Optimal Implementation Strategies for Critical Peak Pricing

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***Abstract*—Critical peak pricing (CPP) is an important means of demand response in electricity markets. As a flexible tariff mechanism, making rational CPP implementation strategies and selecting suitable critical days are crucial to its successful implementation. Based on an analysis of tariff scheme and implementation process of CPP, customer response to CPP is described by a price elasticity matrix of demand, and electricity prices are forecasted by a hybrid electricity price model. Furthermore, a CPP decision model which considers the interests of both customers and load serving entity (LSE) is introduced and then solved by 0-1 integer programming. Numerical results are finally used to prove the effectiveness of the proposed model, which is beneficial to saving customer electricity bills, reducing electricity purchase cost of LSE, hedging against electricity purchasing risk for LSE in wholesale market, and realizing multi-party win.**

***Index Terms*—Critical peak pricing (CPP), critical days, demand response, electricity markets, time-of-use (TOU) pricing.**

NOMENCLATURE

A. Constants

N_{CPP}	Maximum permitted number of critical days.
m	Number of study time period (h).
N_{MC}	Monte-Carlo simulation times.
r	rate discount of off-peak and mid-peak periods in non-critical days (%).
φ	Regression coefficient of Δp_t.
θ	Standard deviation of p_t ($/MWh).

B. Variables

a	Load change factor.
b	Specified threshold of load rate.
e	Price elastic of demand.
e_{ii}	Coefficient of self-elasticity.
e_{ij}	Coefficient of cross-elasticity.
i_s	The starting day of study period.
i_e	The ending day of study period.
l_t	Load rate sequence.
p	Electricity price ($/MWh).
$p_{0,i}$	Electricity selling price of time period i (pre-CPP implementation) ($/MWh).
$p_{0,ij}$	Electricity selling price of the jth hour in the ith day (pre-CPP implementation) ($/MWh).
$p_{CPP,i}$	Electricity selling price of time period i (post-CPP implementation) ($/MWh).
$p_{CPP,ij}$	Electricity selling price of the jth hour in the ith day (post-CPP implementation) ($/MWh).
p_{off}	Electricity price of off-peak($/MWh).
p_{mid}	Electricity price of mid-peak($/MWh).
$p_{mid,i}$	Electricity price of mid-peak in the ith day ($/MWh).
p_{on}	Electricity price of on-peak($/MWh).
$p_{on,i}$	Electricity price of on -peak in the ith day ($/MWh).
$p_{critical}$	Electricity price of critical-peak($/MWh).
p_t	Wholesale market price of time period t ($/MWh).
$p_{b,ij}$	Purchasing price of jth hour in ith day($/MWh).
$p_t(i)$	Price sequence of ith Monte Carlo simulation.
$\overline{p}_t$	Mean values of p_t ($/MWh).
q	Customer demand (MWh).
$q_{0,i}$	Customer demand of time period i (pre-CPP implementation) (MWh).
$q_{0,ij}$	Customer demand of the jth hour in the ith day (pre-CPP implementation) (MWh).
$q_{CPP,i}$	Customer demand of time period i (post-CPP implementation) (MWh).
$q_{CPP,ij}$	Customer demand of the jth hour in the ith day (post -CPP implementation) (MWh).
$q_{mid,i}$	Customer demand of mid-peak in the ith day (MWh).
$q_{on,i}$	Customer demand of on-peak in the ith day (MWh).
t_k	Implementation time of kth critical event
Δp_t	Residual sequence of p_t ($/MWh).
Δp	Change of Electricity price ($/MWh).
Δq	Change of customer demand (MWh).
Δt_{min}	Minimum time interval between two adjacent critical events
ε_t	White noise, $\varepsilon_t \sim WN(0,1)$ distribution.
x_i	0-1 decision variable to denote whether ith day is critical day (1 means yes and 0 means no).

C. Matrixes

$\boldsymbol{E}$	Price elasticity matrix of demand.
$\boldsymbol{q_0}$	Customer demand matrix (pre-CPP implementation) (MWh).
$\boldsymbol{q_{CPP}}$	Customer demand matrix (post-CPP implementation) (MWh).
$\boldsymbol{x}$	Critical day decision vector.

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I. Introduction

PRICE-BASED demand response (DR) [1]–[3] programs include time-of-use (TOU) rates [4], real-time pricing (RTP) [5] and critical peak pricing (CPP) [6]–[11]. TOU is a kind of static pricing scheme and can only reflect long-term electricity cost of power systems. RTP is the ideal pricing scheme, but the full implementation of RTP is difficult yet due to the technical limitation of demand side. CPP tariff, a dynamic pricing scheme based on TOU and RTP, augments a time-invariant or TOU rate structure with a flexible pre-set high price during periods of system stress [6]. Although CPP is not as economically efficient as RTP, CPP reduces the potential price risk associated with RTP, reflects short-term costs of critical periods, helps encourage customers to reduce peak load, and lower LSE electricity procurement risk. Therefore, CPP is more economically efficient than TOU, and also achieves a good compromise between TOU and RTP.

CPP has not been as widespread as TOU and RTP so far in the U.S. and Europe. Only several utilities have carried out pilot CPP programs, as optional or default service, towards large commercial and industrial (C&I), and residential customers, e.g., California Statewide Pricing Pilot (SPP) [8]. Statistical results show that CPP has achieved good implementation effect in a broad range of customers [8]–[10].

CPP mainly includes four schemes [3]: fixed-period CPP (CPP-F), variable-period CPP (CPP-V), variable peak pricing (VPP) and critical peak rebates. CPP sponsors typically release in advance the triggering conditions of CPP events and corresponding values of critical peak prices. Critical days and non-critical days are known as the days with and without critical events. Customers are typically informed of critical events day-ahead, and accordingly customers can adjust their plans of electricity consumption day-ahead.

With respect to the CPP implementation scheme, when only limited critical days are available, it is important for an energy service provider to investigate the optimal CPP implementation strategies to maximize its profit [11]. The optimal CPP implementation strategies can be obtained based on electricity prices prediction and swing option evaluation. However, several important points are not considered in [11], e.g., customer response to CPP, the electricity price discount during on-peak periods and mid-peak periods of non-critical days, and the profits difference between pre-CPP and post-CPP implementation.

This paper conducts research on CPP-F. In this scheme, the beginning and ending time of critical periods, critical peak rate and maximum permitted number of critical days are all pre-determined [3]. Nonetheless, which specified days to be set as critical days can be flexibly arranged by CPP sponsors, e.g., load serving entity (LSE). Therefore, the issue of optimal CPP implementation strategies can be concluded as how to fully use the limited critical days, and how to choose appropriate critical days, in order to realize multi-party win.

This paper analyzes the optimal implementation strategies for CPP. Customer response to CPP is described by a price elasticity matrix of demand. A CPP decision model which considers the interests of both customers and LSE is introduced based on a hybrid electricity price forecast model.

The remaining of this paper is organized as follows. Section II provides the decision basis of CPP implementation, including the analysis of CPP tariff scheme, implementation process of CPP. Section III analyzes customer response to CPP and an electricity price forecast model. Section IV formulates the optimal CPP implementation strategies framework which considers interests of both customers and LSE. Section V is a case study based on the electricity market of New England. Section VI provides concluding remarks and several interesting fields for further study.

II. CPP Implementation Scheme

In order to allow customer to participate conveniently, CPP contracts are usually sign up based on TOU contracts, and CPP rate structures include the tariffs of critical days and non-critical days [2]. Table 1 shows the tariff structure comparison between TOU and CPP. In order to compare the two tariff structures more clearly, Fig. 1 provides an example of CPP tariff. Based on the analysis above, since customers can respond to CPP price signals, e.g., reduce or shift peak demand during critical days, and obtain rate discount of off-peak and mid-peak periods during non-critical days, they will be actively encouraged to participate in CPP.

TABLE I
Comparison Between TOU And CPP

		off-peak	mid-peak	on-peak	critical-peak
TOU		p_{off}	p_{mid}	p_{on}	-
CPP	non-critical days	p_{off}	rp_{mid}	rp_{on}	-
	critical days	p_{off}	p_{mid}	p_{on}	$p_{critical}$

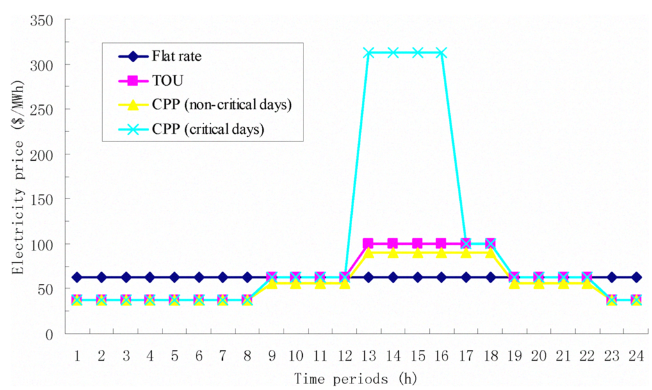

Fig. 1. An example of CPP tariff.

As the bridge between generation side and demand side, on one hand, LSE purchases electricity at fluctuating wholesale market price. On the other hand, LSE sells electricity to customers at relatively fixed retail prices. The price difference between generation side and demand side brings great market risk to LSE [12]. CPP is a flexible pricing strategy adopted to balance risks and benefits of electricity procurement and selling, and CPP plays an important role similar to that of interruptible/curtailable (I/C) service.

Based on Fig. 1, Fig.2 provides option theory based model of CPP contract, in view of I/C service contract [13], [14]. As illustrated in Fig.2, LSE can effectively hedge against electricity purchasing risk in wholesale markets through selecting proper critical days and accordingly implementing the critical-peak rate in demand side when wholesale prices become too high. Similar to I/C service, there are maximum times limit to the implementation of critical-peak rate, and minimum time interval limit to two adjacent critical days.

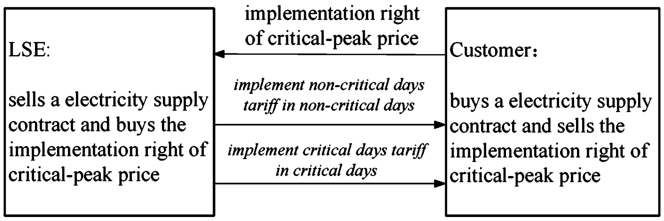

Fig. 2. Obligations for CPP contract.

Fig.3 analyzes the specific process of CPP implementation. As can be seen from Fig.3, based on customer response model and price forecast, maximum entire benefits can be realized through making rational CPP implementation strategies and selecting proper critical days, after CPP rate system is determined.

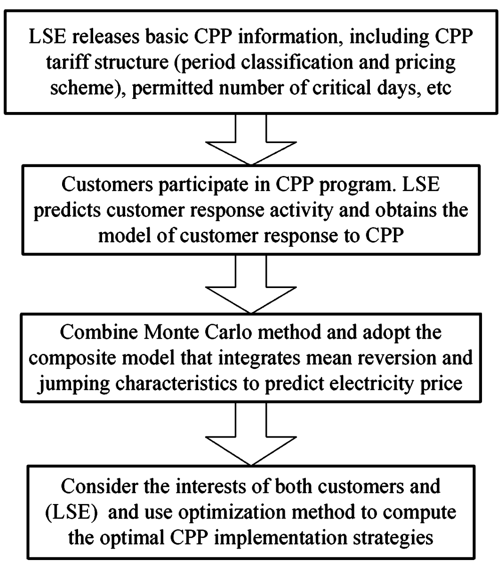

Fig. 3. Implementation process of CPP.

III. CPP Decision Base

A. Customer Price Response Model

Electricity prices play the key economic role in electricity markets. Investigating the law of customer demand response to electricity price is crucial for LSE in designing rational electricity price mechanism. Customer response to electricity price is reflected by adjusting their own power consuming periods, changing their own power consuming patterns, etc. Price elasticity of demand means the relative change of demand caused by the relative change of electricity price, i.e., the ratio of demand change percentage and price change percentage during certain time period:

$$e = \frac{\Delta q / q}{\Delta p / p} \tag{1}$$

Customer demand in a certain period is not only related to the price in this period, but also affected by the prices in adjacent periods. In order to quantify customer response to price, coefficients of self-elasticity and cross-elasticity are adopted respectively to describe customer response in single period and in multi-period. The price elasticity matrix of demand [15] integrating the two coefficients above is adopted to describe the overall price elasticity of demand:

$$\begin{bmatrix} \Delta q_1 / q_1 \\ \Delta q_2 / q_2 \\ \vdots \\ \Delta q_m / q_m \end{bmatrix} = \boldsymbol{E} \begin{bmatrix} \Delta p_1 / p_1 \\ \Delta p_2 / p_2 \\ \vdots \\ \Delta p_m / p_m \end{bmatrix} \tag{2}$$

Where, $\boldsymbol{E}$ can be represented as:

$$\boldsymbol{E} = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1m} \\ e_{21} & e_{22} & \cdots & e_{2m} \\ \vdots & \vdots & & \vdots \\ e_{m1} & e_{m2} & \cdots & e_{mm} \end{bmatrix} \tag{3}$$

Where, $e_{ii}=(\Delta q_i/q_i)/(\Delta p_i/p_i)$, $e_{ij}=(\Delta q_i/q_i)/(\Delta p_j/p_j)$.

Considering that critical peak periods are typically defined with time interval of 1h, price elasticity matrix of demand can be created with m=24. Thus after the implementation of CPP, customer demand will be changed to:

$$\boldsymbol{q}_{CPP} = \boldsymbol{q}_0 + \mathrm{diag}(\boldsymbol{q}_0)\boldsymbol{E}\boldsymbol{p} \tag{4}$$

Where, $\boldsymbol{q}_{CPP}=[q_{CPP,1}, q_{CPP,2},\ldots,q_{CPP,\mathrm{m}}]^{\mathrm{T}}$, $\boldsymbol{q}_0=[q_{0,1}, q_{0,2},\ldots,q_{0,\mathrm{m}}]^{\mathrm{T}}$; subscript 0 and CPP denote pre- and post- CPP implementation respectively.

B. Electricity price forecast

Since LSE often implements critical-peak rate only when price peak appears in wholesale market, CPP implementation strategies is closely related to forecasted wholesale market electricity prices. Therefore in this study, the composite model integrating mean reversion and jumping model is adopted to reflect the characteristics of mean reversion and critical-peak respectively. Thus the specific pricing model is showed as:

$$p_t = \overline{p}_t + \varphi p_{t-1} + \theta\varepsilon_t + \tan(\max(0, a(l_t - b)))\bullet N(\mu, \sigma^2) \tag{5}$$

The first item of the right side of (5) is mean electricity price; the second item is the influence of last price data; the third item is random fluctuation; the fourth item reflects price mutation according to load rate. Considering there are several stochastic variables in (5), Monte Carlo simulation method can be used to obtain price sequence:

$$p_t = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} p_t(i) \tag{6}$$

IV. Optimal CPP Implementation Strategies model

The assumption of the model includes: 1) LSE purchases electricity in wholesale market, and LSE is a price taker; 2) LSE's purchase equals their sale; 3) taking the CPP-F scheme for analysis and the optimal CPP implementation strategies should consider the benefits of both customers and LSE.

After implementing CPP, customers can reduce their electricity charges through adjusting their demand pattern during critical days, and obtaining rate discount of off-peak and mid-peak periods during non-critical days. The benefit function of customers can be obtained as:

$$\begin{aligned} B(\boldsymbol{x}) = & \sum_{i=i_s}^{i_e} x_i \sum_{j=1}^{24} (p_{0,ij} q_{0,ij} - p_{CPP,ij} q_{CPP,ij}) \\ & + (1-r) \sum_{i=i_s}^{i_e} (1-x_i)(p_{mid,i} q_{mid,i} + p_{on,i} q_{on,i}) \end{aligned} \quad (7)$$

Where: $\boldsymbol{x}=\{x_i \mid i=i_s, i_s+1,\cdots, i_e\}$, and $q_{cpp,ij}$ is obtained from (4). The first item of the right side of (7) denotes electricity charges reduction in critical days. The second item denotes electricity charges reduction caused by rate discount of mid-peak and on-peak in non-critical days.

After implementing CPP, LSE can lower electricity purchasing cost. Since LSE is assumed as price taker, the benefit function of LSE can be obtained as:

$$C(\boldsymbol{x}) = \sum_{i=i_s}^{i_e} x_i \sum_{j=1}^{24} p_{b,ij} (q_{0,ij} - q_{CPP,ij}) \quad (8)$$

Where: $p_{b,ij}$ denotes wholesale market price, which can be obtained from (5) and (6).

After implementing CPP, the profit change of LSE is determined by the difference between purchasing cost reduction and selling income reduction (i.e., customer electricity charges reduction). In order to increase the activity of LSE in CPP implementation, LSE should be ensured to gain profit increment with CPP implementation, i.e.,:

$$C(\boldsymbol{x}) - B(\boldsymbol{x}) \geq 0 \quad (9)$$

The benefits of implementing CPP include electricity charges saving for customers and purchasing cost saving for LSE. Optimal CPP implementation strategies can be concluded as how to efficiently use the limited critical days, and how to choose proper critical days to maximize the entire benefits. Therefore the objective function is:

$$\max\ A(\boldsymbol{x}) = \max\ B(\boldsymbol{x}) + C(\boldsymbol{x}) \quad (10)$$

Constraints are:

$$B(\boldsymbol{x}) \geq 0 \quad (11)$$

$$C(\boldsymbol{x}) \geq 0 \quad (12)$$

$$C(\boldsymbol{x}) - B(\boldsymbol{x}) \geq 0 \quad (13)$$

$$\sum_{i=i_s}^{i_e} x_i \leq N_{CPP} \quad (14)$$

$$t_k - t_{k-1} \geq \Delta t_{\min} \quad (2 \leq k \leq N_{CPP}) \quad (15)$$

(10) is objective function; (11) guarantees that customers can receive electricity charges saving after participating in and responding to CPP; (12) guarantees that LSE can receive purchasing cost saving after implementing CPP; (13) guarantees that LSE can obtain profit increment after implementing CPP; (14) denotes the constraint of maximum permitted number of critical days; (15) denotes the constraint of minimum time interval between two adjacent critical events.

The above model is a 0-1 integer programming problem, and the decision variables are x_i ($i=i_s, i_s+1,\cdots, i_e$). The optimal CPP implementation strategies can be obtained with MATLAB 0-1 integer programming function.

The decision results through computing the model above are merely preliminary strategies due to the error of price prediction. In CPP-F mode, LSE usually makes decision on whether the next day will be regarded as critical day according to the prices in day-ahead market (i.e., inform customers one day in advance). Consequently, the progressive approach, i.e., daily re-calculating the decision model composed of remaining study period, can be used to promote the rationality of decision results. The specific process is to replace the predicting price in the next day with the actual price in day-ahead market, update other parameters in current decision model (e.g., the starting day of study period i_s and the remaining critical days N_{CPP}), and then re-calculate the decision model composed of remaining study period. In this way, the actual price in the next day and the predicting price in remaining study period can be integrated effectively into model solving process. The flow chart is shown below:

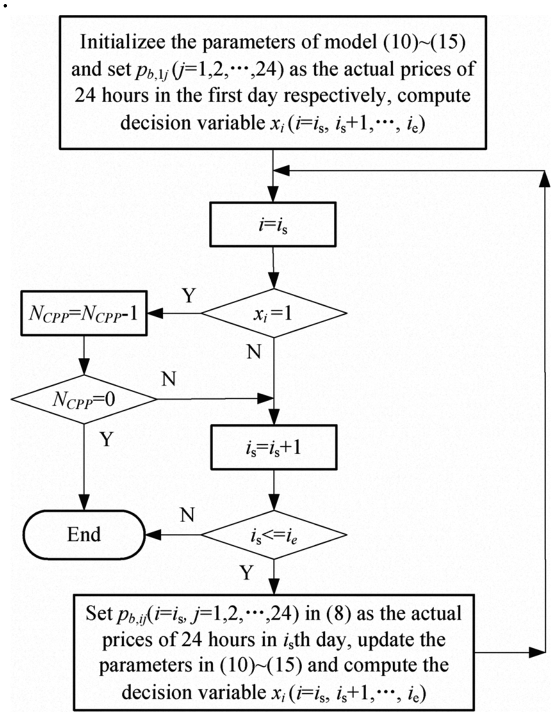

Fig. 4. Actual decision process.

V. Case Study

In this section, the U.S. New England electricity market is taken as an example for analysis to illustrate the performance of the proposed decision-making framework. A time span of one month, i.e., August 2002, is considered in this section for case study and a LSE offered CPP to its all customers in August 2002. Based on [16], the historical prices data of New England market from January 2000 to July 2002 [17] are statistically analyzed to formulate the parameters of stochastic price model:

$$\begin{aligned} p_t = & \overline{p}_t + 0.8567 p_{t-1} + 5.29\varepsilon_t \\ & + \tan(\max(0, 40(l_t - 0.935))) \bullet N(300,100) \end{aligned} \quad (16)$$

Then the stochastic price model is adopted to estimate the day-ahead wholesale market prices of August 2002. In order to represent the probability distribution of day-ahead market prices, Monte Carlo simulation times N_M is set to 4000.

LSE demand is regarded as 1% of system demand in each period respectively. The 24-rank price elasticity matrix of demand $\boldsymbol{E}$ can be obtained through statistical regression analysis of historical data. Let i_s=1, i_e=31, i.e., the study periods span 31 days, N_{CPP}=4， and Δt_{min}=24h. Combining Fig.1, CPP is implemented based on TOU, and the time classification of CPP is: 22:00~8:00 as off-peak, 8:00~12:00 and 18:00~22:00 as mid-peak, 12:00~18:00 as on-peak, and 12:00~16:00 as critical-peak. Accordingly pricing scheme of CPP are: p_{off}=37.5\$/MWh, p_{mid}=62.5\$/MWh, p_{on}=100\$/MWh, $p_{critical}$= 312.5\$/ MWh, and r=0.95.

With the aforementioned method, the optimal CPP implementation strategies can be obtained: $x_5=x_{13}=x_{14}=x_{15}=1$, i.e., the optimal CPP implementation strategies are: selecting 5th, 13th, 14th, and 15th days as critical days in August 2002. Electricity charges saving for customers is 1.27×10^5\$ (reduction percent is 1.58%). Purchasing cost saving for LSE is 5.53×10^5\$ (reduction percent is 8.52%), and profit increment is 4.26×10^5\$ (increasing percent is 27.50%). The optimal total benefit is 6.79×10^5\$, which realizes multi-win-win.

Combining the actual day-ahead price data of New England electricity market in August 2002, Fig.5 shows the optimal CPP implementation strategies, in which those 4 segments of red line represent the critical periods and selling prices in those 4 critical days of this month. It is clear that the actual prices in day-ahead market are relatively high, e.g., the prices in 14:00~17:00, August 14th 2002 all reach the price cap 1000\$/MWh. Meanwhile LSE can effectively stimulate customers to reduce their demand in critical period by implementing critical-peak rate in demand side. Taking August 14th 2002 as an example, Fig.6 illustrates the effect of implementing CPP on peak demand reduction in this day. It can be seen from Fig.6 that, on the one hand, reduction of on-peak load is realized during the four-hour critical periods from 12:00 to 16:00; on the other hand, the slight reduction of purchasing in critical periods can also lower the high purchasing cost of LSE, hedge against the purchasing risk in wholesale market, balance purchasing fee and selling income, help to ensure the reliability of system, and relieve the power shortage in peak hours of the whole system.

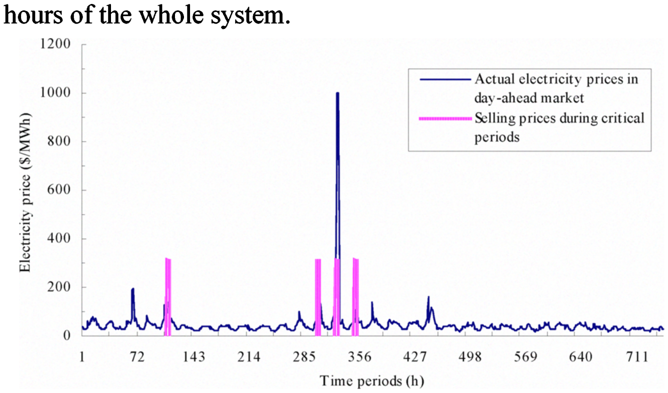

Fig. 5. Optimal CPP implementation strategies.

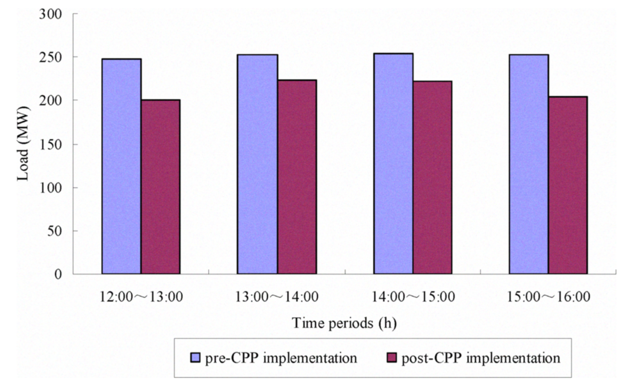

Fig. 6. Role of CPP in peak-clipping.

Table I1 illustrates the influence of different values of N_{CPP} on decision results when other parameters remain invariant. It can be seen from Table I1 that as N_{CPP} increases, the number of actual executing critical days increases, electricity charges saving for customers decreases, while purchasing cost saving and profit increment for LSE increase. This is because: i) for customers, combining (7), on the one hand, as the number of actual critical days increases, their electricity charges saving which is realized by reducing/shifting their demand during critical periods increases; on the other hand, as the number of actual non-critical days decreases, their bill credit accrued from rate discount during non-critical days decreases. In addition, as N_{CPP} increases, the increment of the former is less than the decrement of the latter, and accordingly leading to reduction of electricity charges saving for customers. Similarly, ii) for LSE, combining (8), as the increment of actual critical days would stimulate customers to adjust their own demand pattern, purchasing cost saving for LSE will increase.

However, when N_{CPP} increases to a certain degree, decision results will not change. For example, when N_{CPP}=5, the number of actual executing critical days is 4 (critical days are 5th, 13th, 14th and 15th days), which equals the decision results when N_{CPP}=4. This is due to that as N_{CPP} increases, the total benefit of customers and LSE tends to be stable. Under this circumstance, if N_{CPP} keeps increasing, although LSE can gain more benefit, customers' benefit will be jeopardized, and therefore the total benefit will be affected. This also indicates when N_{CPP}=5, the optimal total benefit can be obtained when only actually executing 4 critical days.

TABLE II
IMPACT OF N_{CPP} ON DECISION RESULTS

N_{CPP}	Actual critical days	Electricity charges saving for customers (\$)	Purchasing cost saving (\$)	Profit increment (\$)
2	5,14	2.25×10^5 (2.80%)	4.48×10^5 (6.91%)	2.23×10^5 (14.39%)
3	5,13,14	1.76×10^5 (2.19%)	5.04×10^5 (7.76%)	3.28×10^5 (21.17%)
4	5,13,14,15	1.27×10^5 (1.58%)	5.53×10^5 (8.52%)	4.26×10^5 (27.50%)
5	5,13,14,15	1.27×10^5 (1.58%)	5.53×10^5 (8.52%)	4.26×10^5 (27.50%)

VI. Conclusion

This paper studies CPP implementation scheme, measures customer response to CPP with price elasticity matrix of demand, and combines pricing forecast to analyze the optimal CPP implementation strategies. Numerical results are finally used to prove the effectiveness of the proposed model, which is beneficial to customers in saving electricity bills, to LSE in reducing electricity purchase cost and hedging against electricity purchasing risk in wholesale market, and ultimately realizing multi-party win.

Since price implementation scheme is a complicated issue which covers a wide range, this paper still stays in exploration stage. Since the tariff structure in CPP-F scheme is pre-set and only critical days can be selected flexibly, future research could be conducted towards the optimal implementation strategies of CPP-V. In CPP-V scheme, both the beginning and ending time of critical periods, and which days to be set as critical days are not pre-determined, but are determined in real-time market [3]. Accordingly this scheme is more flexible than CPP-F scheme.

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