Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 2469 – 2482

doi:10.3906/elk-1402-74

Residential electricity pricing using time-varying and non-time-varying scenarios: an application of game theory

Najmeh KHALEGHI FAR[1], **Hamid AMADEH**[2], **Mohammad Hossein REZAEIAN KOOCHI**[3,*]
[1]Department of Energy Economics, Power and Water University of Technology, Tehran, Iran
[2]Faculty of Economics, Allame Tabataba'i University, Tehran, Iran
[3]Department of Electrical Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

Received: 08.02.2014 • **Accepted/Published Online:** 19.08.2014 • **Final Version:** 15.04.2016

Abstract: The aim of this work is to analyze and describe the interaction between a residential consumer and the power network. With the growth of power systems and the advent of new energy sources, such as solar energy, it seems to be more essential to investigate how the network and the consumer can interact with each other to achieve more financial benefits. To do that, a static game is defined considering the fact that there is a direct relationship between the amount of load shifted by the consumer and the incentive offered by the network. It is concluded that the Nash equilibrium of this game is when the consumer decides to cooperate with the network during non-peak hours. Finally, a simple optimization problem is defined in which both the consumer and power network try to achieve better financial benefit considering the fact that in the real world the total load of a typical residential consumer can be divided into the flexible and inflexible parts. A time-varying pricing scenario as well as time-of-use and constant pricing scenarios is used. It is concluded that the more convenient scenario for the consumer is the time-of-use scenario, whereas the power network would prefer to use a dynamic one as it leads to more financial benefit.

Key words: Energy pricing, game theory, Nash equilibrium, residential consumer, energy consumption optimization

1. Introduction

Correct and rational use of energy and its products is associated with human behavior. Considering this issue, different solutions have been proposed to minimize the amount of energy consumption, such as environmental design, enforcement by the government, and use of modern technologies. However, many experts believe in voluntary energy saving by consumers as the best way to achieve efficient use of energy. Thus, many works have focused on finding ways for encouraging people to reduce their total use of energy.

In the case of electrical energy consumption optimization, both the consumer and the energy provider should be taken into account. This means that it may be useful to know the amount of consumer demand during each daily or monthly period and also the mechanism used for electricity pricing by the energy provider during these periods.

Economic efficiency is one of the main goals of energy pricing and is considered in determining electricity tariffs. Each consumer should pay the cost that is imposed to the network to provide electricity. Since electricity is considered as a commodity that should be produced and sold from the perspective of the consumers and the network respectively, different economic theories can be used for electricity pricing based on the economic efficiency criterion. According to this criterion, the marginal cost of producing goods or services is used as

---

*Correspondence: mh_rezaian@yahoo.com

the basis of the pricing procedure. Therefore, it may seem rational to use the long-term costs as the basic criterion for electricity pricing. If so, all consumers are not charged with a same electricity price, i.e. each consumer's energy payment is different and is proportional to the cost that is imposed to the power system by him. However, there are some challenges such as the variation of electricity production during peak and non-peak hours that make policy makers use the average cost of energy consumed during a prespecified time period instead of marginal cost. Therefore, it is reasonable to consider electricity as a commodity and manage its consumption using economical concepts and methods.

Many studies have been published on the energy pricing issue and the basis of almost all of them is time-varying pricing methods. In [1] the market clearing price was estimated a day ahead. In [2] and [3], game theory and the behavior of price suggested by other companies were proposed respectively for choosing the optimal pricing strategy. The real-time pricing method is one of the best appropriate approaches for peak-shaving and load-shifting, which was investigated in [4–7]. Doostizadeh and Ghasemi in [8] determined real-time prices by solving an optimization problem based on maximizing the benefit of the energy provider, while [9–11] used the detailed data of residential consumers to investigate the effect of daylight savings time on electrical energy consumption. In [12] it was also shown that in the electrical energy market in Sweden, consumers had shifted their consumption to non-peak periods in accordance with the real-time pricing signals. In [13] energy provided from renewable sources such as solar energy was emphasized and electricity generation from photovoltaic panels according to different tariffs related to different daily hours was studied. Furthermore, [14] showed that two important factors that determine the amount of residential consumption are climate conditions and building characteristics. It was also remarked in this study that freezers and refrigerators determine the amount of base load of a residential consumer, while high consuming appliances such as electrical heaters and air conditioners are related to the peak load consumption. On the other hand, the time-of-use (TOU) pricing strategy, which is one of the most common methods of demand-side management, was investigated in [15–18]. In [19] it was shown that households are significantly price-elastic from the statistic point of view and they respond to real-time pricing scenarios by shifting their energy consumption from peak hours. In [20] the effect of rebound of urban residential electrical energy consumption in China using a linear approximation of the almost ideal demand system model was investigated. It showed that the effect of rebound after the implementation of increasing-block electricity tariff policy was improved. In [21] it was shown how technologies can affect the consumer willing to accept the real-time pricing methods. In [22] it was also demonstrated that pricing as a function of demand variability, which is called first derivative ratio pricing, has advantages over the TOU pricing method. In [23–25] the existing potential of residential demand response aiming at greenhouse gas reduction was investigated, and [26–29] also used different pricing strategies for peak and non-peak hours to smooth the household load curve.

Despite this interest in the field of electrical energy pricing, most previous works only focused on the formulization of real-time pricing methods in the form of mathematical equations. However, a neglected issue is that almost none of these papers considered the related concepts of this field all together, such as the relationship between the incentive offered by the power network and the amount of load shifted by the consumer, the type of the consumer's load, or the equilibrium point when both the consumer and power network decide to take part in a game. This paper tries to analyze some of these concepts and bring them together. This paper also investigates which types of pricing methods will lead to the best financial benefit for the consumer and the power network in the electrical energy market of Iran. To do that, the prices enacted by the Ministry of Energy of Iran are used.

In this paper, 3 different pricing methods including constant and time-varying ones and related approaches are investigated. First the relationship between the incentive offered by the network and the amount of shifted load is described. The behavior of a typical residential consumer against different prices during peak and non-peak hours determined by the network is then analyzed in the form of a static game. In the next section, the collaboration of both the consumer and the power network is illustrated and finally numerical results are presented.

2. Incentive offering and load shifting

In order to make our analyses practical, we can introduce the pay-off functions for each participant. This was fully detailed in [30]. In [30] both the power network and the consumer have their own pay-off functions, and an additional cost function is also introduced, which is related to the amount of energy consumption shifted to another time period per kWh. As described in [30], this kind of cost function should have 4 special characteristics: 1) its first derivative should be positive for positive x, 2) its second derivative should also be positive, 3) it should have a vertical asymptote, and 4) it should be equal to zero at $x = 0$. These characteristics will make the cost function more practical. It should be noted that x is the amount of shifted load. Furthermore, the vertical asymptote is used because the amount of load that the consumer can shift is limited to a due to the physical conditions. Considering these characteristics, it may be possible to use a logarithmic cost function as in [30] or an exponential one as below.

$$f(x) = \frac{e^{a} - e^{(a-x)}}{a-x} \tag{1}$$

Although this is not the case, it should be noted that in the above formula choosing the amount of a is arbitrary and is related to the physical conditions of the consumer. Other parameters that should be considered are the network's benefit obtained through load shifting and the incentive payment per unit of the shifted load. In [30] the authors showed that, from their mathematical point of view, when there is no incentive payment there will be no load shifting. On the other hand, the consumer will decide to shift some parts of his load when the incentive offered by the network or the energy provider is more than zero. Interestingly, this relationship shows that the amount of incentive offered by the network affects the amount of shifted load positively. Although this fact is obvious, it should be noted that this is obtained from a mathematical point of view considering several assumptions, which makes the results more practical.

3. Static game

Considering the relationship between the offered incentive and the shifted load, which was described in the last section, a static game is formed in which the consumer and the power network are players. These players and their strategies are defined as follows.

3.1. Players of the game

Network: In this paper, the Iran Grid Management Company is considered as the network and is represented in the formulas as *NET*. The grid manager or the network has a duty to transfer the electricity from the supplying point to the delivery point. The transition of energy is in fact the injection of the electricity into the grid at a point (point of supplier) and receiving the reduced amount of energy due to the losses at another point (point of consumer).

Household (residential consumer): The residential consumers (natural persons) have all or part of their required electricity supplied by one or more electricity providers and receive it through the power network. In this paper, the household is represented by C. Refrigerators, freezers, heating and cooling systems, and other appliances, such as washing machines, form the major part of this kind of consumer load.

3.2. Strategies of players

Network: Buying and selling electricity, energy market management, organizing the transmission of information between suppliers and consumers, and the associated financial needs are done by the grid management company (GMC), which in this paper is named as the market manager or grid manager. The market manager can determine different prices for selling electricity per kWh in peak and non-peak periods. The network thus has 2 strategies: determining the price of electricity during peak hours (λ) and during non-peak hours (v). The set of strategies can be shown as below.

$$S_{NET} = \{\lambda, \nu\} \tag{2}$$

Household: The residential consumer reacts to the high prices determined by the GMC during peak hours in 3 ways. These are: 1) reducing the consumption and not shifting the amount of reduction to non-peak hours, 2) reducing the consumption and shifting the amount of reduction to non-peak hours, and 3) self-generation of electricity. The disadvantages of these 3 ways are losing social welfare, needing further scheduling, and additional costs due to the fuel and maintenance of generators, respectively.

If the benefits of reduction of consumption during peak hours exceed the costs generated, the households will reduce their consumption. Otherwise, they will be indifferent to the high prices assigned for peak hours and no reduction in their consumption will happen. The household strategies can be written as cooperation with the GMC (Q) or disassociation from it (μ).

$$S_C = \{\mu, Q\} \tag{3}$$

3.3. Payoffs of the game

The game is stationary because the second player (the consumer) does not have any knowledge about the prices of electricity suggested by the GMC during peak and non-peak hours, but he knows that prices during peak and non-peak hours are high and low, respectively, and also there is no other information about the exact prices. Therefore, as will be described later, this situation will lead to the shifting of load from peak hours to non-peak hours.

In conclusion, 4 possible situations according to both players' strategies are as follows:

- Situation 1: The network chooses strategy λ and the consumer chooses strategy μ.
- Situation 2: The network chooses strategy v and the consumer chooses strategy μ.
- Situation 3: The network chooses strategy λ and the consumer chooses strategy Q.
- Situation 4: The network chooses strategy v and the consumer chooses strategy Q.

This game can then be defined in the following form:

a) Set of players

$$N = \{NET, C\} \tag{4}$$

b) Set of strategies related to each player

$$S_C = \{Q, \mu\} S_{NET} = \{\lambda, \nu\} \tag{5}$$

c) Set of 4 possible situations

$$S = S_{NET} \times S_C = \{\lambda, \nu\} \times \{Q, \mu\} = \{(\lambda, Q), (\nu, Q), (\nu, \mu), (\lambda, \mu)\} \tag{6}$$

d) Payoffs for each player: since in this game there are 2 players with independent strategies, the payoffs for each of them is ranked in the range of 1 to 4 as shown in Table 1.

Table 1. Player's payoffs.

$U_{NET}(\lambda, \mu) = 1$	$U_C(\lambda, \mu) = 1$
$U_{NET}(\nu, \mu) = 2$	$U_C(\nu, \mu) = 3$
$U_{NET}(\lambda, Q) = 3$	$U_C(\lambda, Q) = 2$
$U_{NET}(\nu, Q) = 4$	$U_C(\nu, Q) = 4$

Elements of S show all the situations that are the combinations of the strategies of both players. The aim is to find the combination of strategies that leads to the best payoff for each player. This is called the equilibrium point of the game. It should be noted that in this game both players are assumed to be rational, i.e. whatever the other player chooses, none of them will choose the strategy that leads to less benefit for themselves. Another assumption is that there is no collusion behavior between the network and the consumer. The payoffs are shown in Table 2.

Table 2. Player's payoffs in the strategic form of the game.

		GMC	
		λ	ν
Household	μ	1.1	3.2
	Q	2.3	4.4

There are 2 numbers in each cell of Table 2. The left and right numbers represent the payoffs of the consumer (C) and the grid manager (NET), respectively. It should be noted that, according to game theory, there might be one or more answer for a typical game, which are called the Nash equilibrium points of the game. Furthermore, Nash equilibrium is reached when both players play rationally. This means that first each player should choose the strategy that leads to the best payoff for him according to the strategy that is chosen by the other player, and secondly each player should have a correct preassumption about the strategy that the other player may choose. Accordingly, in this paper, there is only one Nash equilibrium point for the game described in Table 2, as below.

$$N(G) = \{(S^*_{NET}, S^*_C) : (\nu, Q)\} \tag{7}$$

According to Table 2, the payoff for each player that leads to Nash equilibrium is 4. In Table 2, the best payoff for each player is underlined and, as can be seen, Nash equilibrium occurs when the consumer and the grid manager choose strategies Q and v, respectively. Choosing strategy v by the grid manager means that he decides to apply low prices during non-peak periods in order to decrease the cost of electricity generation. In fact, this is an incentive for households to shift their load from peak hours to non-peak hours and therefore the energy demand during peak hours will decrease. On the other hand, choosing strategy Q by the consumer also means that the best strategy for him is to shift his load from peak hours to non-peak hours according to prices suggested by GMC. It can be concluded that Nash equilibrium of this game occurs when the grid manager suggests a price for non-peak periods and the consumer decides to cooperate with him.

Until now, it was concluded that there is a positive relationship between the amount of load shifted by the consumer and the incentive offered by the network, and also the best strategy for the consumer is to cooperate with the network. These facts, which were obtained from a mathematical point of view, exist in the real world and any rational consumer or grid manager will choose these strategies when meeting these situations.

4. Energy consumption optimization problem

In this section, it is assumed that both the consumer and the power network are in the equilibrium point of the game, which means that the consumer decides to cooperate with the network during non-peak hours. This was described in the last section. Considering this assumption, a simple optimization problem is defined in which the network tries to maximize his financial benefit, whereas the consumer is interested in minimizing his cost. To make this optimization problem more practical, it is also assumed that a part of the total load of a residential consumer is flexible and the remainder part is considered as inflexible. This is because there are many appliances in a typical house that can be divided into 2 groups: those that should be plugged in daily and have a fixed energy consumption, such as refrigerators, and those that are used occasionally or those that have flexible energy consumption, such as washing machines or several types of cooling and heating systems. In fact, the inflexible part of total load is constant and the consumer has no ability to change the amount of it or to shift the hourly consumption from one hour to another one.

4.1. Network optimization problem

In the formulation of the network optimization problem both flexible and inflexible loads are included as the network's revenue. On the other hand, the GMC or the network should buy the amount of energy demanded by the consumer from the energy providers (power stations). This is considered as a cost in the optimization problem. The cost function of the power network that should be maximized for a period of $N_m = 24$ h is as below.

$$f_{NET} = \sum_{t=1}^{N_m} \left[p_t^s \left(l_t^f + l_t^i \right) - p_t^k E_t^k \right] \tag{8}$$

Here, p_t^s and p_t^k are the price of energy charged to the consumer and the price charged to the GMC from energy providers, respectively. l_t^f and l_t^i represent the amount of flexible and inflexible load, whereas E_t^k is the energy purchased by GMC. It should be noted that p_t^s is the only variable that should be optimized in the optimization problem of the network during a prescribed period of time. In this paper, the energy optimization problem is considered between a single residential consumer for which the consumption will not exceed several kW and a power network for which its duty is to provide the energy demanded by this consumer. Since in this paper there is not a wide perspective on the problem, i.e. there is just one single residential consumer, the optimization problem is a simple one, and no constraint on power balance between load and energy purchased by GMC is included. In this model, it is assumed that both players had agreed on the maximum, minimum, and average value of the energy price for every 24 h. These are formulated as follows.

$$\forall t \in m \qquad p_t^s \geq p_{\min} \tag{9a}$$

$$\forall t \in m \qquad p_t^s \leq p_{\max} \tag{9b}$$

$$\frac{1}{24}\sum_{t=1}^{24} p_t^s = p^{AVG} \tag{9c}$$

Here, p_{min} and p_{max} are the minimum and maximum price charged to the consumer, respectively, whereas p^{AVG} is the average daily price. The first constraint shows that the price suggested by the power network should be placed within the range $[p_{\min},\ p_{\max}]$. The second constraint describes that the power network should consider low prices during some periods to keep the average value fixed. In the absence of this constraint, the power network has no obligation to choose low prices and will prefer high prices for all the day.

4.2. Consumer optimization problem

As described in the first paragraph of this section, the consumer has the ability to shift only the hourly consumption of the flexible part of his load. In this paper, a heat pump is considered as the flexible load. This kind of load consists of a heating pump, a condensed tank, and the floor heating pipes, which are used to keep the indoor temperature of the room within the comfort band. This kind of load and its characteristics and the associated dynamic model were fully described in [31]. In this model, first the state space model of the heating system is defined, and then the discrete form of the state model is used as the constraints of the optimization problem. The objective function of the consumer optimization problem that should be minimized is as below.

$$f_C = \sum_{t=1}^{N_m} \left[p_t^s l_t^f + \lambda \varphi_t \right] \tag{10}$$

In the above formula, φ_t and λ represent the deviation from the comfort band and the associated penalty, respectively. It should be noted that l_t^f and φ_t are the variables that should be optimized. This objective function consists of 2 terms. The first one is the cost that the consumer should pay to the GMC for the consumption of energy during the simulation period. The second one is the penalty that enforces the consumer to keep the temperature of the room within the reference band. Three groups of constraints are also defined for this optimization problem.

$$T_t^i = a_{11}T_{t-1}^i + a_{12}T_{t-1}^f + a_{13}T_{t-1}^w + b_1 l_{t-1}^f + e_1 T_{t-1}^o \tag{11a}$$

$$T_t^f = a_{21}T_{t-1}^i + a_{22}T_{t-1}^f + a_{23}T_{t-1}^w + b_2 l_{t-1}^f + e_2 T_{t-1}^o \tag{11b}$$

$$T_t^w = a_{31}T_{t-1}^i + a_{32}T_{t-1}^f + a_{33}T_{t-1}^w + b_3 l_{t-1}^f + e_3 T_{t-1}^o \tag{11c}$$

$$l_t^f \geq l_{\min}^f \tag{12a}$$

$$l_t^f \le l_{\max}^f \tag{12b}$$

$$T_t^i + \varphi_t \ge T_{t,\min}^i \tag{13a}$$

$$T_t^i - \varphi_t \le T_{t,\max}^i \tag{13b}$$

$$\varphi_t \ge 0 \tag{13c}$$

Here, T_t^i, T_t^f, T_t^w, and T_t^o are the indoor temperature, floor temperature, water tank temperature, and outdoor temperature, respectively. $T_{t,\min}^i$ and $T_{t,\max}^i$ represent the minimum and maximum of indoor temperature, and $l_{\min}^f$ and $l_{\max}^f$ are the minimum and maximum amounts of flexible load. Eqs. (12a)–(12c) represent the constraints obtained from the state space model of the heating system. Eqs. (13a) and (13b) state that the energy consumption of the heat pump should stay within a lower and upper limit. Eqs. (14a) and (14b) also describe the conditions in which the temperature room may deviate from the comfort band. If so, an additional cost ($\lambda\varphi_t$) is added to the cost of energy consumption.

4.3. Pricing methods

In order to analyze the interaction between the network and the consumer, 3 scenarios are used for pricing. These scenarios are called constant, TOU, and dynamic pricing, and they are fully described in the next subsections.

Constant pricing scenario: In this scenario, the GMC guarantees to provide the required electricity for the consumers with a constant price. On the other hand, the GMC should buy this amount of energy from the energy providers with a variable price. This kind of pricing might be favorable for those consumers who cannot forecast their hourly consumption, those who are not interested in taking risks, and those who have low energy consumption. It should also be noted that there is no interaction between the consumer and the network in this scenario, and therefore the network optimization problem is not included.

TOU pricing scenario: This pricing method uses different prices for different periods. In this method the 24 h of a day are split into peak, flat, and valley hours according to the daily recorded consumption of a residential consumer, and then 3 different prices are allocated for these periods. Therefore, in comparison with the constant pricing method, the consumer takes some of the risk of energy management. Using this method, the consumers become more interested in consuming energy during non-peak hours because of the associated low prices. In fact, those consumers for whom most of the energy consumption occurs during non-peak periods or consumers that have the ability to shift their load to low price periods can get more benefits from this kind of pricing. As a result, like in the constant pricing scenario, in this scenario the network optimization problem will not be included.

Dynamic pricing scenario: The third kind of pricing method and the most interesting one is called dynamic pricing, in which the GMC suggests different energy prices for every hour of the day. In the other words, prices change hourly and both players, i.e. the grid manager and the consumer, have an active role in the energy market.

It should be noted that in the case of a dynamic pricing scenario, the average value of the prices for every 24 h should be constant and equal to the value of the constant pricing scenario. This is important because this constraint forces the network to consider low prices for some periods. Without this limitation it is reasonable that the power network suggests high prices to the consumer all the time. Furthermore, making a comparison between 3 scenarios is possible in this way.

4.4. Results and discussion

Figure 1 shows the prices of energy that are charged to the GMC by the energy providers. These chosen prices are available from the website of the Iran Grid Management Company, pertaining to 28 January 2011, which is a winter day. This is because, in this paper, a heat pump that is used to keep the buildings warm is considered as the flexible load, and so a winter day is chosen for simulations. In this paper, 20% of total load in each hour is considered to be flexible, i.e. the consumer can shift all or part of this load to the next or previous hours if necessary. After obtaining the total load from the website of the Iran Grid Management Company, 80% of this load is considered as the inflexible or constant part of the load and is illustrated in Figure 2. It should be noted that the total load available from this website pertains to the total consumption of all consumers in Iran including residential, commercial, and industrial consumers in each hour. Therefore, the share of the residential section is obtained by multiplying the total load by 0.3087. The energy consumption of every single residential consumer is then obtained by dividing the total consumption of the residential section by 22,216,000. These numbers are obtained by the Ministry of Energy of Iran and are available on the website of the Iran Grid Management Company (http://www.igmc.ir/en/).

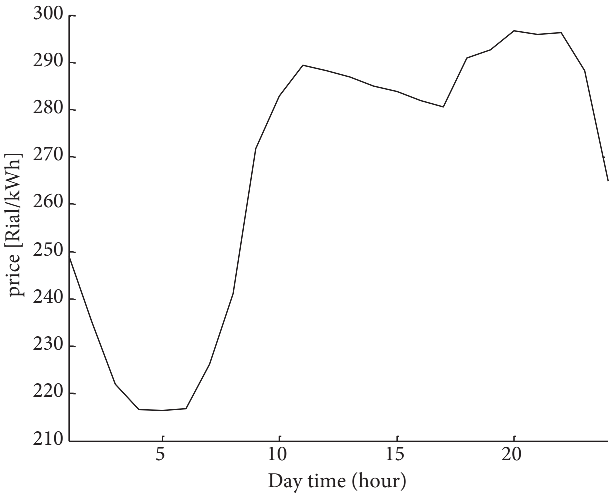

Figure 1. Hourly prices that are charged to the grid manager.

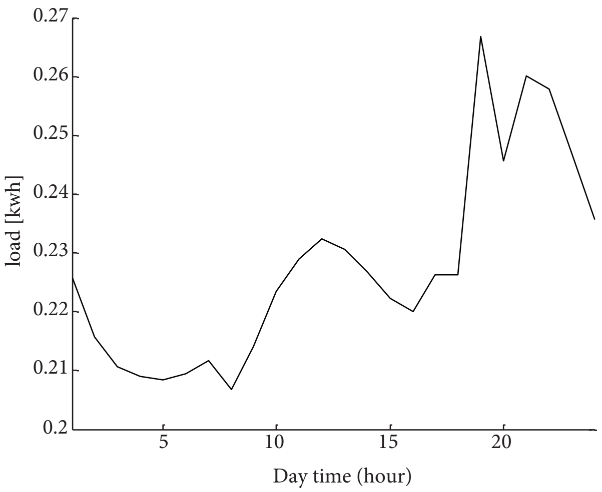

Figure 2. Residential consumer hourly load curve.

During non-peak hours the energy consumption is low, and so the cost of electrical energy generation is low due to the using of a combined cycle power plant for providing electrical energy. On the other hand, during peak hours where energy demand is high, the energy providers have to use low-efficiency power plants, such as natural gas-fired power plants, to provide the additional required energy. Therefore, the cost of generating electrical energy will increase, and as a result the price of energy delivered to consumers will also increase. As shown in Figures 1 and 2, the price of electrical energy is high and low during peak and non-peak hours, respectively. Furthermore, it should be noted that, in this paper, the amount of parameters needed for the objective function and the constraints of the consumer optimization problem are the same as those defined in [31].

Constant pricing scenario: As described in the last section, in this scenario the price of energy charged by the network is considered to be constant during the simulation period. In this paper, the price of energy is set to the value of 485 rial/kWh. It should be noted that the rial is the basic monetary unit of Iran. The amount of flexible load in each hour is shown in Figure 3. It can be seen that there is no significant difference between the minimum and maximum amount of flexible load during 24 h. In fact, because there is no financial incentive for the consumer due to the constant price suggested by the network, he has not decided to apply any shift in his energy consumption and has preferred to choose an approximately constant consumption.

TOU pricing scenario: In this kind of pricing method, the grid manager suggests 3 prices for peak, valley, and flat periods. In this paper, it is considered that the consumption is charged at 785, 485, and 335 rial/kWh during peak, flat, and valley periods, respectively. These prices are the same as those suggested by the Grid Management Company of Iran to be applied to the residential consumers. It should also be noted that, in this paper, the first 8 h of the day (24–8) are considered as the valley period where the consumption is low, the next 12 h (9–20) constitute the flat period, and the last 4 h (21–24) are the peak period. As can be predicted, this scenario can provide incentive for the consumer to shift his load from peak hours to flat or valley hours and therefore reduce his energy consumption cost. Figure 4 shows the amount of flexible load for each hour. It can be seen that the consumer has shifted a big part of his load to the first hours of the simulation period where the energy prices are low. It should be noted that, because there is a need to keep the room temperature within the comfort range, it is obvious that there should be a little consumption during peak hours. In this scenario the consumer consumes the same amount of energy as in the constant scenario, but reduces the cost that should be paid to GMC.

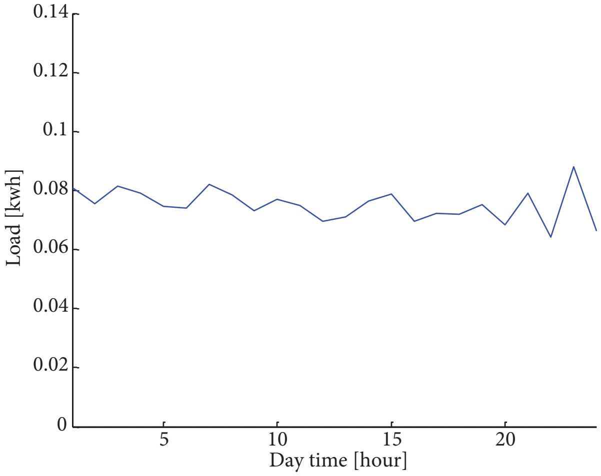

Figure 3. Flexible load curve obtained in the case of constant pricing scenario.

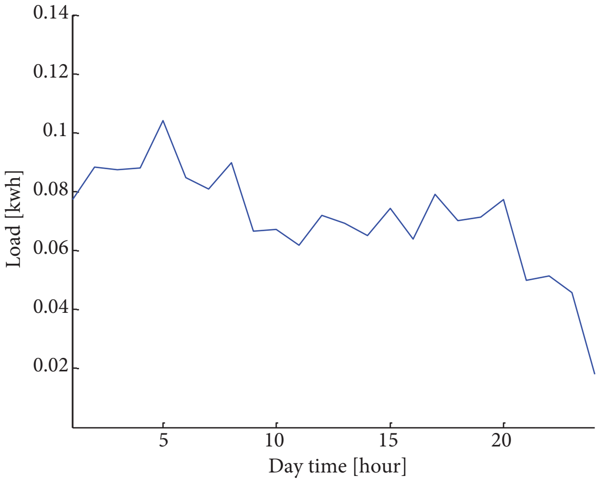

Figure 4. Flexible load curve obtained in the case of TOU pricing scenario.

Dynamic pricing scenario: In the dynamic pricing scenario, the consumer tries to adjust his hourly consumption to the prices suggested by the network. On the other hand, the grid manager wants to maximize his revenue in accordance with the hourly energy consumption of the consumer. As described in Section 4.1, in this scenario the average value of the energy price should equal the price suggested in the constant pricing scenario. On the other hand, an amount of p_{min} and p_{max} equal to the minimum and maximum amount of prices is suggested by the network in the case of the TOU pricing method. Figure 5 shows the hourly prices charged by the grid manager in the dynamic pricing scheme. It can be seen that there are several hours with low prices in the peak period and also several hours with high prices in the valley period. In fact, in this scheme the

GMC has suggested some low prices in the peak period to provide an incentive for the consumer to encourage him to consume a part of his required energy during peak hours. However, it should be noted that the average price in the peak period is still greater than the prices in the valley and flat periods, and also the average value of all prices in the 24-h simulation period is the same as the price in the constant pricing case.

Figure 6 shows the hourly flexible load consumption. It can be seen that the amount of consumption in each hour is related to the price suggested by the network, i.e. when the price is low the consumption is high, and vice versa. As mentioned before, in this paper just a single residential consumer is considered, whose electrical energy consumption will not exceed several kW. In the case where there are a group of residential consumers with different types of appliances, the hourly prices suggested to each of them by the network and also their load curves will differ from each other. On the other hand, the total load curve is obtained by combining the load curves of all consumers. In this way, the sharp rise and decline between successive hours, which is shown in Figure 6, will be mitigated.

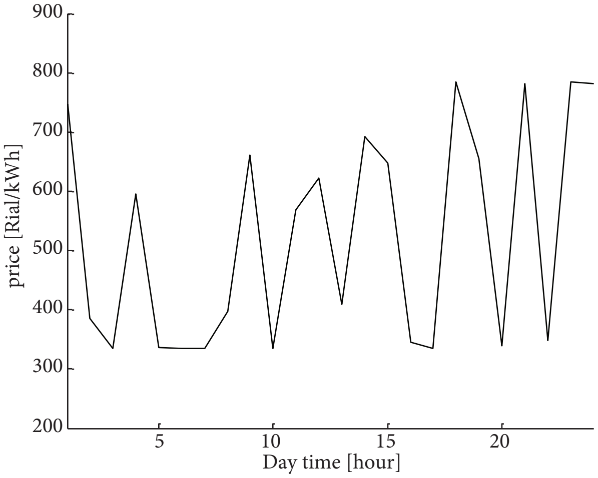

Figure 5. Hourly prices suggested by the network in the case of dynamic pricing scenario.

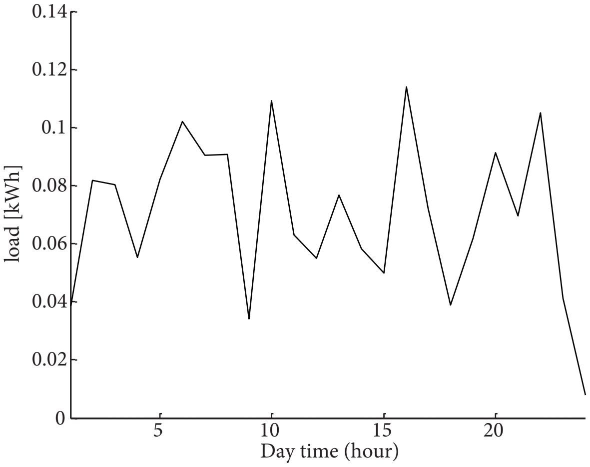

Figure 6. Flexible load curve obtained in the case of dynamic pricing scenario.

4.5. Numerical results

Figure 7 shows the results obtained for the consumer. It should be noted that the consumer's cost is equal to the grid manager's revenue. According to Figure 7, in the case of the dynamic pricing scenario, the total cost of buying energy from the network is maximum for the consumer. On the other hand, the TOU pricing scenario results in the minimum cost. In fact, the cost of required energy for the flexible part of the total load is maximum in the constant pricing scenario and minimum in the dynamic one. Therefore, it can be concluded that the consumer has succeeded in minimizing his cost through shifting a part of his flexible load to the periods with lower prices. It may thus be better for him to enter the contract with the network based on the TOU or dynamic pricing.

According to Figure 7, the consumer has a daily cost of 3454.1256 rial in the case of the TOU pricing scenario, which is the most cost-effective one among these 3 scenarios. Therefore, he is to pay 103,623.768 rial per month (30 days). Since electricity bills are issued every 2 months in Iran, this kind of consumer will receive a bill for 207,247.536 rial for 2 months. It should be noted that almost 90% of residential consumers had to pay 200,000 to 300,000 rial per month in 2012, which shows that our results are rational. In the same way, the cost of energy for the consumer will be 219,681.696 rials in the case of dynamic pricing for a 60-day period. As a result, the maximum and minimum amount that should be paid by the consumer is 207,247.536 Rials and 219,681.696 Rials in the cases of TOU and dynamic pricing scenarios, respectively.

It may be useful to see how these different pricing methods can affect the network's benefit. This is shown in Figure 8. It can be seen that in the case of the dynamic pricing scenario, both the cost and revenue of the network is higher in comparison with the other scenarios. Considering the fact that the network's revenue is the consumer's cost, we can observe that the total benefit is considerably higher again in the case of the dynamic pricing method. On the other hand, the TOU pricing method has led to less revenue and benefit for the network, and therefore it might be concluded that this type of pricing is the least profitable scenario for the network. It should be noted that the network optimization problem should not be solved when using constant and TOU pricing scenarios, because in these cases there is no interaction between the consumer and the network. Another thing that should be pointed is that, in these simulations, minimizing the cost of the consumer is considered as the basis of dynamic pricing scenario. As it can be seen, in the dynamic pricing scenario the network's revenue, or in other words, the consumer's cost, is considerably high compared to the other methods.

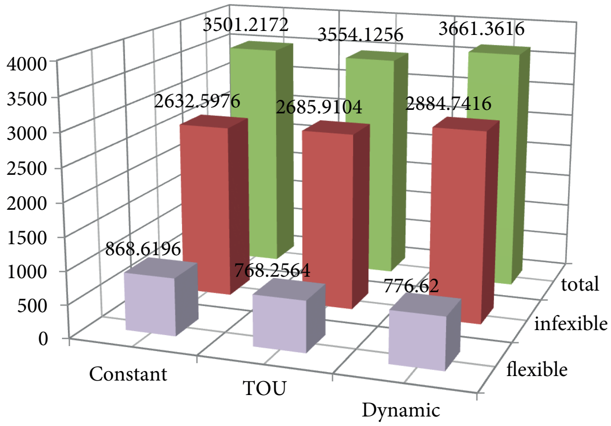

Figure 7. Consumer results with 3 pricing scenarios.

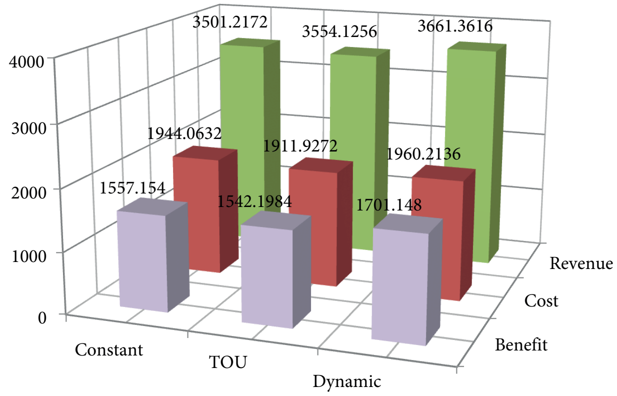

Figure 8. Network results with 3 pricing scenarios.

5. Conclusion

In this paper, first the positive relationship between the amount of load shifted by a typical consumer and the incentive suggested by the power network was described. This means that the consumer will incur fewer penalties because of less consumption during peak hours, and is also given more discount for more consumption during non-peak hours. A static game was then defined in which the residential consumer and the network were the players of the game. It was concluded that the best strategy for the consumer is to cooperate with the network during non-peak hours.

A simple optimization problem was also defined, in which a typical residential consumer tried to minimize his costs, whereas the network was interested in maximizing its financial benefits. In this paper, the total hourly load of the consumer was divided into the flexible and inflexible parts. To make our analysis practical, a heating system was considered as the flexible part of the load and its consumption was assumed to be 20% of the total load. Simulations showed that among the 3 different pricing methods, the best one for the consumer and the network are the TOU and dynamic methods, respectively.

References

[1] Mielczarski W, Michalik G, Widjaja M, editors. Bidding Strategies in Electricity Markets. Proceedings of the 21st IEEE International Conference on Power Industry Computer Applications. New York, NY, USA: IEEE, 1999.

[2] Ferrero R, Shahidehpour S, Ramesh V. Transaction analysis in deregulated power systems using game theory. IEEE T Power Syst 1997; 12: 1340-1347.

[3] Yu Z, Sparrow F, Morin T, Nderitu G, editors. A Stackelberg price leadership model with application to deregulated electricity markets. In: IEEE Power Engineering Society Winter Meeting; 2000. pp. 1814-1819.

[4] Gans W, Alberini A, Longo A. Smart meter devices and the effect of feedback on residential electricity consumption: evidence from a natural experiment in Northern Ireland. Energ Econ 2012; 36: 729-743.

[5] Gyamfi S, Krumdieck S, Urmee T. Residential peak electricity demand response—Highlights of some behavioural issues. Renew Sust Energ Rev 2013; 25: 71-77.

[6] Salies E. Real-time pricing when some consumers resist in saving electricity. Energ Policy 2013; 59: 843-849.

[7] Zugno M, Morales JM, Pinson P, Madsen H. A bilevel model for electricity retailers participation in a demand response market environment. Energ Econ 2012; 36: 182-197.

[8] Doostizadeh M, Ghasemi H. A day-ahead electricity pricing model based on smart metering and demand-side management. Energy 2012; 46: 221-230.

[9] Fong WK, Matsumoto H, Lun YF, Kimura R. Energy savings potential of the summer Time concept in different regions of Japan from the perspective of household lighting. J Asian Archit Build 2007; 6: 371-378.

[10] Kotchen MJ, Grant LE. Does daylight saving time save energy? Evidence from a natural experiment in Indiana. Rev Econ Stat 2011; 93: 1172-1185.

[11] Shimoda Y, Asahi T, Taniguchi A, Mizuno M. Evaluation of city-scale impact of residential energy conservation measures using the detailed end-use simulation model. Energy 2007; 32: 1617-1633.

[12] Bartusch C, Wallin F, Odlare M, Vassileva I, Wester L. Introducing a demand-based electricity distribution tariff in the residential sector: demand response and customer perception. Energ Policy 2011; 39: 5008-5025.

[13] White LV, Lloyd B, Wakes SJ. Are Feed-in tariffs suitable for promoting solar PV in New Zealand cities? Energ Policy 2013; 60: 167-178.

[14] Kavousian A, Rajagopal R, Fischer M. Determinants of residential electricity consumption: using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior. Energy 2013; 55: 184-194.

[15] Faruqui A, Malko JR. The residential demand for electricity by time-of-use: a survey of twelve experiments with peak load pricing. Energy 1983; 8: 781-795.

[16] Friedman LS. The importance of marginal cost electricity pricing to the success of greenhouse gas reduction programs. Energ Policy 2011; 39: 7347-7360.

[17] He Y, Wang B, Wang J, Xiong W, Xia T. Residential demand response behavior analysis based on Monte Carlo simulation: the case of Yinchuan in China. Energy 2012; 47: 230-236.

[18] Torriti J. Price-based demand side management: assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy. Energy 2012; 44: 576-583.

[19] Allcott H. Rethinking real-time electricity pricing. Resour Energy Econ 2011; 33: 820-842.

[20] Lin B, Liu X. Electricity tariff reform and rebound effect of residential electricity consumption in China. Energy 2013; 59: 240-247.

[21] Dütschke E, Paetz A. Dynamic electricity pricing—Which programs do consumers prefer? Energ Policy 2013; 59: 226-234.

[22] Nelson T, Orton F. A new approach to congestion pricing in electricity markets: Improving user pays pricing incentives. Energ Econ 2013; 40: 1-7.

[23] Gilbraith N, Powers SE. Residential demand response reduces air pollutant emissions on peak electricity demand days in New York City. Energ Policy 2013; 59: 459-469.

[24] Hu Y, Li X, Li H, Yan J. Peak and off-peak operations of the air separation unit in oxy-coal combustion power generation systems. Appl Energ 2013; 112: 747-754.

[25] Sun C, Lin B. Reforming residential electricity tariff in China: block tariffs pricing approach. Energ Policy 2013; 60: 741-752.

[26] Berg SV. Causal responsibility and peak load pricing. Energ Econ 1982; 4: 246-250.

[27] Newsham GR, Bowker BG. The effect of utility time-varying pricing and load control strategies on residential summer peak electricity use: a review. Energ Policy 2010; 38: 3289-3296.

[28] Thorsnes P, Williams J, Lawson R. Consumer responses to time varying prices for electricity. Energ Policy 2012; 49: 552-561.

[29] Woo C, Li R, Shiu A, Horowitz I. Residential winter kWh responsiveness under optional time-varying pricing in British Columbia. Appl Energ 2013; 108: 288-297.

[30] Pettersen E, Philpott AB, Wallace SW. An electricity market game between consumers, retailers and network operators. Decis Support Syst 2005; 40: 427-438.

[31] Halvgaard R, Poulsen NK, Madsen H, Jorgensen JB, editors. Economic model predictive control for building climate control in a smart grid. In: IEEE PES Innovative Smart Grid Technologies Conference; 2012.