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Peak-load management in steel plants

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Abstract

Mini steel-plants in India, using electric-arc furnaces for steel manufacturing, are highly energy intensive. In the context of increasing electricity prices and the introduction of time varying electricity rates by utilities, mini steel-plants can reschedule their operations to reduce their electricity bills. This paper presents a load model, which incorporates the characteristics of batch-type loads common to any type of process industry. The model is coupled with an optimisation formulation utilising integer programming for minimising the total electricity-cost satisfying production, process flow and storage constraints for different tariff structures. The methodology proposed can be used for determining the optimal response for any industry under time varying tariffs. The case study of a steel plant shows that significant reductions in peak-period demand (about 50%) and electricity cost (about 5.7%) are possible with optimal-load schedules. The utility can also get significant reduction in the peak coincident demand if large industries optimally reschedule their productions in response to time-of-use (TOU) tariff.

Keywords: Load scheduling; Batch process; TOU Tariff

1. Introduction

In many developing countries, the electricity supply is unable to keep pace with the increasing demands of the growing economy causing energy shortages

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and peak demand deficits. System demand is affected by many factors, like the type of customers and their loads, and changes hourly, daily, seasonally and annually. The character of the system's load variations is determined by the consumers' electricity-use pattern. While meeting growing demand on one hand, utilities have to balance the peaks and troughs of electricity use on the other. Many utilities have already implemented or are planning to implement TOU electricity tariff rates as a viable load management (LM) technique to flatten the system load curve. The industries being the bulk consumers, the impact of LM action like load scheduling under TOU tariff on peak demand reduction is high [1]. The industries can also control their electricity costs by optimal load schedule under TOU tariff.

The steel sector consumes approximately one quarter of the total industrial electric consumption in India [2]. This ratio will increase as the steel production through the arc-furnace route increases from the present share of 25%. For iron-and-steel industries, the electricity costs about 30% of the total production costs. Most of the present process scheduling in the industries, as a part of production planning, is aimed at the fulfilment of the target production with resource constraints. This paper presents a formulation coupled with an optimisation framework for optimal process schedule of the steel plant for a specified tariff, minimising the total operating cost satisfying production, process flow and storage constraints. The model proposed is generalised so that the formulation can be extended for any type of process industry.

2. Review of load models

Steel manufacturing involves both batch and continuous processes. Many approaches, mathematical formulations and solution algorithms attempting to exploit the characteristics of specific categories of batch-scheduling problems have been proposed in the literature [3,4]. Starting with forecast-demand data, a methodology is reported for the production schedule, which provides smooth continuous operations in steel manufacturing [5]. The production schedule aims at the target production level. A model for flow maximization in steel manufacturing is also reported [6] for maintaining consistency rules, not for optimisation. The production-scheduling problem in steel manufacturing, as a multi-stage job shop scheduling problem, is also reported [7]. Most of the models for steel are centered on process scheduling to achieve the targeted production subject to production constraints and do not give the impact on peak electricity-demand reduction. The optimal schedule to reduce the peak utility load is reported for chemical processes considering reaction kinematics and process constraints [8,9]. An optimisation formulation using mixed-integer programming for load-side demand control is also reported for coal mines [10] where process and storage constraints do not exist. Extending this work, a load model coupled with an optimisation formulation for process industries with batch and continuous type loads is presented here to prescribe optimal load-schedule strategies under different tariff structures.

3. Mathematical formulation

The formulation is based on discrete time representation similar to that proposed for continuous loads. For the planning horizon, one day is split into N intervals with equal time durations of t hours. The proposed model incorporates the following characteristics of batch-process loads: (1) batch time and batch capacity, (2) material input (charging) – time periods and quantity, (3) material output (discharging) – time periods and quantity and (4) power demand – variations with time and quantity, type or quality of material for the batch. Various operating parameters and sequences of the batch process are described with respect to Fig. 1. Material inflow (charging) with quantity P_x to $P_{(x+a)}$ in tons from xth time to $(x+a)$th time and outflow (discharging) from yth time to $(y+b)$th time with quantity P_y to $P_{(y+b)}$, respectively. Power demand in kW from time z to $(z+c)$ is W_z to W_{z+c}.

The decision variable I indicates whether the equipment is started processing a new batch in a particular interval or not, for the production of a specific product. The decision variable

$$\begin{aligned} I_{mjk} &= 1, \quad \Rightarrow \text{the } m\text{th equipment starts a batch for processing } j\text{th product} \\ & \qquad\quad \text{in the interval } k, \\ &= 0, \quad \Rightarrow \text{otherwise.} \end{aligned} \tag{1}$$

The electrical power input in kW to the equipment m at any interval k when it is processing jth product

$$W_{mjk} = \{(A_m * D_{mjk})/\eta_{mjk}\}, \tag{2}$$

where A_m is the rated capacity of the equipment in kW and D_{mjk}, utilisation of the mth equipment at the interval k when it is processing the jth product. D basically represents the de-rating factor of the equipment based on the site conditions and loading conditions and constraints. η_{mjk} is the efficiency of the equipment m at the interval k, is

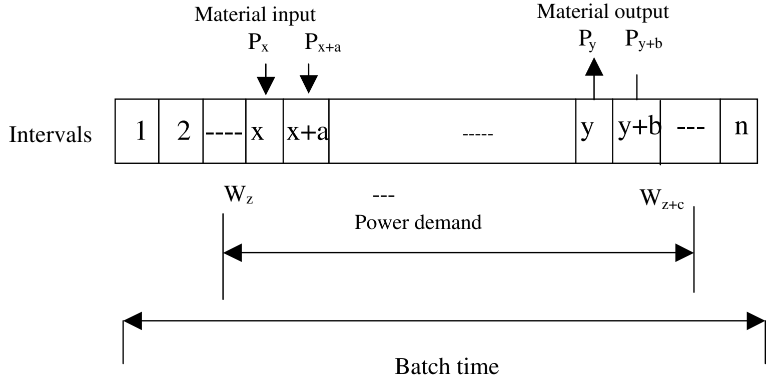

Fig. 1. Batch-time sequence.

obtained from efficiency characteristics corresponding to the percentage loading. The fluctuations in the power demand during steel melting and refining at different intervals due to the variations in the conductivity of the charge are also incorporated for different intervals. The energy consumed in kWh by the equipment m in the kth interval, when processing the product j for the batch started in the dth interval is

$$E_{mjk} = \sum_{d=k-(z+c)+1}^{k-z+1} W_{mjk} * I_{mjd} * t. \tag{3}$$

The objective of load management (LM) strategy is the minimization of the total operating cost, which consists of charges for energy consumed (either under a flat or TOU tariff), charges for the registered maximum demand (MD) and additional operating costs due to shifting of loads, if any. In Indian utilities, the demand charge is not time varying, viz., constant irrespective of the time when the MD is registered for a month.

The objective function minimising the monthly operating cost is

$$(\text{Min.} \sum_{k=1}^{N} \sum_{m=1}^{M} \sum_{j=1}^{J} [(E_{mjk} * C_k) + \{C_{ak} * I_a\} * t]) * H + C_d * \text{MD}, \tag{4}$$

subject to production, process storage and equipment constraints, where C_k is the cost of energy (charge per kWh) for the interval k; H, the number of working days in the month; C_d, the MD charge (charge/kVA/month), M – the particular item of equipment; J, the total number of products; C_{ak}, the additional cost of LM actions for the interval k (charges/interval) and I_a, the selection variable such that $I_a = 1$, if the LM action corresponding to C_{ak} is taking place, or =0 otherwise. The above equation accounts for the total electricity-cost consisting of energy charges C_k and the maximum demand charge C_d. The capital cost of an additional installation, if any, or any additional cost for implementing the load-management programme is reflected by the term C_{ak}.

Production constraint to keep the total production Q_j of a product j in the planning horizon is,

$$\sum_{k=1}^{N} \sum_{m=1}^{M} P_{mjk} * I_{mjk} \geqslant Q_j, \tag{5}$$

where P_{mjk} is the production (discharge) in a batch quantity for the machine m for the product j for the batch started in the kth interval.

Total production of the plant Q_T is

$$\sum_{j=1}^{J} Q_j \geqslant Q_T. \tag{6}$$

Availability of raw material for production is ensured by

$$\sum_{m=1}^{M} \sum_{k=1}^{N} R_{mjk} * I_{mjk} \leqslant R_T, \tag{7}$$

where R_{mjk} is the quantity of raw material required for the mth equipment for the product j for the batch started in the kth interval and R_{T} is the total raw-material available.

Until one batch is completed, the same equipment should not be allocated to any other batch or product. In order to prevent allocation clashes, the following constraint is included

$$\sum_{d=k}^{k+n-1} I_{mjd} \leqslant 1. \tag{8}$$

Process loads with storage space are modelled with maximum capacity limitations. Net inflow into the storage for the interval k is

$$S_k = \left[\sum_{m=1}^{M}\sum_{k=1}^{N}\sum_{d=k-(y+b)+1}^{k-y+1} P_{mjk} * I_{mjd} - \sum_{r=1}^{R}\sum_{i=k}^{N}\sum_{d=k-(x+a)+1}^{k-x+1} P_{rji} * I_{rjd}\right]. \tag{9}$$

Material inflow for all the equipment M giving discharge to the storage and material outflow for all the equipment R from the storage when processing the product j for the batch started at the interval d is considered.

Taking the maximum storage capacity as S_{m} and initial storage level as S_0, the storage constraint is given by

$$S_0 + \sum_{i}^{N} S_{k-(i-1)} \leqslant S_{\mathrm{m}}. \tag{10}$$

It is often required to maintain a separate operational sequence for the units in any manufacturing process. The condition for the start of the mth unit at an interval k after t intervals from the start of $(m-1)$th unit is modelled as

$$t * I_{mjd} \leqslant \sum_{d=k-t}^{k} I_{(m-1)jd}. \tag{11}$$

Unavailability of the equipment m during maintenance intervals from d to e is incorporated as

$$I_{mjk} = 0,\ \text{for all intervals},\ k = d \text{ to } e \text{ for all products } J. \tag{12}$$

The solution to the above integer programming formulation, for minimizing the total operating cost of the industry subject to the constraints, gives the optimal response for a given production capacity under specified electricity tariff rates.

4. Case study

To illustrate the model, a case study for a mini steel-plant is conducted [11]. The plant has steel melting (SMS) and finished product sections. SMS melts and refines scrap steel or iron to form stainless steel or alloy steel blooms. These blooms are milled in bar mill or wire mills to get the finished products – steel bars, plates, rods and wires of different specifications. The electric-arc furnace operates as a batch melting process producing batches of molten steel. Conversion of the molten steel into the final finished products is by continuous casting and milling operations. So the steel plant has both batch and continuous processes.

The plant has an installed capacity of producing 19,500 t of steel in a month, operating in three shifts except Sundays. Present monthly average production is 10,400 t (approximately 55% of the installed capacity) with a production mix of 40% steel and the rest alloy-steel. Contract demand (CD) of the plant is 70 MVA with average daily energy consumption of 520 MWh. The plant has installed a power factor correction capacitor bank with automatic control schemes at the incoming supply side to maintain the power factor nearly unity. Specific electric energy consumption varies depending on the scrap mix and the furnace selected for melting. The typical charge mix used by the plant for stainless steel (light scrap, skull, HBI, pig iron, shredded and commercial scrap in the ratio 20:15:35:20:5:5) and alloy-steel (light scrap, skull, ferro-chrome, steel scrap, shredded and commercial scrap in the ratio 20:10:20:20:10:20) are used in this analysis. Load cycles (corresponding to 'tap to tap' time) with instantaneous power demand of melting arc furnaces for typical conditions of scrap mix and grade of steel quality are measured from the furnace transformer control-panel. Average of the power demands over every 5-min interval are noted and its variation is shown in Fig. 2 for the batch time of melting furnaces. The process-flow diagram of the plant operation is shown in Fig. 3. Specifications of major plant equipment are shown in Table 1. Electric arc furnaces, which account for 69% of the connected load, are fed from furnace transformers. The load-cycle variation is considerably smaller for the ladle furnace and hence taken as constant. Load data used in the study (active power in MW) for the furnaces is obtained from site measurements. The present equipment de-rating factor (D), average power factor (pf) for the existing plant production requirement are obtained for each furnace transformer. Smaller loads in the mills, which cannot be controlled independently, are grouped together with the major loads. Based on the observed utilization of the loads, efficiency parameters are considered as per the standard or manufacturers' characteristics. Auxiliary load of the plant consists of continuously-run loads like

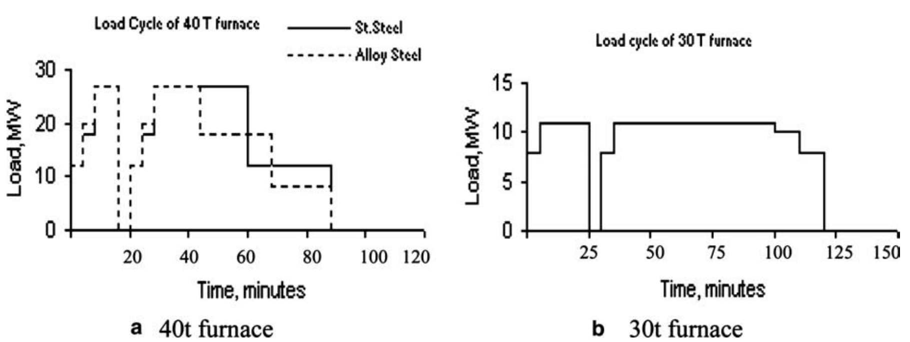

Fig. 2. Load cycles of melting furnaces.

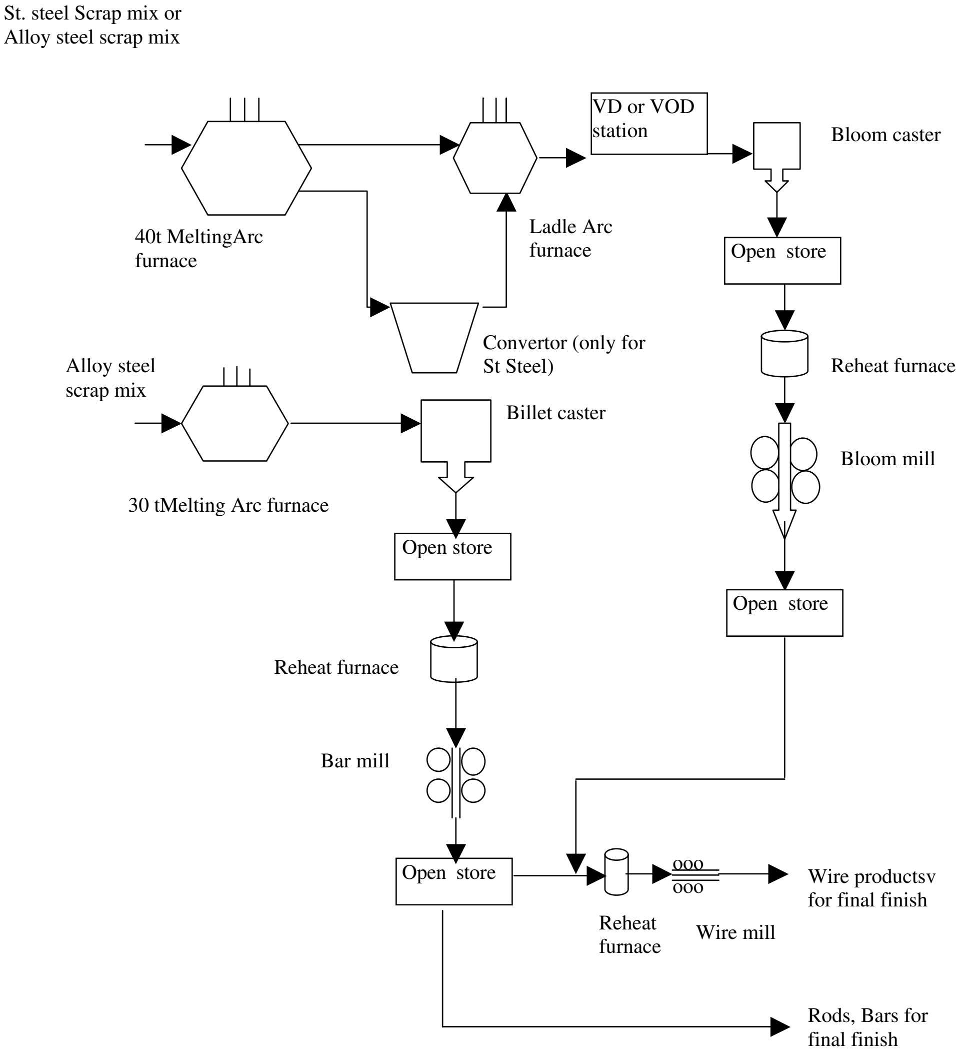

Fig. 3. Process flow diagram of steel plant.

pumps, non-controllable loads like lighting and miscellaneous loads of the oil-fired furnaces and finishing lines. The daily average auxiliary energy-consumption is 65 MWh.

Many state electricity boards (SEBs) in India are still following a flat-tariff for industrial consumers. SEBS like Maharashtra State Electricity Board (MSEB) has already introduced TOU tariff for the industrial sector. A comparative study of optimal response of the industry under flat and TOU tariff structures, as shown in Table 2, is done to bring out the potential of load scheduling in minimizing the electricity cost and reducing the coincidence peak energy-demand.

Table 1
Major loads on the plant for the present manufacturing requirement

Load	Connected electrical load	D, pf, E	Electrical load (MW), batch time (minutes) and loading rate (t/h)	
40 t Arc furnace	40 MVA	$D = 0.9$, $pf = 0.75$	Peak power demand – 27, batch time – 120 min	
30 t Arc furnace	15 MVA	$D = 0.92$, $pf = 0.8$	Peak power demand – 11, batch time – 150 min	
40 t Ladle furnace	10 MVA	$D = 0.95$, $pf = 0.9$	Peak power demand – 8, batch time – 60 min	
Bloom caster	0.650 MW	$D = 0.95$, $E = 0.9$	0.686	Continuous casting, 20 t/h
Billet caster	0.765 MW	$D = 0.9$, $E = 0.95$	0.725	Continuous casting, 20 t/h
Converter station	–	–	–	60 min
VD/VOD station	–	–	–	90 min
Bloom mill	Main motor – 3.1 MW Aux. motors – 0.918 MW	$D = 0.95$, $E = 0.9$ $D = E = 0.85$	4.2	35 t/h
Bar mill	Main motor –3.0 MW Aux. motors – 0.718 MW	$D = 0.95$, $E = 0.9$ $D = E = 0.85$	3.9	25 t/h
Wire/rod mill	5.1 MW	$D = 0.8$, $E = 0.85$	4.8	18 t/h

Table 2
Tariff rates for the load-management study

Type of tariff	Energy rate, Rs./kWh		Demand charge, Rs./kVA
Flat	3.35		300
Flat tariff with night concessions	3.35		300
	10 p.m. to 6 a.m.	2.85	
TOU {MSEB – HTP-l rates as on July 2001}	10 p.m.–6 a.m.	2.85	300
	9 a.m.–12 noon	3.65	
	6–10 p.m.	3.95	
	Rest of day	3.35	

Night-shift operation of the plant incurs additional expenditure like allowances for employees and other miscellaneous charges. As the plant employs 15 employees for the 40 t furnace line and 12 employees for the 30 t furnace line, and 5 each for 3 mills in a shift, the monthly additional expenditure of the plant for the night-shift operation is Rs. 240,000. This is distributed to each process as an additional cost for the concerned intervals according to the number of employees engaged and the process time, and is included in the objective function.

The optimisation model as per the Eq. (4), is developed based on the equipment and process data. The corresponding integer programming formulation, consisting of 432 decision variables and 630 constraints, is solved using hyper LINDO [12].

5. Results and discussion

Table 3 gives the results of optimal schedules under flat and TOU tariff structures. Corresponding load-curves are shown in Figs. 4 and 5. Under flat tariff, optimal

Table 3
Results of optimal schedules under different electricity-tariff structures (with 55% production capacity)

Daily energy-consumption (MWh) under different periods (average power for the period (MW) in brackets)					Total energy-consumption for the day (MWh)	MD (MVA)
Tariff types	Peak (6–10 p.m.)	Partial peak (9–12 a.m.)	Rest of day	Off peak (10 p.m.–6 a.m.)		
Flat tariff	92.0 (23.0)	78.4 (26.0)	227.2 (25.2)	107.2 (13.4)	504.8	31.3
TOU tariff	47.0 (11.7)	36.4 (12.0)	197.6 (21.9)	223.3 (27.9)	504.3	32.4

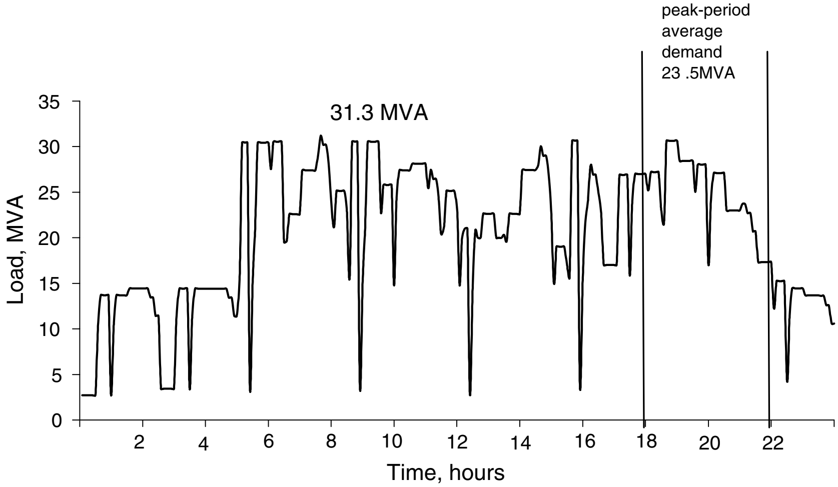

Fig. 4. Optimal load-response under flat tariff.

schedule results in a maximum demand of 31.3 MVA. Additional cost for the night-operation shifts the off-peak energy consumption under the flat tariff. With the TOU tariff, the optimal schedule shows a maximum demand of 32.4 MVA and an off-peak energy consumption of 223.3 MWh. The reduction in the average power, under peak and partial peak periods with TOU tariff (approximately 50% of that with flat tariff), shows its effectiveness to reduce coincident system peaks.

As most of the utilities in India have a flat tariff, the saving with the optimal schedule under the TOU tariff is calculated and compared with that under flat tariff and shown in Table 4. If the utility implements the TOU tariff, industry can reduce the electricity bills by adopting the corresponding optimal strategy. For 400 t daily production, the loading strategy followed by the plant is – 40 t furnace – 7 heats and 30 t furnace – 4 heats, as it provides an equal sharing of employees for the production between the furnaces for the alloy-steel manufacturing and steel manufacturing. The optimal schedule changes the furnace loading strategy – 40 t furnace – 4 heats and 30 t furnace – 8 heats as shown in Table 5. The change in the loading pattern reduces the daily energy consumption by 3.1%.

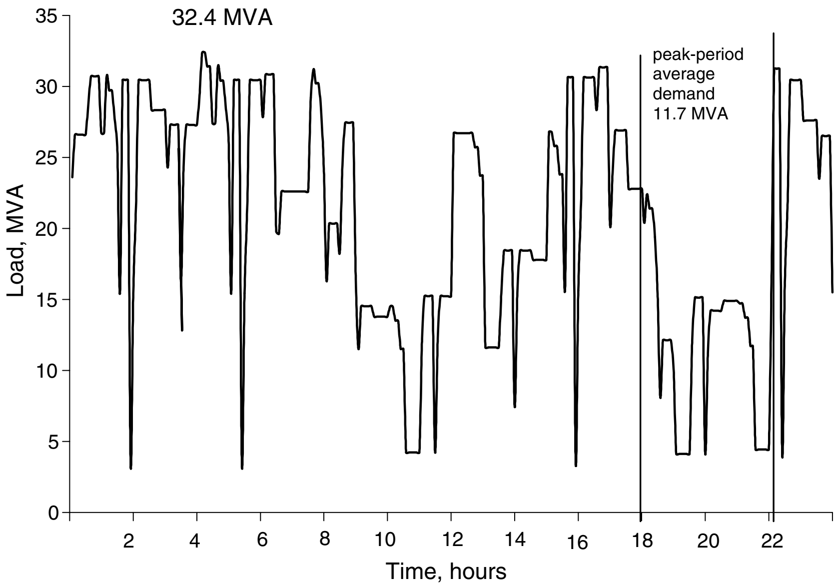

Fig. 5. Optimal load-response under TOU tariff.

Table 4
Comparison of economics of under flat and TOU tariffs (with 55% production capacity)

Tariff type	Monthly electricity cost for the optimal strategy (Rs. million)	Monthly electricity cost, if the optimal flat strategy is followed (Rs. million)	Savings per month (Rs. million)
Flat tariff	53.6		
TOU tariff	52.4	55.3	2.9 (5.5%)

The above analysis is done for 55% production level of the maximum capacity. As the production level of industry can vary, the effect of different production capacities on optimal response under flat and TOU tariffs is analysed. With low production levels, flexibility is greater. With 25% production, the entire production gets shifted to daytime under the flat tariff due to additional night-shift charges. Under the TOU tariff, there exists a trade-off between additional night-shift charge and off-peak energy charge. This results in 62% off-peak energy consumption. The effect of production levels on peak-period demand is shown in Fig. 6. At low production levels, the

Table 5
Change in the loading strategy of furnaces (with 55% production capacity)

Equipment	Maximum daily production, tons	
	Existing condition	With the optimal strategy
40 t Furnace	280 (7 heats)	160 (4 heats)
30 t Furnace	120 (3 heats)	240 (8 heats)

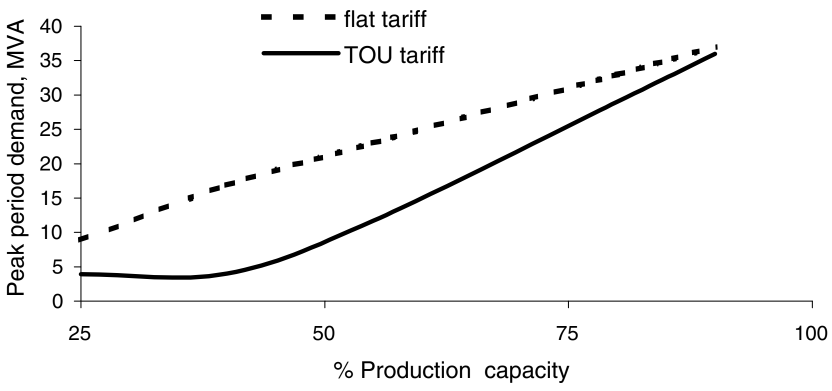

Fig. 6. Impact of production capacity on peak period demand.

TOU tariff shifts off complete production from the peak period resulting in only the plant's essential auxiliary loads during the peak period. As the production level increases, the flexibility gets reduced resulting in only a small difference in peak period demand under the flat or TOU tariff.

6. Conclusions

An optimisation formulation based on load models incorporating equipment, process and storage constraints for LM in process industries has been developed. The model represents both batch and continuous-type loads and is capable of determining the industry response under different tariff-structures.

Most of the industries in India are unaware of the potential of load scheduling, with the time-varying tariff structure, in minimizing their electricity bill. The strategies followed with the existing flat-tariff are also sub-optimal in many cases. The case study for a typical steel plant shows that reduction of the total electricity cost is possible by optimal process-scheduling. The optimal schedule under the TOU tariff results in a 5.7% saving in the electricity bill as compared to the continuation of the loading strategy under the flat tariff. The adoption of TOU tariff with optimal load schedule can result in peak period demand savings. The peak coincident demand reduces from 23 MVA under the flat tariff to 11.7 MVA with optimal response under the TOU tariff (i.e. 50% saving).

The utility can achieve a significant peak-demand reduction, if industries reschedule the process in response to the TOU tariff. The optimisation tool developed in this paper facilitates this by helping industries to determine the optimal response.

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