Optimization model for the calculation of residential peak-valley time-of-use electricity price under the ladder electricity price

SE 543 project

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Abstract

To design time-of-use (TOU) tariff based on the existing residential multi-step electricity price, and combine the two kinds of prices, which further lead to the rational use of electricity and improve energy efficiency, this paper proposes the optimization model and method of residential TOU tariff calculation under multi-step electricity price. First, according to the user coverage of current each step price, we divide whole residential households into the corresponding subgroup market subdivision. Second, we construct the TOU tariff responsive function of every market subdivision, as well as the corresponding optimization objective function set of TOU tariff. Third, we build the constraint condition set of TOU tariff in every market subdivision. Last, we construct the TOU tariff optimization model of every segment market with combining the objective function and the constraint condition, whose output result is the optimal TOU tariff for each step. The rationality and feasibility of the model are verified in the example simulation, and the sensitive analysis further reveals the changing law of the optimal TOU tariff results for each step with the demand response.

CONTENTS:

1. Introduction

To solve the problem of cross-subsidy for industrial electricity and residential electricity, in most areas of China, since 2012, the step-by-step increase in electricity price for residents has been implemented. Differential pricing of market segments is achieved through segmented electricity, thereby improving energy utilization efficiency to a certain extent. From the point of view of the electricity price structure, most of such tiered prices are not subject to peak-valley time-of-use pricing, that is, the electricity price of any tiered price is a uniform price that does not vary over time. In this way, changing the price system will not be able to adjust the shape and characteristics of the residents' load curve, which will further optimize the behavior of electricity consumption.

On the other hand, as the proportion of household electricity consumption continues to increase, the power grid load curve is constantly showing new changes. In order to improve the power supply reliability, power quality and power grid load rate of the power grid, and guide the power consumption of residential users, it is necessary to formulate the peak-valley time-of-use electricity price based on the already implemented residential tiered electricity price based on the load characteristics of the residents in different periods, so as to achieve The purpose of adjusting the peak and valley load of the power grid, improving the system load curve, shaving peaks and filling valleys, alleviating the power shortage, increasing the load rate, improving the safety and economy of the power grid, and enhancing the operating efficiency and stability of the power system. Therefore, studying how to formulate residential peak-valley time-of-use electricity prices based on the existing tiered electricity prices, to comprehensively utilize the roles of the two price systems in improving energy utilization efficiency, will surely become a problem with both theoretical innovation and engineering practice significance at the same time.

1.1 Electricity Usage Situation

Electricity performs an important part of modern life in U.S. economy. There are many ways to use electricity like lighting, heating, cooling, and transporting etc. The total consumption of electricity in U.S. has increased 13 times greater than the usage in 1950 than 2021, which was about 3.93 trillion kWh. The total consumption of electricity includes retail sales of electricity to customers and direct use of electricity. Direct use of electricity is produced and used by the customers. The greatest part of direct use of electricity by industrial. There were about 3.79 trillion kWh retail sales of electricity, about 97% of total electricity consumption in 2021. Other 3% in direct use were used by all end-use sectors, which was about 0.14 trillion kWh.

Since the economy recovered from the effects of the pandemic through 2021, the consumption of total U.S electricity has increased 2% than in 2020. Electricity retail sales to the industrial sector in 2021 were about 7% lower than in 2000, the peak year of U.S. retail sales to the industrial sector. The industrial sector’s percentage share of total U.S. electricity retail sales was 31% in 2000 and 26% in 2021. Residential retail sales increased by about 1% in 2021 from sales in 2020. [1]

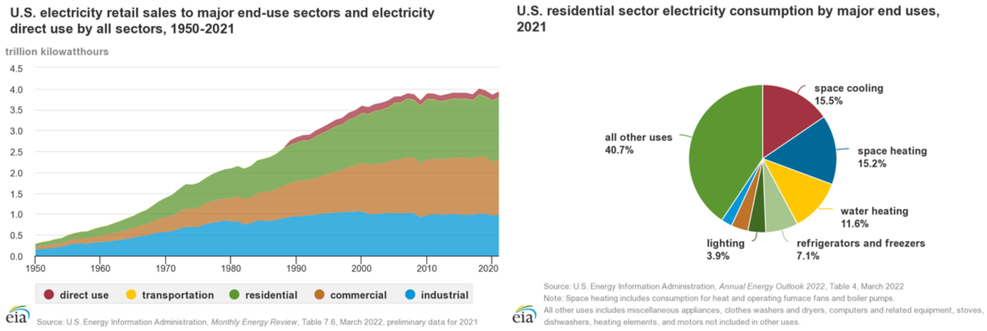

Fig1 U.S. electricity usage

There are raising some concerns about seriously environmental effects like greenhouse gas emissions, ozone layer depletion, global warming, etc. Also has the concerns about supply difficulties and energy resources shortages due to the rapidly growth in usage of energy over the world. With the growth of the population, people's demand for the service performance and comfort of the building increases, and the time spent in the building increases, which will continue to increase the demand for energy in the future. The global contribution of buildings to residential and commercial energy consumption has grown steadily, reaching 20% to 40% in developed countries, and surpassing other major sectors: industry and transportation. For this reason, today's national and even international energy policies primarily target the energy efficiency of buildings. Among building services, the growth in energy use of HVAC systems has been particularly significant (50% of building energy consumption and 20% of total energy consumption in the United States). Reference [2] analyzes the available information on building energy consumption, especially in relation to HVAC systems. Comparisons between different countries are presented specifically for commercial buildings. The office case is analyzed in more detail.

In China, from 1970 to 2012, China's energy use emissions increased by a factor of 12.53, driven by a combination of rapid personal income growth and slow population growth, offset by technological advances since 1980. The accelerated growth in energy use since 2000 is the result of faster growth in personal income and a downward trend in energy intensity, that is, technological progress. Unlike China, in India the long-term growth in energy use has outpaced the long-term growth in personal income. In addition, India has yet to see a strong trend of declining energy intensity. As a result, India's energy use increased by a factor of 7.39 from 1970 to 2012, due to relatively rapid population growth and relatively slow income growth, not effectively offset by technological progress. It shows that market-driven economic and energy reforms need to send the right price signals to promote energy-efficient technologies that increase energy efficiency, which is key to achieving a sustainable energy future in China and India. [3]

1.2 Greenhouse Gas Emission Situation

Several states and countries have proposed drastic reductions in greenhouse gas emissions by 2050, but there has been little physical reality modeling of the energy and economic transitions needed. Reference [4] uses detailed modeling of infrastructure stock, resource constraints, and power system operability to analyze the infrastructure and technology pathways required to achieve California's goal of an 80% reduction below 1990 levels. They found that technologically feasible levels of energy efficiency and decarbonized energy supply alone are not enough; transport and other sectors need extensive electrification. Decarbonized electricity will become the dominant form of energy supply, presenting challenges and opportunities for economic growth and climate policy. This transition requires technologies that have not yet been commercialized, as well as coordination of investment, technology development, and infrastructure deployment.

Solar and nuclear power generation technologies are generally considered "carbon-free" because their operation does not produce any carbon dioxide. However, this is not the case when considering the entire life cycle of its energy production. Carbon dioxide and other gases are also emitted during the extraction, processing, and disposal of related materials. Reference [5] is based on a review of the nuclear fuel life cycle from 12 photovoltaic (PV) companies, as well as the United States, Europe, and Japan. Previous GHG estimates have varied widely, ranging from 40 to 180 CO2 eq/kWh for photovoltaics and 3.5-100 CO2 eq/kWh for nuclear power. Country-specific parameters explain many of these differences, which are exacerbated by outdated information. Instead, they concluded that under actual production conditions and average solar radiation, lifetime greenhouse gas emissions from the U.S. solar and nuclear fuel cycles are comparable, 22-49 g CO2-eq./kWh (U.S. average), and solar power generation is 17-39 g CO2-eq./kWh (southwest), nuclear power 16-55 g CO2-eq./kWh. However, several factors could significantly change this over the next 5 years, and some unresolved questions about the nuclear fuel cycle require further analysis.

While the key to increasing the penetration of variable renewable energy is energy storage, the impact of energy storage on Greenhouse Gas emissions is uncertain. Several studies have shown that certain operations in energy storage can increase emissions even when energy storage has 100% turnover efficiency. Furthermore, previous studies have relied on country-level data and paid little attention to the impact of storage on local emissions. This is an important omission, as carbon intensity can vary widely on a national scale. Reference [6] introduces a new method for calculating regional marginal emission factors based on a validated power system model and regression analysis. These techniques were used to investigate the impact of UK storage operations on CO2 emissions in 2019 under a range of operational scenarios. The study found that there are significant regional differences in energy storage emission factors, and in areas with low wind curtailment rates, energy storage tends to increase emissions when used for wind energy balance. By contrast, the greatest emissions reductions can be achieved when charging and discharging using otherwise curtailed renewable energy sources to reduce peak demand in areas that consume a lot of fossil fuel electricity. Across all regions and modes of operation studied, the difference between the highest reduction in emissions and the highest increase in emissions was considerable, at 741 grams of CO2 per kWh. It is concluded that power system regulators should pay more attention to the impact of energy storage operation on system CO2 emissions.

1.3 Motivation

Reference [7] studies the impact of electricity consumption, economic growth, and globalization on carbon dioxide emissions in the top ten electricity consuming countries. Empirical results show that there are long-term associations between these variables; electricity consumption and economic growth have a positive and significant impact on carbon dioxide emissions in these countries. In contrast, globalization has had a clear negative impact on carbon dioxide emissions, which means an improvement in the quality of the environment. The findings also confirmed the existence of the Environmental Kuznets Curve (EKC) hypothesis, which is a bidirectional causal relationship between economic growth and carbon dioxide emissions, between electricity consumption and carbon dioxide emissions, and between globalization and economic growth in the sample countries. One-way causality was also found from economic growth to electricity consumption, from electricity consumption to globalization, and from globalization to carbon dioxide emissions. Based on the findings, policy guidelines are proposed.

Reference [8] studies the situation in Malaysia, and the results show that electricity consumption and its determinants are cointegrated. Specifically, empirical results show that income has a positive impact on electricity consumption in the long run, while energy prices and technological innovation have a negative impact on electricity consumption in Malaysia. Therefore, policymakers should increase investment in electricity infrastructure to ensure that electricity supplies are sufficient to support economic growth and development, while encouraging technological innovation to minimize the use of fossil fuels. This can strike a balance between Malaysia's environmental quality and economic growth.

The invention and application of electric power technology triggered the second industrial revolution in human history, marking the entry of human society into the electric age. Electricity provides sustainable power for economic and social development. With the rapid development of the economy, electricity consumption is also increasing. The increase in electricity consumption has further contributed to the progress of the industrial economy. To achieve the goal of improving the level of economic development while reducing energy consumption, it is necessary to reveal the relationship between electricity consumption and economic growth. The study in [9] is a broad overview of the literature surrounding the topic. It focuses on the relationship between electricity consumption and economic growth in China. Firstly, the general situation of China's electricity consumption and economic development is analyzed. Then, it explores the relationship between China's electricity consumption and economic growth from three dimensions: time dimension, regional dimension, and industry dimension. Finally, key issues in the study of the relationship between electricity consumption and economic growth are studied, including variable selection, model construction, and result discussion. This work shows that the nature of China relations can be explored from a broader perspective by developing an appropriate comprehensive methodological framework.

In this paper, an optimization model is proposed that tries to minimize the electricity cost of customers based on the price set by the leader. Consumers can also choose to buy electricity from the leader's competitors. Competitors act as boundary conditions for leaders to set prices. When the leader sets a much higher rate than the competitor, then the follower buys electricity from the competitor. To meet demand, leaders use different fuel sources to generate electricity, such as coal, oil, and natural gas, which have different costs and emission levels. Evaluate a leader's profit by considering the impact of carbon emissions. If leaders want to minimize emissions, the model can also change based on price, profit, generation, and the behavior of customers' electricity demand. The purpose of this study is to determine how carbon emissions affect price setting, profit, and demand shifting behavior of customers.

2. Problem Statement and Formulation

2.1 Problem Description

The basic idea of this paper is to build a residential peak-valley time-of-use electricity price calculation optimization model based on the ladder electricity price:

First, all residential users are classified. Since the current tiered electricity price for residents in most parts of China is divided into three parts, the first part is set based on the daily needs of most residents, especially the low-income groups; The electricity setting mainly considers the residents who meet the normal and reasonable electricity demand, and the electricity price is gradually adjusted to a level that makes up for the normal and reasonable costs of the power company and obtains reasonable income; the third part of the electricity consumption setting of the unit households mainly considers the users with higher quality of life needs , the price of electricity is increased to the basis of making up for costs and obtaining benefits, and appropriately adding the cost of environmental damage, that is, carbon dioxide emissions. Therefore, this paper classifies residential users according to the idea of tiered electricity price, and marks all residential users within the implementation range of the first tiered electricity price in a certain region as the first type of subgroup market segment; the second tiered electricity price implementation scope All residential users within the range are marked as the second type of sub-group market segment; all residential users within the implementation range of the third-tier tiered electricity price are marked as the third type of sub-group market segment.

Secondly, the demand response model of peak-valley time-of-use electricity price is constructed for each sub-group segmented market, and the average response law of electricity load in each sub-group segmented market to the change of peak-valley time-of-use electricity price is obtained.

Third, establish the objective function set and constraint condition set of the peak-valley time-of-use electricity price optimization model for various sub-group market segments, and complete the peak-valley time-of-use electricity price calculation corresponding to each sub-group segment market on this basis. Build the optimization model.

Finally, the optimal solution output by each sub-group model is the estimated value of the peak-to-valley time-of-use electricity price of the corresponding steps.

As shown in Figure 2, it is the technical route of the optimization model of the peak-valley time-of-use electricity price calculation under the ladder electricity price.

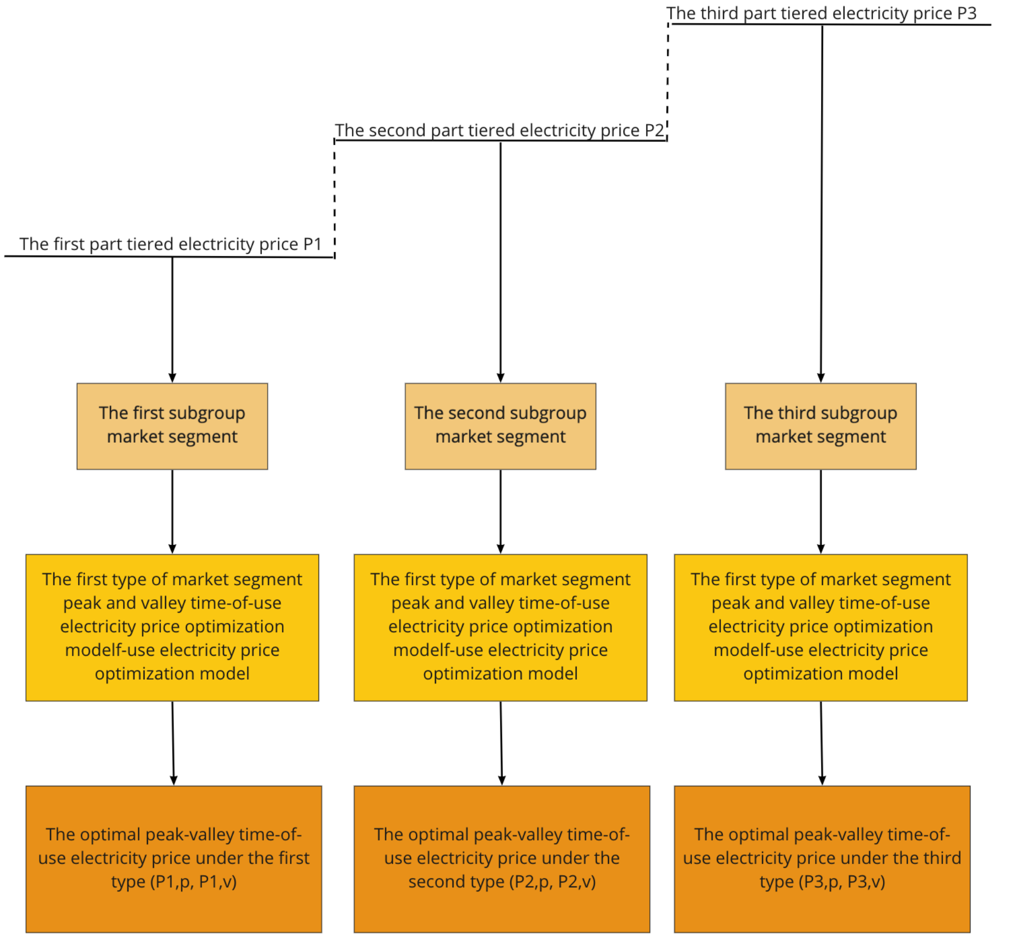

Fig 2 Technical route of TOU tariff under multi-step electricity price

2.2 Parameters Setting

There are significant differences in income and living habits among users in various sub-group segments, and these are important factors that affect the demand response of users' peak-to-valley time-of-use electricity prices. Therefore, the average demand response law of residential users to the peak-valley time-of-use electricity price in each subgroup segment market should be analyzed separately.

Taking the northeastern region of China as an example, it is assumed that the study area has already divided the peak (p) and valley (v) periods of residential electricity consumption in the area according to the shape characteristics of the residential electricity load curve. And located in this area, the approximate numerical relationship between the electricity load of residents p and v in each period and the peak-valley time-of-use electricity price in the i-th ($i = 1,2,3$) sub-group segment corresponding to the i-th electricity price ladder can be expressed as:

$$L_{i,p} = L_{i,p}^{(0)} + L_{i,p}^{(0)} \cdot e_{pp}^{(i)} \cdot \frac{P_{i,p} - P_i}{P_i} + L_{i,p}^{(0)} \cdot e_{pv}^{(i)} \cdot \frac{P_{i,v} - P_i}{P_i} \tag{1}$$

$$L_{i,v} = L_{i,v}^{(0)} + L_{i,v}^{(0)} \cdot e_{vp}^{(i)} \cdot \frac{P_{i,p} - P_i}{P_i} + L_{i,v}^{(0)} \cdot e_{vv}^{(i)} \cdot \frac{P_{i,v} - P_i}{P_i} \tag{2}$$

where, P_i is the electricity price implemented by the $i\text{-}th$ step before the implementation of the peak-valley time-of-use electricity price; $P_{i,p}$, $P_{i,v}$represent the peak and valley electricity prices implemented for the $i\text{-}th$ subgroup market segment respectively. $L_{i,p}^{(0)}$, $L_{i,v}^{(0)}$, $L_{i,p}$, $L_{i,v}$ are respectively expressed as the average loads corresponding to each period p and v before and after the implementation of the peak-valley time-of-use electricity price for all residents in the sub-group market segment of the $i\text{-}th$ subgroup. The electricity demand of users in the $i\text{-}th$ subgroup market-time-of-use price matrix can be expressed as

$$E_i = \begin{bmatrix} e_{pp}^{(i)} & e_{pv}^{(i)} \\ e_{vp}^{(i)} & e_{vv}^{(i)} \end{bmatrix} \tag{3}$$

Obviously, when P_i, $L_{i,p}^{(0)}$, $L_{i,v}^{(0)}$ and E_i are the parameters, it can be seen from equations (1) and (2) that the average load $L_{i,p}$, $L_{i,v}$ of all residents in the $i\text{-}th$ subgroup market segment at each time period is the $i\text{-}th$ step peak-valley time-sharing The function of the electricity price vector $P_i = \left(P_{i,p}, P_{i,v}\right)$ that is, the demand response function of the peak-valley time-of-use electricity price.

2.3 Linear Programming

After determining the demand response functions of various types of users, the corresponding peak-to-valley time-of-use price calculation optimization models on each electricity price ladder can be established according to the demand response characteristics of various subgroups of users.

(1) Objective function set determination

The ultimate purpose of implementing the peak-valley time-of-use price is to save various social costs to the greatest extent by changing the shape of the electricity load curve. Therefore, the objective function set for constructing the optimization model in this paper should contain the following two objective elements:

$$Ob_i = \{object_i(1), object_i(2)\} \tag{4}$$

The above formula represents the objective function set of the optimal model for the calculation of peak-to-valley time-of-use electricity prices for the $i\text{-}th$ subgroup (corresponding to the $i\text{-}th$ electricity price ladder). where:

The objective function $object_i(1)$ represents the maximum reduction of the load in the p period

$$min \;\; L_{i,p} = f_{i,p}(P_i) = L_{i,p}^{(0)} + \sum_{t=p,v} L_{i,p}^{(0)} \cdot e_{pt}^{(i)} \cdot \frac{P_{i,t} - P_i}{P_i} \tag{5}$$

The objective function $object_i(2)$ indicates that the load difference in the p, v period is minimized

$$min\ \ f_{i,p}(P_i) - f_{i,v}(P_i) \\ = (L_{i,p}^{(0)} - L_{i,v}^{(0)}) \\ + \sum_{t=p,v} \left[L_{i,p}^{(0)} \cdot e_{pt}^{(i)} \cdot \frac{P_{i,t} - P_i}{P_i} - L_{i,v}^{(0)} \cdot e_{vt}^{(i)} \cdot \frac{P_{i,t} - P_i}{P_i} \right] \tag{6}$$

(2) Constraints set determination

When constructing the peak-valley time-of-use price optimization model, some necessary constraints must be considered to ensure the reasonable realization of the final goal. In this paper, it is determined that the set of constraints for the optimal model for the calculation of peak-valley time-of-use electricity price estimation in the construction of the $i\text{-}th$ subgroup (corresponding to the $i\text{-}th$ tiered electricity price) can be expressed as:

$$Con \\ = \{condition_i(1), condition_i(2), condition_i(3), condition_i(4)\} \tag{7}$$

(i) $condition_i(1)$ price constraint

To ensure that the interests of users are not damaged, after the implementation of the peak-valley time-of-use electricity price alternative, the average electricity purchase price of residents will not increase

$$\frac{P_{i,p}L_{i,p}T_p + P_{i,v}L_{i,v}T_v}{L_{i,p}T_p + L_{i,v}T_v} \le P_i \tag{8}$$

where, T_p, T_v respectively represent the duration of each period of p and v in the study period

(ii) $condition_i(2)$ time constraint

After the peak-valley time-of-use price is implemented, the p, v period cannot be inverted, that is, which satisfied:

$$L_{i,v} \le L_{i,p} \tag{9}$$

The significance of formula (9) is that after the user responds to the demand of the peak-valley time-of-use electricity price, the average load in the p period should not be lower than the v period, otherwise the p and v periods will no longer have practical significance, and should be re-divided. , the effect of the optimization goal will also be offset to a certain extent (that is, because the time distribution of peak load and valley load is shifted at this time, the load peak-valley difference that can be eliminated still exists).

(iii) $condition_i(3)$ cost constraint

The price of electricity in each period should not be lower than a certain lower limit P_d, which is set according to the power supply cost of the power system.

$$P_{i,t} \geq P_d, \qquad \forall t = p, v \tag{10}$$

(iv) $condition_i(4)$ electricity Price Constraint

To ensure that the user coverage of the original tiered electricity price does not change significantly under the tiered peak-valley electricity price, after the peak-valley time-of-use electricity price is implemented for each tier. The user's total electricity consumption per household in the entire analysis period cannot exceed the corresponding step-by-step electricity consumption

$$\frac{\Delta \mathrm{L}_{i,p} T_p + L_{i,v} T_v}{N_i} \leq Q_i \tag{11}$$

where, N_i is the number of households in the market segment of the $i\text{-}th$ subgroup, and Q_i is the upper limit of the per capita tiered electricity for the $i\text{-}th$ tiered electricity price.

Combined formula (5), (6), (8), (9), (10), (11) can obtain the peak-valley time-of-use electricity price calculation optimization model corresponding to the $i\text{-}th$ tiered electricity price:

$$min \quad L_{i,p} = f_{i,p}(P_i) = L_{i,p}^{(0)} + \sum_{t=p,v} L_{i,p}^{(0)} \cdot e_{pt}^{(i)} \cdot \frac{P_{i,t} - P_i}{P_i} \tag{12}$$

$$\begin{aligned} minf_{i,p}(P_i) - f_{i,v}(P_i) &= \left(L_{i,p}^{(0)} - L_{i,v}^{(0)}\right) \\ &+ \sum_{t=p,v} \left[L_{i,p}^{(0)} \cdot e_{pt}^{(i)} \cdot \frac{P_{i,t} - P_i}{P_i} - L_{i,v}^{(0)} \cdot e_{vt}^{(i)} \cdot \frac{P_{i,t} - P_i}{P_i}\right] \end{aligned}$$

s.t.

$$\begin{gathered} \frac{P_{i,p} L_{i,p} T_p + P_{i,v} L_{i,v} T_v}{L_{i,p} T_p + L_{i,v} T_v} \leq P_i \\ L_{i,v} \leq L_{i,p} \\ P_{i,t} \geq P_d, \qquad \forall t = p, v \\ \frac{\mathrm{L}_{i,p} T_p + L_{i,v} T_v}{N_i} \leq Q_i \end{gathered} \tag{13}$$

2.4 Model Solving

According to the common processing method of multi-objective function optimization, the problem of the above two objective functions can be simplified into an optimization problem of one objective function

(1) Solve the single-objective optimization model according to $object_i(1)$ and $object_i(2)$ respectively and calculate the corresponding output values of (5) and (6) under their respective optimal decision-making schemes: $L_{i,p}^*$,

ΔL_i^*.

(2) Considering that when $object_i(1)$ and $object_i(2)$ are of equal importance, the weights can be equally distributed between them, so $object_i(1)$ and $object_i(2)$ can be transformed into the following single-objective problem:

$$min\left\{\frac{1}{2}\left|\frac{L_{i,p}(k)-L_{i,p}^*}{L_{i,p}^*}\right|+\frac{1}{2}\left|\frac{\left[L_{i,p}-L_{i,v}\right]-L_i^*}{L_i^*}\right|\right\} \tag{14}$$

The above formula is the comprehensive optimization objective function of the processed peak and valley time-of-use electricity price.

3. Experiment Setup

3.1 Data Preparation

This paper collects the current tiered electricity prices for residents in Beijing, China [10]: the first-tier electricity price is \$0.49(/kWh), the second-tier electricity price is \$0.54(/kWh), and the third-tier electricity price is \$0.79(/kWh). Among them, the first tiered electricity price covers about 80% of the residents in the area, the second tiered electricity price covers about 15% of the residents, and the third tiered electricity price covers about 5% of the residents.

This paper uses the city's 2019 residential user load data as the simulation data source. The data sample includes a total of 22,541 households with high, medium, and low incomes in the city (this data is valid data after screening), and each household has a load value at each time point throughout the year on 365 days of the year. Based on the tiered electricity price requirement in this area, the residents with annual power consumption of 4800kWh and heavy rain are further divided into the third subgroup, with a total of 1083 households; the residents with annual power consumption less than 2640kWh are divided into the first subgroup, a total of 19,631 households; the residents whose annual electricity consumption is between the two are divided into the second subgroup, a total of 2,827 households. By selecting a certain number of typical users from the above three types of sub-groups for research and combining with the historical data of other areas where residents have implemented peak-valley electricity prices in Shanghai and other areas, the market segment of each sub-group is estimated. The value of the electricity price matrix is shown in Table 1.

first market segment	second market segment	third market segment
$\begin{bmatrix} -0.0359 & 0.0144 \\ 0.0144 & -0.0317 \end{bmatrix}$	$\begin{bmatrix} -0.1004 & 0.0305 \\ 0.0305 & -0.0938 \end{bmatrix}$	$\begin{bmatrix} -0.0513 & 0.0234 \\ 0.0234 & -0.0447 \end{bmatrix}$

Table 1 Matrix of segment market

In addition, according to the consideration of the power supply cost of the power system in the region, the lower limit of the electricity price during the valley period is set at \$0.307(/kWh).

3.2 Result Analysis

The obtained data are processed to obtain the values of the relevant parameters in the formula (5), (6), (8), (9), (10), (11) in each subgroup. Use MATLAB to edit the particle swarm algorithm program to solve the optimization model. The output results of the three-type subgroup market segmentation optimization model correspond to the optimal peak-valley time-of-use electricity price under the third-grade tiered electricity price, and the specific results are shown in Table 2.

Tier	Peak hours(\$/kWh)	Valley hours(\$/kWh)	Average electricity price(\$/kWh)
First tier	0.5551	0.4347	0.4807
Second tier	0.5995	0.4923	0.5309

Third tier	0.9025	0.7123	0.7812

Table 2 Optimal multi-step TOU tariff results

Tier	Peak hours electricity price($/kWh)	Valley hours electricity price($/kWh)	Peak hours average load (Kw)	load peak-to-valley difference (Kw)
First tier	0.4900	0.4900	4414.30	1790.00
	0.5551	0.4347	4386.13	1740.43
Second tier	0.540	0.5400	1718.52	613.18
	0.5995	0.4923	1658.10	540.60
Third tier	0.7900	0.7900	1313.11	408.96
	0.9025	0.7123	1300.50	389.37

Table 3 Comparison of implementation effect of TOU tariff

To show the effect of the optimal peak-valley time-of-use electricity price for each step listed in Table 3 on the user load curve in terms of “reducing peak load”, “shaving peaks and filling valleys”, etc. Compare the original tiered electricity prices for peak-valley time-of-use price adjustment (comparison on the user sample set).

Analysis of Tables 2 and 3 shows that:

(1) After the implementation of the peak-valley time-of-use electricity price for the three-stage ladders, the average electricity price level is maintained near their respective current ladder electricity prices (as shown in Table 3), and the maximum floating amount is only \$0.0093/kWh. This shows that, on average, the implementation of the peak-valley time-of-use electricity price has not seriously changed the level and structure of the original tiered electricity price, thus ensuring that each tiered price after the peak-valley time-sharing does not cover the electricity consumption of residents in the area. Significant changes will occur, and the various roles played by the current tiered electricity price system will not be lost due to the reasonable peak-valley time-of-use price adjustment for each tier.

(2) As far as the electricity price in each step is concerned, the indicators such as the load peak-valley difference before and after the peak-valley time-of-use price adjustment have been improved to a certain extent (as shown in Table 4). That is to say, the time-of-use electricity price of each step peak and valley plays the role of "reducing the peak load" and "cutting the peak and filling the valley" on the load curve.

(3) If the dual objective function in the model is changed to a single objective function of load peak-valley difference minimization (or peak load minimization), the time-of-use electricity price of each step peak and valley output by the model can play a better role in "cutting peaks and filling valleys" (or "Reduce Load") effect.

To sum up, setting the peak-valley time-of-use electricity price reasonably on the basis of the tiered electricity price can effectively improve the shape of the load curve of users in the corresponding sub-group segments while ensuring the full play of the functions of the original tiered electricity price. , so as to further improve the power supply reliability, power quality and grid load rate of the power grid, and guide residential users to consume electricity reasonably.

3.3 Sensitivity analysis

(1) Demand response of residential peak-valley time-of-use electricity prices

Considering the lack of historical data accumulation in China's residential electricity demand elasticity research, through user surveys and comparison with historical data from other provinces and cities, the predicted electricity price matrix values for residential households in each sub-group segment must have a certain degree of variance. error. Therefore, it is necessary to conduct a single-factor sensitivity analysis on the final output of the optimal electricity price system results according to the changes in the response law of the peak-valley time-of-use electricity price by residents in each market segment (taking the individual changes of e_{pp} and e_{pv} as an example to carry out a single-factor sensitivity analysis).

e_{pp} rate of change		-10%	-5%	0	5%	10%
First tier	Peak price	0.5394	0.5453	0.5551	0.5828	0.6042
	Valley price	0.4401	0.4379	0.4347	0.4007	0.3518
Second tier	Peak price	0.5831	0.5890	0.5995	0.6348	0.6753
	Valley price	0.5002	0.4965	0.4923	0.4619	0.4401
Third tier	Peak price	0.8944	0.8993	0.9025	1.0362	1.1438
	Valley price	0.7150	0.7136	0.7123	0.6743	0.6447
e_{pv} rate of change		-10%	-5%	0	5%	10%
First tier	Peak price	0.5602	0.5586	0.5551	0.5519	0.5498
	Valley price	0.4294	0.4326	0.4347	0.4357	0.4385
Second tier	Peak price	0.6102	0.6054	0.5995	0.5807	0.5731
	Valley price	0.4884	0.4907	0.4923	0.4976	0.5029
Third tier	Peak price	0.9158	0.9094	0.9025	0.8977	0.8906
	Valley price	0.7078	0.7100	0.7123	0.7145	0.7163

Table 4 Sensitivity analysis of dem

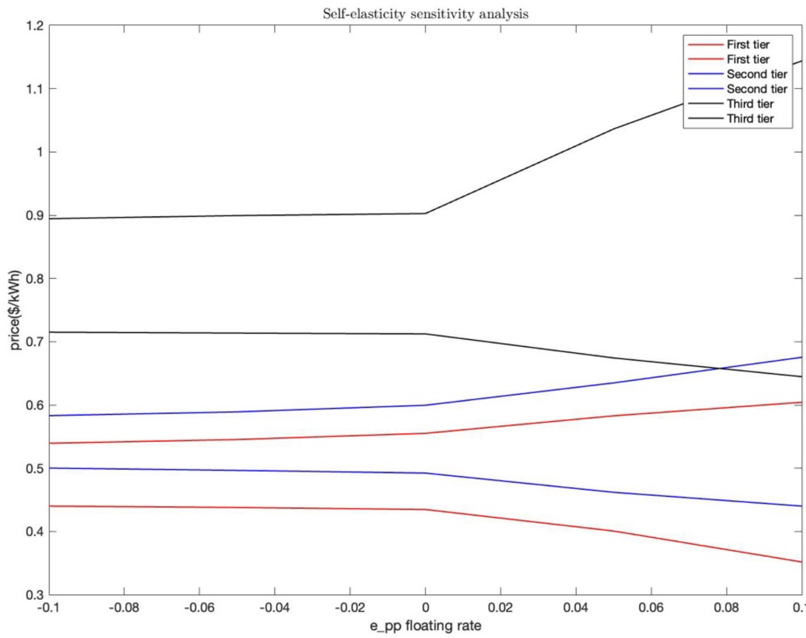

Fig3 Self-elasticity sensitivity analysis

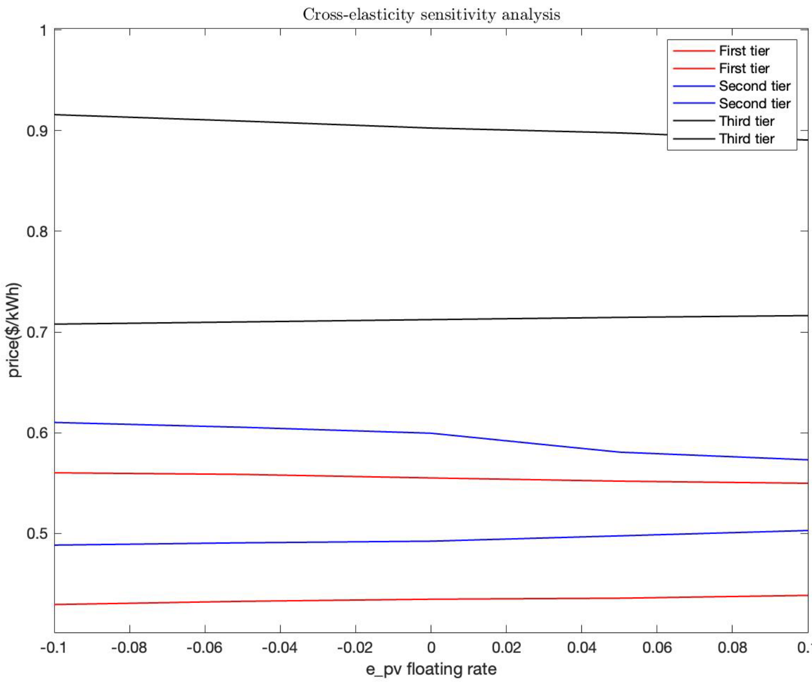

Fig4 Cross-elasticity sensitivity analysis

From the analysis of Table 4, it can be seen that (i) for self-elastic e_{pp}, the lower the value is, the smaller the peak-valley price difference is in each optimal plan output by the model, and vice versa, the greater is the peak-valley price difference. The elasticity value shows a monotonically increasing relationship; (ii) for the cross elasticity e_{pv}, the lower the value is, the greater the peak-valley price difference in each optimal plan output by the model, and vice versa, that is, the peak-valley price difference It has a monotonically decreasing relationship with the value of cross elasticity. (As shown in Figure 3, 4)

From the comparison of Figures 3 and 4, it can also be seen that the time-of-use price of the ladder peak and valley is more sensitive to the change of the self-elastic e_{pp}.

(2) The weight of the objective function

The previous method for simplification of the dual objective function is to assign a weight of $1/2$ to both optimization objectives in the formed comprehensive objective function. However, in practice, price makers can flexibly adjust the weight distribution between the two optimization objectives according to their own needs. Suppose the weight given to the objective function formula (5) is $\lambda(\lambda \in [0\ 1])$, and Table 5 shows the sensitivity analysis results of the first step ladder time-of-use electricity price as an example.

λ		0	0.25	0.5	0.75	1
First tier	Peak price	0.6296	0.5897	0.5551	0.6154	0.6733
	Valley price	0.3214	0.3782	0.4347	0.4029	0.3759

Table 5 Sensitivity analysis of λ

4. Conclusions

(1) Based on the original tiered electricity price, it is reasonable and feasible to divide the residential users into corresponding sub-group market segments and establish an optimization model in each segmented market to solve the optimal peak-valley time-of-use electricity price under each tier. of. If the objective function and constraint conditions are set reasonably in the model, based on ensuring that the original tiered electricity price can solve the price cross-subsidy and improve the energy utilization efficiency, it can be further realized through the setting of the peak-valley time-of-use electricity price. The purpose of optimizing the shape of residential electricity load curve, cutting peaks, and filling valleys, alleviating power tension, increasing load rate, improving power grid security and economy, and enhancing the operating efficiency and stability of the power system.

(2) It can be seen from the sensitivity analysis that the user's demand response law is very important to reasonably calculate the optimal peak-valley time-of-use electricity price for each ladder. In the absence of historical data on peak-to-valley electricity price elasticity of user demand, it is necessary to obtain relatively real corresponding data through a large sample survey of corresponding residential user groups.

(3) The model method constructed in this paper can also be extended to the problem of designing time-of-use electricity prices for peak, flat and valley periods based on the solution of electricity prices. From the perspective of the implementation effect, there is no obvious difference between the first step and then the peak valley pricing, or the first peak valley and then the step pricing. However, the order in which the two prices are formulated is different, which will lead to significant differences in the specific model process.

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