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***Abstract*— Consumer choice theory is a branch of microeconomics. This theory relates to adjusting consumption expenditures and consumer demand curve. Consumer choice science is trying to realize the buyer's decision-making process. This science studies customer characteristics, such as behavioral criteria, to understand the consumer's need. The concept of price elasticity of demand (PED) has also been derived from this theory. In fact, the PED is the percentage of changes in the amount of demand relative to the price changes. In consumer choice theory, for each consumer according to behavioral criteria, a unique response to price changes is considered. Therefore, the consumer demand curve is a unique curve versus price changes. In the concept of PED, the elasticity investigation is performed only in a single point or over a small interval of the curve instead of the whole curve which is not suitable. Since most demand response (DR) models have been developed based on this concept, this will also be deemed as a disadvantage for them. In this paper, we propose an economic DR model based on economic theories and mathematical methods. In addition to abate the defects of price-elasticity based DR models, the proposed model has the ability to respond to the various consumers with distinct responses to price changes and can also adjust the consumer's demands according to the consumer's preferences during different periods of a day.**

Keywords— Demand-side management (DSM), price elasticity of demand (PED), economic DR model, consumer utility function, Cobb-Douglas utility function.

I. Introduction

With the advent of electricity markets, the supply-side quickly adapted to the new environment but it took longer for the demand-side to become aware of this toughie due to absence of enough information and confronting tools to participate imposingly in the electricity markets [1].To tackle this issue, demand-side tried to find appropriate tools which eventually led to the emergence of a new subject called Demand Side Management (DSM) in electricity market. Implementation of DSM programs offers many benefits to a large number of stakeholders in deregulated energy markets [2]. DSM refers to initiatives and technologies that persuade customers to optimize their electric energy consumption. Numerous DSM techniques have been proposed in the literatures. One of these is Demand Response (DR) programs. DR programs, as defined by U.S. Department of Energy (DOE), are the programs that improve the electricity consumption patterns of industrial, commercial, and residential customers so as to reduce peak loads and thereby achieve better prices as well as improved network reliability [3]. To make the power demand more manageable, a DR program can change the pattern of electricity usage by reducing the peak load or shifting the consumption from the peak to the off-peak hours [4]-[5].

Most existing DR models have constructed by the concept of Price Elasticity of Demand (PED). This concept is extracted from consumer choice theory that is a branch of microeconomics. This theory is related to adjusting consumption expenditures and consumer demand curve. This science combines cases such as psychology, sociology, social anthropology and economics. Consumer choice is trying to understand decision-making process of buyers, whether in the form of one by one or group [6]. PED demonstrates the relationship between price and quantity demanded and in fact the percentage changes in quantity demanded with respect to price changes. Each consumer has a unique reaction to price changes and this difference among consumers is identified according to many parameters such as consumer behavior, income, etc. [7]. Therefore, the demand curve can be unique for each consumer. Existing price-elasticity based DR models have paid less attention about this matter. In general, the behavior of consumers by observing costs of electrical energy can be divided into three main groups [1]. These categories are shown in Figure (1). Each group of consumers with regard to their behavior can manage the electric energy consumption at different times. The concept of consumption management refers to a specific class of electric loads, which have the ability to transfer between different hours [8]. It should be noted that, electrical loads categorized into two groups: non-flexible and flexible loads [2]. The flexible loads are significantly controllable in terms of amount and time of use, such as a washing machine, a dishwasher and some heating and cooling equipment [2]. Therefore, the consumer can manage consumption according to the price changes.

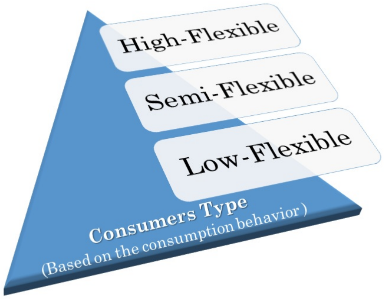

Fig.1. Consumers' reactions to price changes [1]

This topic in economics refers to the concept of substituting goods meaning that demand for one good increases when other goods prices rise, and vice versa. This concept is similar to the concept of power consumption shift from times with high prices to time intervals with lower prices. So, consumption of electricity with different prices can be considered as different goods that due to the features of flexible loads have the ability to be substituted with one another.

As mentioned above, consumer's reaction to price changes is denoting the elasticity concept. PED is the percentage change in quantity demanded to the price changes that could be represented as follows [9]:

$$E_P = \frac{\Delta Q}{\Delta P} \cdot \frac{P}{Q} \tag{1}$$

In this equation, ΔQ is the change in the quantity demanded and ΔP is the change in price. It should be noted that the inverse of the slope of the demand curve (ΔQ / ΔP) is only a part of the equation and its value is negative. Because the price and quantity are in opposite directions, when P increases Q decreases and vice versa.

Significant researches have been done on consumer responses to electricity prices [10]. Recently, much works have been dedicated to model the price elasticity in electricity markets [11]-[15]. For example, in [11], a DR model is introduced based on consumer behavior with the PED concept. The main idea of this model is economic and psychological analysis that accepts the difference between the effects of rewards and punitive programs and argues that reward is a superior method of creating habit compared to the punishment. In [12], a responsive load model is designed based on the concept of PED. The mathematical model is introduced to calculate elasticity of any DR program based on the price of electricity before and after the implementation of DR programs. Reference [13] offers an optimized DR model that allows a consumer to adjust the hourly demand in response to the hourly electricity price to maximize his/her profits. In [14], authors propose a model to discover the demand elasticity of consumers through demand-side bidding by electricity market complex adaptive system and an agent-based model that simulates electricity markets.

As seen on most of DR models is constructed on the basis of elasticity concept in which only a given point on the demand curve will be investigated. Since PED varies in different points of curve, this method is not an attractive way. For instance, in [15], a procedure is proposed with the help of economic models of demand to evaluate the effects of DR programs on the electricity market. In this research, PED is intended a preset constant, whereas, the PED in each period varies due to the different prices of energy which leading to changes in consumer behavior. Therefore, a robust DR model requires the consideration of flexible PED which finite models have provided this feature. References [16]-[17] provides a DR model that provides two key features of an effective DR program: adaptability to different consumers with different disagreements over the DR program and adjustability to consumer time preferences. In this paper, using economic theories and mathematical formulas, we are presenting a model that can make these two features a good DR model.

The proposed DR model is implemented according to Time-of-use (TOU) pricing mechanism. TOU usually divides a day into different time periods and proposes different prices for each time period. In this model, it is assumed that the consumer does not intend to reduce his/her consumption. Instead, he/she can be incentivized to participate in the DR program to increase his/her profit. Therefore, according to the behavioral criteria and considering the concept of substitute goods and the purpose of increasing profit, the consumer can shift a part of his/her energy consumption from peak times with high energy price spikes to the off-peak or shoulder times with lower prices. As a whole, the contributions of this paper could be summarized as follows:

- A new model for TOU-based DR program is proposed based on economic theories and mathematical methods for benefit maximization,
- An efficient structure is presented for residential load management by considering different levels of participation in DR programs.

The organization of this paper is as follows. The consumer theory is introduced in Section II. Also, this section explains the mathematical formulation of the proposed DR model. Section III presents a sensitivity analysis to study the effect of model parameters on consumer participation in DR programs. Section IV provides numerical results and shows validity of the proposed model. Finally, Section V concludes the paper by summarizing the main results and discussing future works.

II. CONSUMER THEORY

Consumer theory in the microeconomics examines how each consumer spends the money according to his/her priorities in term of the budget limits. Two important tools in this theory are utility functions and budget constraints. The interaction of these two tools enables a consumer to make an optimal decision [18].

To express the utility function of consumers, there are many functions that can be selected. Cobb-Douglas utility function is one of the most famous utility functions that economists extensively use in macroeconomics [19].

$$Maximize \;\; U(D_1, D_2) = D_1^{a} D_2^{1-a} \quad 0 < a < 1 \tag{2}$$

$$subject\ to$$
$$B = P_1 D_1 + P_2 D_2 \tag{3}$$

As mentioned, the reaction of customers to the price changes, i.e., the degree of participation in DR programs is the same as the concept of elasticity which is presented in (2) using the elasticity parameter "*a*". In fact, this parameter is a control parameter.

Equation (3) is a constraint, indicating that the cost of purchasing electrical energy must be equal to the allocated budget, where B is the total budget of the customer and P_1 and P_2 are the prices of the goods (D_1 and D_2, respectively).

Here we are dealing with an optimization problem with a utility function and several constraints. There are many methods for solving the optimization problem such as Lagrange method which could determine optimal points for utility functions $f(x)$ with one or more equality constraints $h_j(x)$. Considering a constrained optimization and Lagrange multiplier method, we can state that:

$$\begin{aligned} &Maximize\ f(x) \\ &subject\ to \\ &h_j(x) = 0 \quad \mathrm{j} = 1,2,3,..... \end{aligned} \tag{4}$$

If x^* is a local maximum, then there will be a fixed constant such $\lambda_j (\mathrm{j} = 1,2,3,.....)$ that:

$$\begin{aligned} &\nabla f(x^*) + \sum_{j=1}^{l} \lambda_j \nabla h_j(x^*) = 0 \\ &h_j(x^*) \le 0 \ ; \ for\ all\ j = 1,2,...,l \end{aligned} \tag{5}$$

To combine these conditions into an equation, we present an auxiliary function:

$$L(x, \lambda) = f(x) + \lambda h(x) \tag{6}$$

and solve:

$$\nabla_{x,\lambda} L(x, \lambda) = 0 \tag{7}$$

So, in this way we will have:

$$L = D_{peak}^{a} . D_{off-peak}^{1-a} + \lambda \cdot \{\mathrm{B\text{-}D}_{peak} . \mathrm{P}_{peak} \text{ - } \mathrm{D}_{off-peak} . \mathrm{P}_{off-peak}\} \tag{8}$$

$$\begin{aligned} &\frac{dL}{dD_{peak}} = a.D_{peak}^{a-1} . D_{off-peak}^{1-a} - \lambda P_{peak} = 0 \\ &\Rightarrow \ \lambda = \frac{a.D_{peak}^{a-1} . D_{off-peak}^{1-a}}{P_{peak}} \end{aligned} \tag{9}$$

$$\lambda = \frac{(1-a).D_{peak}^{a} . D_{off-peak}^{-a}}{P_{off-peak}} \tag{10}$$

$$\begin{aligned} &\frac{dL}{d\lambda} = B - \mathrm{D}_{peak} . \mathrm{P}_{peak} \text{-} \mathrm{D}_{off-peak} . \mathrm{P}_{off-peak} = 0 \\ &\Rightarrow B = \mathrm{D}_{peak} . \mathrm{P}_{peak} + \mathrm{D}_{off-peak} . \mathrm{P}_{off-peak} \end{aligned} \tag{11}$$

By comparison of (9) and (10), one can write:

$$D_{peak} = \frac{a.P_{off-peak}}{(1-a).P_{peak}} D_{off-peak} \tag{12}$$

By replacing (12) in (11):

$$\mathrm{D}_{off-peak} = \frac{(1-a).B}{\mathrm{P}_{off-peak}} \tag{13}$$

and replacing (13) in (12):

$$D_{peak} = \frac{a.\mathrm{B}}{P_{peak}} \tag{14}$$

in this context, D_{peak} and $D_{off\text{-}peak}$ represent electric power consumed in peak, and off-peak period, respectively. To obtain the power consumption at each time interval of the study period, one must use the following equations:

$$D_{t\,peak} = \mathrm{D}'_{t\ peak} \times \frac{D_{peak}}{D'_{peak}} \tag{15}$$

$$D_{t\,off-peak} = \mathrm{D}'_{t\ off-peak} \times \frac{D_{off-peak}}{D'_{off-peak}} \tag{16}$$

where D'_{peak} and $D'_{off\text{-}peak}$ represent demand in peak, and off-peak period, respectively before implementation of DR programs.

III. Sensitivity Analysis

To find the appropriate range for each parameter, there are different methods that can be used to do so: (1) trial and error (2) sensitivity analysis. In this section, we use the sensitivity analysis to find the range of elasticity parameter "*a*". Sensitivity analysis refers to the impact study of the input variables of a statistical model to output variables [20]. As indicated in (3), the accepted general range for the elasticity parameter is 0< *a* <1. As shown in Fig.3, by increasing this parameter in the mentioned range and observing the output, it is clear that the amount of consumption in the peak time increases while opposite happens in off-peak time. So, a consumer can choose this parameter with regard to his/her sensitivity toward the price changes. So, if a consumer selects the small value for this parameter, the participation of that consumer in the DR program is more, meaning that this consumer is deemed as a High Flexible type.

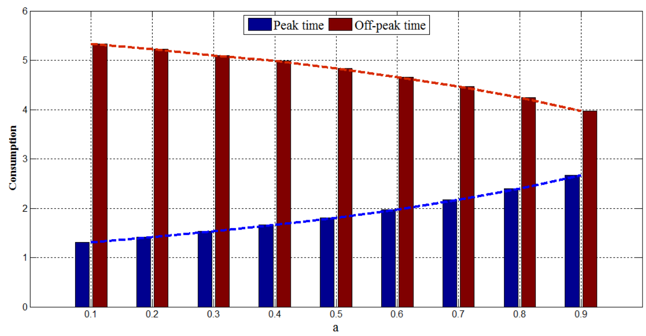

Fig.3. Changes in the elasticity parameter "*a*" and the amount of consumption in each time period

In this section, we determine the proper value for this parameter by making changes to the value of the elasticity parameter "*a*" and observe the output. As shown in Fig. (4), with implementation of a DR program and selecting different values for "*a*", the amount of consumption at peak time changes. Since the purpose of a DR program is to reduce consumption at peak time, increasing "a" is to some extent justified that the amount of consumption at peak period is less than the amount of consumption when there is no DR program. Therefore, according to the results depicted in Fig. (3), the appropriate value is $0 < a < 0.8$. Now if the sensitivity analysis for off-peak time is also done, we will find similar results as shown in Fig. (5).

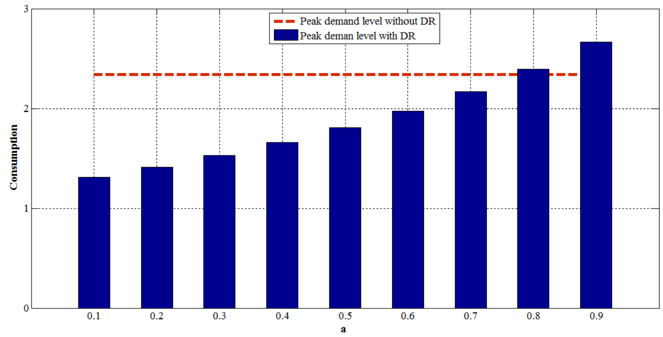

Fig.4. Consumption levels for different rates of elasticity parameter "a" (peak period)

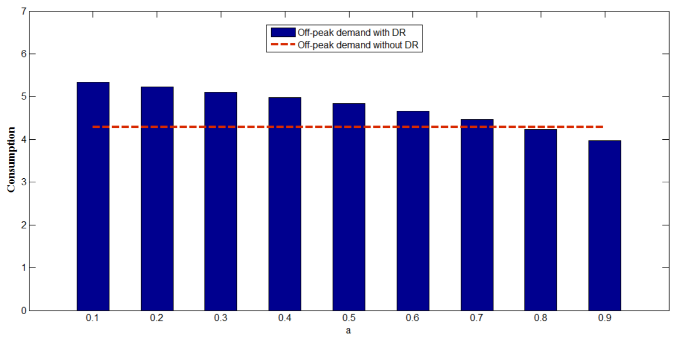

Fig.5. Consumption levels for different rates of elasticity parameter "a" (off-peak period)

IV. RESULTS AND DISCUSSION

To evaluate the performance of the proposed model, a typical load profile is adopted from [21]. In this load profile, as shown in the Fig. (6), 24 hours a day are divided into two periods. The price of electrical energy for each period is shown in Table (I).

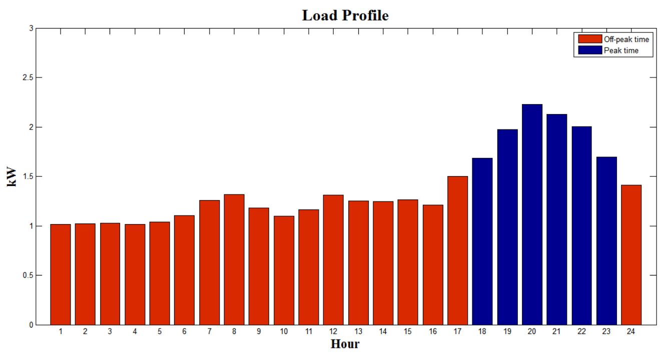

Fig.6. Load profile used for assessment [21]

Table.I Price of electricity in different time periods [22]

Demand level	P_{peak}	$P_{off\text{-}peak}$
Time Period	18:00-23:00	Other hours
Price (cents per kWh)	16	8

The results from the implementation of the proposed model at peak time and off- peak time for various values of elasticity parameter "a" according to the sensitivity analysis results are shown in the Tables (II)- (III).

Table.II Changes in the power consumption during the peak time

Elasticity parameter "a"	0.1	0.2	0.3	0.4	0.5	0.6	0.7
D_{peak} (kWh) **(Proposed DR model)**	6.54	7.06	7.63	8.30	9.04	9.86	10.84
D_{peak} (kWh) **(Base Case-Without DR)**	11.71						

Table.III Changes in the power consumption during the peak time

Elasticity parameter "a"	0.1	0.2	0.3	0.4	0.5	0.6	0.7
$Doff\text{-}_{peak}$ (kWh) **(Proposed DR model)**	26.67	24.14	25.50	24.91	24.17	23.29	22.32
$D_{off\text{-}peak}$ (kWh) **(Base Case-Without DR)**	24.43						

As previously mentioned, a decrease in parameter "a" would result in an increase in the willingness of consumers to participate in the DR program. Since at peak time the prices are higher than the other periods, with the increase of consumer's willingness, consumption in this period would decrease as reported in the Table (II). On the other hand, at off-peak times due to the lower prices, consumption increases with increasing consumer's willingness which is clearly visible in the Table (III). As shown in the Table (IV), the electric energy consumption with DR implementation during the study time period (D_{all}) is approximately constant for different values of elasticity parameter "a", and this amount is the same as the demand in the absence of the DR program. Therefore, in the presented model, only the levels of electrical energy consumption have been displaced in response to prices at time periods. On the other hand, as indicated in the same table, the amount of budget allocated to purchasing electrical energy has decreased with increased willingness to participate to DR programs.

Table.IV Changes in total demand and budget

Elasticity parameter "a"		0.1	0.2	0.3	0.4	0.5	0.6	0.7
With DR	**D_{all} (kwh)**	33.2	33.20	33.1	33.2	33.2	33.1	33.1
	Budget ($)	3.18	3.22	3.26	3.32	3.38	3.44	3.52
Without DR	**D_{all} (kwh)**	33.1						
	Budget ($)	3.58						

In Fig. (7), the consumption profile is drawn for all scenarios in Tables II-III. As it is clear, the peak-time and off-peak time demand levels can be adjusted by changing the values of "a". It should also be noted that the growth of residential electricity demand, along with the advance of smart grids, offers new horizons for using energy management systems in residential buildings (BEMS). In this regard, all the equations and algorithms previously provided can be coded into a BEMS. The level of participation in DR programs (i.e., elasticity parameter "a") can be set by consumer in BEMS at any time.

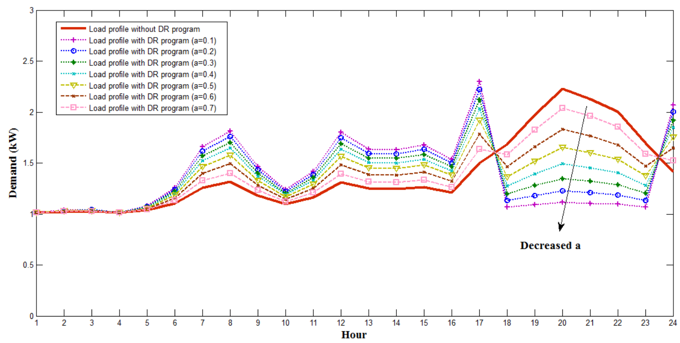

Fig.7. Residential load profile with and without DR programs

V. Conclusion

In this paper, the authors, with the help of mathematical and economic models, proposed a new model for DR programs based on the TOU method. An appropriate DR model can make ability to the consumers to adjust the consumption levels in different time periods and it should also be a compatible model with all types of consumers with any level of flexibility versus price changes. As shown, in this model, with the help of the elasticity parameter "a", it is possible to easily adjust the consumption levels at different time periods for each type of consumers. The results proved that the proposed model could effectively enable DR action based on user's preferences and help them to improve their utility function which in turn demonstrated the significant advantages of the model over price-elasticity based DR models. As a step toward future works, the proposed DR model in this paper can be extended to the models running based on other pricing methods such as Real-Time Pricing (RTP) and Critical Peak Pricing (CPP).

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