of consumption per unit of connected load with respect to price, have been observed for commercial and industrial consumers.

It may be observed from Table II that consumption per unit of connected load continues to decline with the increase in price similar to the trend exhibited by consumption per unit of connected load with respect to price per decade on an all India basis which is used below for the calculation of own price elasticities.

A wide variety of models are available for estimating TOD demand price relationships. The neoclassical model [31] of consumer demand with identically priced commodities has been applied to data from a Wisconsin residential electricity pricing experiment designed to obtain the response of residential consumers to TOD pricing. Significant substitution possibilities between peak and off-peak electricity consumption were found. The issue of pooling residential experimental results, in order to impute the price response for regions that did not have experiments,was addressed by Aigner and Leamer [32]. A Lindley-Smith estimator (1972) for a random coefficient model was applied to inferring TOD pricing responses in the case of the Kansas City Power and Light Company, based upon weather, demographic data and the information from TOD pricing experiments by the Southern California Edison Company and the Los Angeles Department of Water and Power. It has further been found [33], by predicting the response of TOD rates for Wisconsin and North Carolina populations using the model developed on Los Angeles data and comparing the predicted values with those of models derived from Wisconsin and North Carolina data, that TOD rates are similar and transferable. However, these models do not address the question of demand management in a situation where no TOD pricing experiment has been conducted and do not suggest how to estimate cross-price elasticities in situations where data are severely limited, such as those in developing countries. It may be noted that the structured econometric models with the advantage of economic theory lead to functional forms for the estimation equation which often impose restrictions on the relationships among variables. The appropriateness of these restrictions may or may not be testable with the data which are available. Furthermore, it has been shown [34] that the structured econometric studies which have applied the translog functional form to expenditure data are incapable of fitting zero responses but generate coefficients representing shifts in demand, even if, in reality a consumer had not responded at all. For these reasons, a major study of French, English and Welsh data concluded that the structured econometric models were inappropriate [35] as the data base was not suitable for testing the underlying assumptions of the structured econometric models. The approach reported in this paper for developing countries is similar to the model used in the quantitative analysis of French, English and Welsh Industrial consumers' responses to TOD pricing.

V NUMERICAL EXAMPLE AND DISCUSSION OF RESULTS

In this section we present a numerical example based upon estimates of own and cross-price elasticities[36]. Following Mills[37] a linear relationship between consumption per unit of connected load and the average price of electricity has been employed, basically as an approximation around some initial observations of price and quantity of electricity consumed, to obtain consistent own and cross-price elasticities. It should be noted that, when using a linear relationship of this kind it is not appropriate to extrapolate demand for prices representing large deviations from the initial observations .

It has been assumed that prices for peak and off-peak electricity use are separately offered to consumers and demand is a linear function of prices in all periods. The response of consumers to differential pricing is simulated by a cross -price elasticity equation developed for this typical case. The step by step scheme flow diagram is presented in figure 2.

The numerical example relates to Delhi Electricity Supply Undertaking which supplied 1044.35MW during the peak periods in 1987. As explained

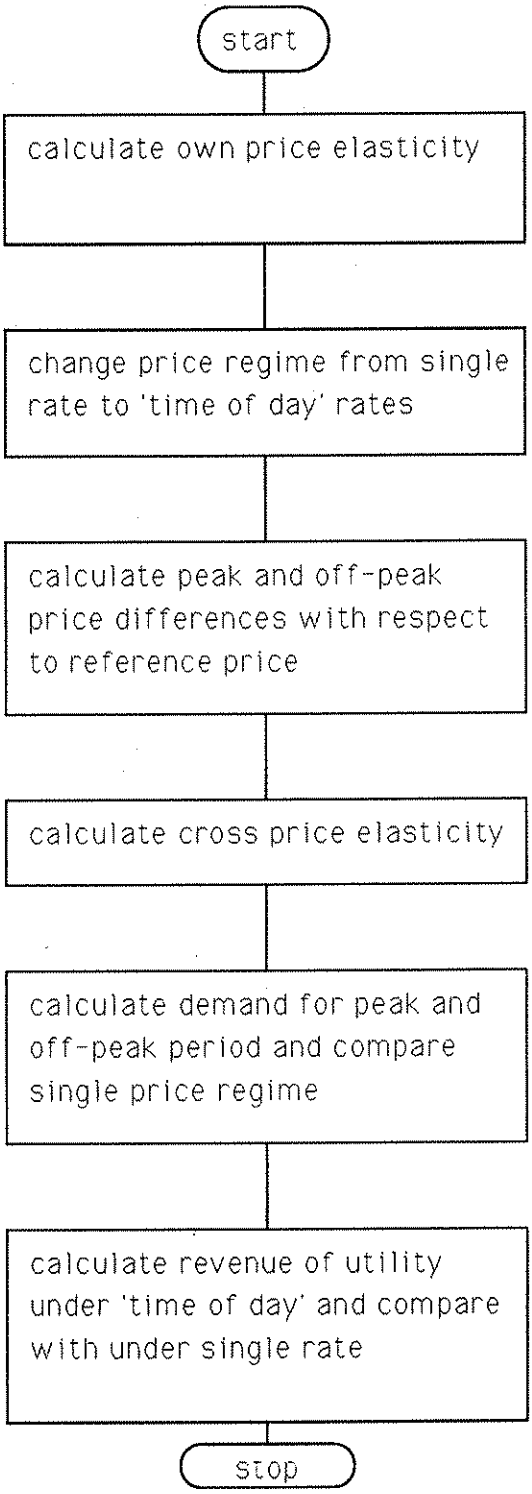

Figure.2 MODEL FLOW DIAGRAM

earlier the consumption per unit of connected load declines with the increase in price. Based upon this, own-price elasticities have been calculated as (-)0.85, (-)0.31 and (-)0.081[1] respectively for domestic, commercial and industrial consumers during 1987. It may be noted that the own price elasticity for domestic consumers is higher than that of commercial and industrial consumers; which in a strict sense can not be said to be highly elastic. On this basis the domestic load curve has been chosen for testing a TOD pricing scheme. However, the cost of TOD metering for domestic consumers would be relatively more significant compared with other categories. This must, however, be compared with the propensity of domestic consumers to contribute to peak and seasonal peak demands which are created by air conditioners and coolers (in summer) and water heating loads (in winter).

A cross-price elasticity for the domestic categories of consumers has been calculated with a peak period price of 60 paise per kwh, which was also the All Board's average in 1987, and maintaining a ratio of 2:1 between peak and off-peak price. The cross price elasticity calculated in this manner comes to (-)0.33. In this case a negative cross-price elasticity suggests that the use of electricity in the two time periods is complementary and rises or falls as price in one period causes the share in both periods to fall or rise. The negative cross-price elasticity has been reported in the literature earlier [35]. Both own price and cross price elasticity effects on domestic load curve are shown in figure3.

After introduction of a TOD pricing scheme the system peak demand is reduced to 305 MW under the cross price elasticity case, against 381 MW under the assumption of constant own price elasticity with a price of paise 49.21 per kwh, representing a 5 percent increase over the average rate for domestic consumers in 1987. It may be observed from this figure that the TOD pricing scheme has resulted in the shifting of loads from peak periods to the off-peak periods, as a result of which consumption during the off-peak periods has increased to 3.36 million units (after the introduction of TOD

[1] The own price elasticities of electricity demand for domestic, commercial and mining and manufacturing sctors have been reported as (-)0.22, (-0.09) and (-0.09) based on All India 1960-1971 data. It may be noted that the estimate for domestic consumers is significantly less elastic. However, because these estimates relate to All India data they are not directly comparable with the figures for Delhi. (Reference: Towards A Perspective on Energy Demand and Supply in 2004-05, Advisory Board of Energy (India), May 1985.)

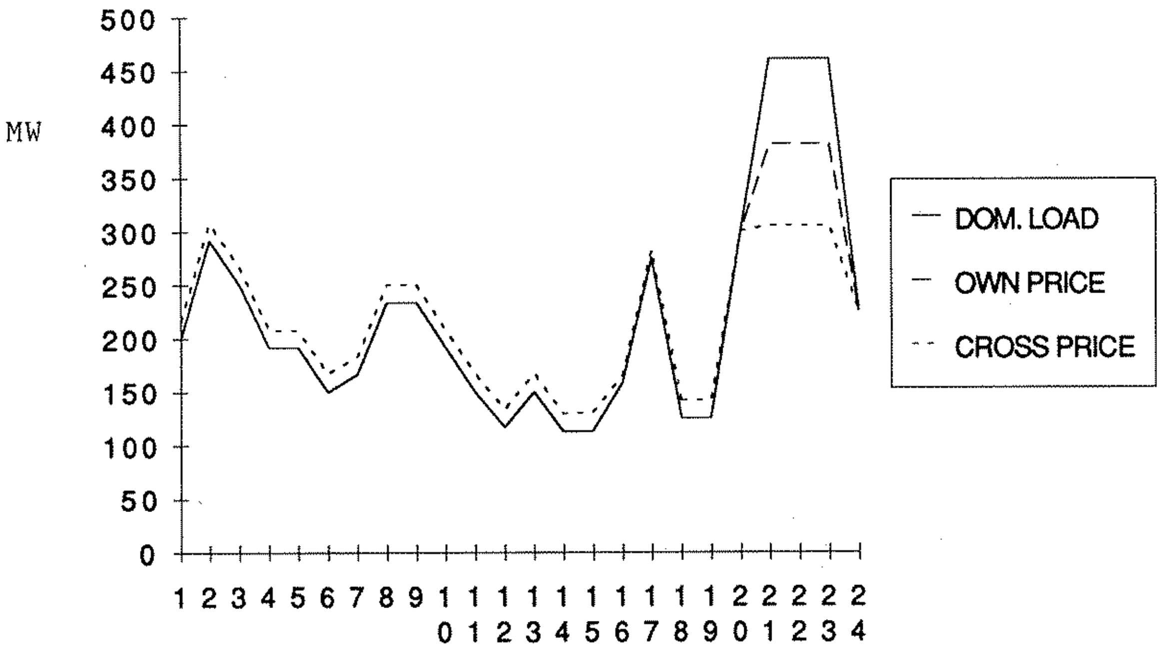

Figure 3 ESTIMATED DOMESTIC LOAD CURVE AND EFFECT OF TIME OF DAY PRICING

pricing) from 3.05 million units (before TOD). The TOD pricing scheme can stimulate consumers to shift typical end uses such as the use of a mixer grinder (8.37%), an electric cooking range (10.04%) ,electric ovens (7.25%), electric stoves(13.5 %), dish washers (10.75 %), etc. to off -peak periods and accelerate the installation of energy-efficient appliances. It may be noted that the numerals bracketed with end uses indicate estimates of penetration of end uses in Delhi as percentage of total penetration of end uses on an all India basis during 1986 [38]. It may further be noted that the population of black and white and colour televisions(TV) in Delhi in 1986 corresponded to 79 MW of connected load. Some slight rescheduling of popular TV serials could reduce the peak demand considerably. Furthermore, if popular television programmes which are networked over several regions were staggered by suitable intervals this would be expected to mitigate nationwide shortages [39].

Before the introduction of TOD rates the revenue expected to accrue on a peak day with an average rate of 46.87 paise per kwh comes to Rs.2.17 million. However after the introduction of TOD rates the average price is reduced to paise 37.91 per kwh which would in turn reduce revenue accrual by 19 % per day. Such a reduction in energy consumption would reduce ultimately the cost of power to be purchased by DESU from the Northern Regional Electricity Board, particularly during the peak periods during which system wide capacity shortages persist.

CONCLUSIONS

The approach presented in this paper has been applied in the case of an electricity utility but such an approach to TOD pricing could be applied to transport and gas utilities which face a peaking problem which imposes an investment need on the utility. Furthermore, TOD rates are justified for large customers, and the utility after the introduction of such rates should follow the behaviour of these customers with the help of a load research programme. TOD rates, jointly with carefully designed energy conservation programmes, could prove innovative in the context of the choice for substitution of technologies and the utilisation of technologies in a cost effective manner. Implementation of TOD rates in the residential sector requires a relatively large expenditure on metering but this must be weighed against the propensity of these consumers to contribute to peak load. The first step in this direction would be to identify those customers whose gains outweigh metering costs. When deciding on the introduction of TOD pricing scheme, the introduction of TOD pricing to domestic consumers might be considered on an optional basis with consumers bearing additional metering costs in exchange for the opportunity to reduce their electricity bills, particularly in metropolitan cities. It is also desirable to assess the potential environmental benefits as TOD pricing obviates the need for additional power plants and so reduces environmental impacts.

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