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Peak shaving and technical loss minimization in distribution grids: a time-of-use-based pricing approach for distribution service tariffs

Osman Bülent TÖR[1,*], **Mahmut Erkut CEBECİ**[1], **Mehmet KOÇ**[1], **Saeed TEIMOURZADEH**[1], **Deren ATLI**[2], **Simona Vasilica OPREA**[3], **Adela BARA**[3]

[1]EPRA Engineering Procurement Research Analysis, Ankara, Turkey
[2]Başkent Elektrik Dağıtım A.Ş., Ankara, Turkey
[3]The Bucharest University of Economic Studies, Bucharest, Romania

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Abstract: Deployment of time-of-use (ToU)-based retail energy tariffs (i.e. tariff for energy consumption – not the tariff for distribution service) is a common practice to incentivize consumers to use more energy at off-peak times. Distribution service tariffs (DSTs) are usually time-independent, which results in insensitivity of load to the distribution service cost. However, DST can also be time-dependent, which is studied in this paper. This study presents a methodology to address the effect of ToU pricing (i.e. time-dependent) of DSTs on peak shaving and technical loss minimization in power distribution grids. Here, the main focus is to assess the level of consumers' responses to ToU-based DSTs. Addressing such a problem necessitates detailed modeling of the distribution grid (including low-voltage grid) on the one hand and accurate modeling of the elasticity of consumers to ToU-based DSTs on the other hand. The other significant factor is the share of DST-originated cost within the total bill of the consumers. Considering these factors, the proposed approach is implemented on the pilot networks in the region of service associated with different distribution companies in Turkey. Response of consumers to ToU-based DSTs are addressed quantitatively in terms of peak shaving and technical loss minimization in the pilot regions. In addition, financial aspects of ToU-based DSTs are outlined from distribution companies and consumers standpoints.

Key words: Time-of-use tariffs, demand response, distribution service tariff, peak-shaving, technical loss, elasticity

Nomenclature

Acronyms

ToU: Time-of-use
DST: Distribution service tariff
DisCO: Distribution company
EMRA: Energy market regulatory authority
GIS: Geographical information system
MV: Medium voltage
LV: Low voltage

Indices

t: Time index
ct: Consumer type index

*Correspondence: osman.tor@epra.com.tr

td: Typical day index

Parameters

RT_t^{ct}: Retail energy tariff of consumer type ct at time t of typical day td

TD_t^{ct}: Actual demand of consumer type ct at time t of typical day td

LL_t^{ct}: Lower limit of demand of consumer type ct at time t of typical day td

UL_t^{ct}: Upper limit of demand of consumer type ct at time t of typical day td

EC^{ct}: Elasticity constant of consumer type ct

FT^{ct}: Flat rate DST of consumer type ct

Variables

EP_{td}^{ct}: Payment of electricity for consumer type ct on typical day td

D_t^{ct}: Demand of consumer type ct at time t of typical day td

DST_t^{ct}: ToU-based DST of consumer type ct at time t of typical day td

1. Introduction

By liberalization of electricity markets and development of retail markets, the total number of consumers subjected to national retail energy tariffs have been exposed to impressive decays as the consumers are now free to select associated electricity suppliers. However, the consumers are not able to select the distribution company (DisCO) and they should be in contact the DisCO whose region of service encompasses the consumer. Activities of DisCOs are regulated by energy market regulatory authorities (EMRAs) given their monopoly in the business. In that sense, revenue requirements of the DisCOs are subjected to the approval of regulatory authorities. EMRAs define distribution service tariffs (DSTs) with the aim of ensuring DisCO revenue requirements of the associated distribution services.

Depending on the level of market availability, small consumers are generally not eligible to select their supplier in retail markets. For instance, in the Turkish electricity market, those consumers with total consumption of less than 1600 kWh/year are subjected to the national retail tariff, which is defined by the regulatory authority of Turkey [1]. In other words, the retail market is available only for consumers that consume more than 1600 kWh/year. Such consumers can make bilateral agreements with retailers for their electricity consumption. On the other hand, retailers can provide a specific pricing scheme to their consumers. Time-of-use (ToU)-based pricing is a common pricing scheme within which the price of electrical energy varies with time and consumers are subjected to different electricity charges at different hours. Here, the consumers can benefit from cheaper rates at off-peak times while they are subjected to higher prices at peak times when all customers call for electricity consumption [2]. Adapting ToU-based pricing can contribute to reducing consumers' expenses for electricity consumption as well as decreasing the retailers' costs for supplying energy. The other method of pricing is the fixed price-based approach, where the customers make contracts and pay a fixed rate for electricity consumption independent of the ToU. Such fixed-price based contracts along with the proliferation of retail businesses may result in the reduction of incentives for consumers to shift their consumption from peak loading hours to off-peak loading hours. This is the recent case in Turkey, where DisCOs are concerned about the lack of incentives for consumers to shift their loads from peak-times to off-peak times. In consequence, the ratio of consumers subjected to the national retail tariff has significantly decreased after reducing the limits for being an eligible consumer. Similar to numerous other countries, the national DST in Turkey is uniform, where consumers are subjected to a constant regulated DST (i.e. flat-rate DST) independent of time and location of usage. The main question that can be posed here is: Can the ToU-based approach also be considered in the national DST mechanism to give incentives for consumers to shift their consumption from peak hours to off-peak hours? This question challenges the DisCOs and EMRAs of Turkey, which is quantitatively addressed in this study through simulations in pilot regions associated with different DisCOs in Turkey.

The literature includes several studies that address the elasticity of consumers to electric prices. In [3], the authors utilized a metaanalysis to quantitatively address price and income elasticities factors of residential consumers. Results of the study help understand the implications of different modeling assumptions and data constraints in relation to their estimates of elasticity. Similarly,the authors of [4] performed two nationwide surveys to measure consumer demand in Great Britain for a range of demand-side response tariffs and test what sort of marketing messages might be most effective in boosting uptake. They surveyed the responses of consumers to different ToU-based tariffs, including static time of use (with set price bands for electricity at different times of day), dynamic time of use (where times of the price bands vary from day to day), and direct load control (where in return for a lower flat rate for electricity, consumers allow their electricity supplier to cycle their heating off and on at certain times). According to survey results, almost 30% of consumers are in favor of switching to a static time-of-use tariff.

Credible elasticity constant ranges, which were proposed in [4] for typical residential, commercial, and industrial consumers, are considered in our study as described in Section 3.2. Some studies demonstrated that consumers reduce their consumption up to 13% during peak periods even without any control mechanism [5]. Such results, which offer convincing evidence that the residential sector can provide substantial contributions to retail demand response, are among the main motivations for our study. The main issues affecting the development of demand response in liberalized electricity markets were addressed in [6]. The study outlines some key concepts and draws on IEA member experience to identify barriers for demand response realization, and possible enablers including more effective real-time pricing, improved metering, and retail market reform, that have the potential to encourage more effective demand response. The study also explores the elasticity of different consumer types to electricity prices. In [7, 8], it was demonstrated how consumers' responses to ToU-based tariffs are predictable through econometric models, which are generally applicable for predicting residential responses to ToU rates. Connection of consumers' demand curves with consumers' choice of rate schedule was addressed in [9] also by econometric models. The authors examined customers' choices between standard and ToU rate schedules. The authors in [10] quantified customer responses to dynamic pricing through experiments. According to the results of the conducted study, sensitivity to price varies with climate zone, season, air conditioning ownership, and other customer characteristics. In line with those results, the ToU-based DST approach addressed in our study considers seasonal and regional aspects. The study showed that traditional ToU rates with a peak-to-off-peak price ratio of about 2 to 1 produce peak-period reductions in the 5% range for residential customers.

It is common to utilize typical load profiles of customers in the studies that address elasticity of consumers to dynamic prices, which is also adopted in our study. In [11], effectiveness of demand-side management using zonal tariffs for households is analyzed in the case of a tariff offer proposed to customers in northwestern Poland. The price elasticity of customers settled according to two zonal tariffs was determined using the standard load profile of customers published by the regional distribution network operator. Similarly, the authors in [12] assessed the impact of the tariff in the short and medium term among Italian customers through typical loading curves at certain periods of the years 2010–2012. The results of analysis showed how the consumption behavior of the customers was affected by the ToU tariff, particularly shifting load from peak to off-peak hours. The level of shifting consumption from peak to off-peak hours depends on the consumers' constraints [13, 14] which are embedded in our proposed approach: 1. comfort constraints, which represent unwillingness of customers to shift their consumption to undesirable time intervals (e.g., after midnight); 2. capacity constraints, which limit the maximum amount of consumption per hour. This study presents methodology and results of analysis to address ToU pricing of DSTs through modeling and simulation of consumer elasticity to ToU-based DSTs. The main focus of the study is to assess the level of responses of power distribution grid consumers to ToU-based DSTs quantitatively in terms of peak shaving and technical loss minimization in the distribution grid. In addition, financial aspects of ToU-based DSTs are investigated from distribution companies' and consumers' standpoints.

The contributions of the study are twofold: first, a methodology is proposed for calculating ToU-based DSTs rationally. High- and low-rate values of ToU-based DSTs should be determined in such a way such that total payments to consumers from current flat-rate DSTs and ToU-based DSTs are equal when the elasticity of consumers is zero. This is essential to make a realistic comparison between flat-rate and ToU-based tariffs. Secondly, this is the first study in the literature that addresses effects of consumer elasticity on the grid in terms of technical losses. This necessitates detailed modeling of the electricity grid at high and low voltage levels. Six pilot regions are selected and their grids are modeled in detail in the study for this aim. Savings of the distribution system operator (DSO) from the reduction of technical losses due to consumer elasticity are calculated.

2. Overview of national tariffs in Turkey and investigated pilot regions

In Turkey, the who are under regulated tariffs (those whose annual consumption is less than 1600 kWh [1] and are connected to the distribution grid) can prefer either flat-rate or ToU-based regulated retail energy tariffs. A breakdown of electricity bills of consumers is presented in Table 1, excluding taxes. Ratios of the current flat-rate DSTs to flat-rate retail energy tariffs are 26%, 30%, and 39% for industrial, commercial, and residential consumers, respectively, as shown in Table 1. Indeed, these ratios are the core motivations for conducting this study, which addresses giving incentives to consumers for shifting their electricity consumption from peak loading hours to off-peak in response to ToU-based DSTs.

Table 1. Regulated tariffs for distribution consumers in Turkey excluding taxes[1].

Consumer type	**Flat-rate retail energy tariff**	**ToU-based retail Energy tariff**			**Flat-rate DST**	**DST/Flat-rate retail energy tariff**
		06:00- 17:00	**17:00- 22:00**	**23:00- 06:00**		
Industrial	49.74	50.25	74.58	30.61	12.91	26%
Commercial	57.39	57.85	84.32	36.78	17.49	30%
Residential	43.45	43.99	64.02	27.98	17.11	39%

This study investigates three different DisCOs, which provide distribution services in different zones in Turkey. Pilot high-voltage (HV) substations are nominated from each DisCO as follows: two substations in each DisCO, one supplying an urban region and one supplying a rural region, as presented in Table 2. Breakdowns of consumers in the pilot regions are illustrated in Figure 1. As an example, the daily load curve of the Karahan HV substation, which is located at the Toroslar DisCO supplying the Mediterranean Region of Turkey (among the hottest regions in the country during summer), is presented in Figure 2 for a typical summer day. The figure illustrates the current ToU-based retail energy tariff for residential consumers and the regulated flat-rate DST. As can be seen, the peak loading in the region occurs during daytime (i.e. between 10:00 and 17:00) when the daytime ToU-based retail energy tariff is implemented. In contrast, loading of the region is reduced significantly during the time when the maximum ToU-based retail energy tariff is implemented (i.e. between 18:00 and 22:00).

Table 2. Distribution companies and corresponding pilot HV substations.

DisCO in Turkey	Pilot HV Substations (SS)	
	Urban Region	Rural Region
AYEDAS	Kartal HV SS	Sile HV SS
BASKENT	Akkopru HV SS	Beypazari HV SS
TOROSLAR	Karahan HV SS	Kadirli HV SS

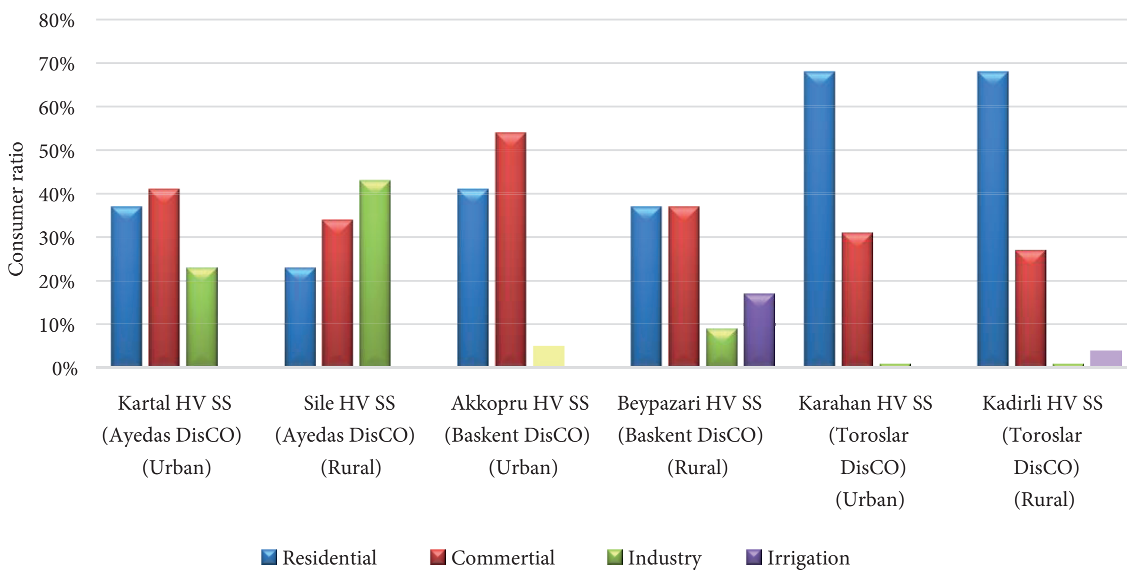

Figure 1. Breakdowns of consumers in pilot regions (2017).

This pilot region is indeed a good example, showing that there are regions in Turkey in which the ToU-based retail energy tariff is losing its effectiveness. The main reasons include the following: 1. ToU-based retail energy tariff periods are determined considering peak- and off-peak loading of the country. However, regional demand characteristics could be different and regional peak loading could happen at time intervals different than that of the country. 2. The threshold for being an eligible consumer (currently 1600 kWh/year) has been decreasing gradually in the country. Eligible consumers make bilateral agreements with retailers, and therefore, they are not subjected to ToU-based regulated retail energy tariffs. This might result in losing shares of consumers subjected to national ToU-based regulated retail tariffs.

The concern with the efficiency of ToU-based regulated energy tariffs poses the following question in the country. Could introducing a ToU-based DST mechanism instead of the current flat-rate DST give some

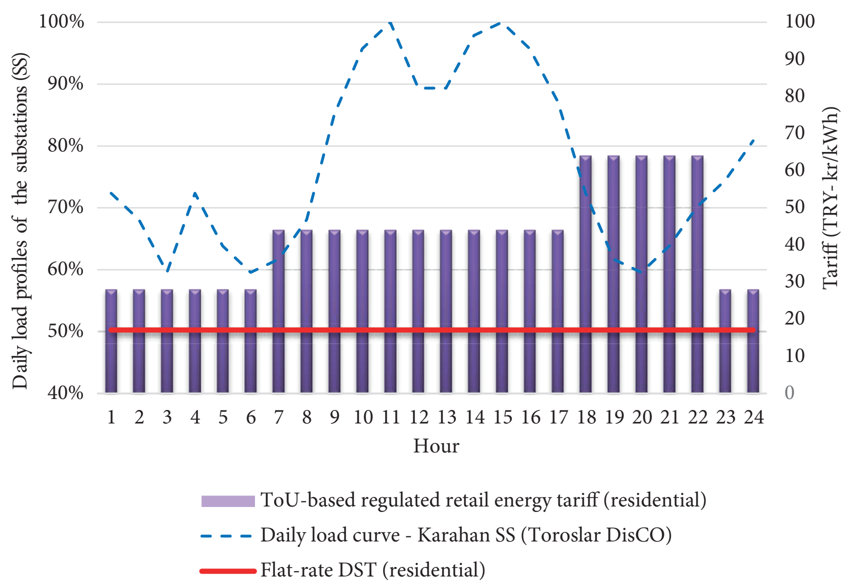

Figure 2. Daily load curve and tariffs (Karahan HV SS – Urban on 7 July 2015).

incentives to consumers for peak-shaving? In the current study, this question is answered quantitatively, as described in the following sections. The key arguments that support the idea of addressing ToU-based DST tariffs are: i) DST is a regulated tariff for every type of consumer connected to the distribution grid; ii) the ratio of the flat-rate DST to national retail energy tariff is considerable in Turkey (see Table 1).

3. The proposed methodology for ToU-based DST

In this section, the methodology for investigating the effect of ToU-based DSTs on peak shaving and technical loss minimization is presented. First, the proposed model for calculating the ToU-based DST is expressed. Afterwards, the model of consumers' elasticity to ToU-based DSTs is devised.

3.1. Modeling and calculation of ToU-based DSTs

The ToU-based DST should essentially include different tariff rates along different time intervals of the day. This necessitates introduction of a positive and negative gap between high-rate and low-rate DSTs and the current flat-rate DST, which is assumed as 1 per unit, respectively. Figure 3 illustrates the schematic representation of high- and low-rate ToU-based DSTs. High-rate and low-rate DSTs should be applied during peak and off-peak loading hours, respectively, to incentivize consumers to shift their consumption to off-peak loading hours.

The following approach and assumptions are made in the study to determine high- and low-rate ToU-based DSTs for each pilot HV SS region separately:

1. High- and low-rate ToU-based DSTs are determined seasonally, which adapts the proposed approach to the seasonal deviations in peak-loading time intervals along the day.

2. High- and low-rate ToU-based DSTs are determined for each consumer type separately to consider differences between peak-loading time intervals of different consumer types.

3. High- and low-rate ToU-based DSTs are assumed to be fixed along the seasons for each type of consumer (i.e. seasonal ToU-based DSTs are constant on weekdays and weekends of the season).

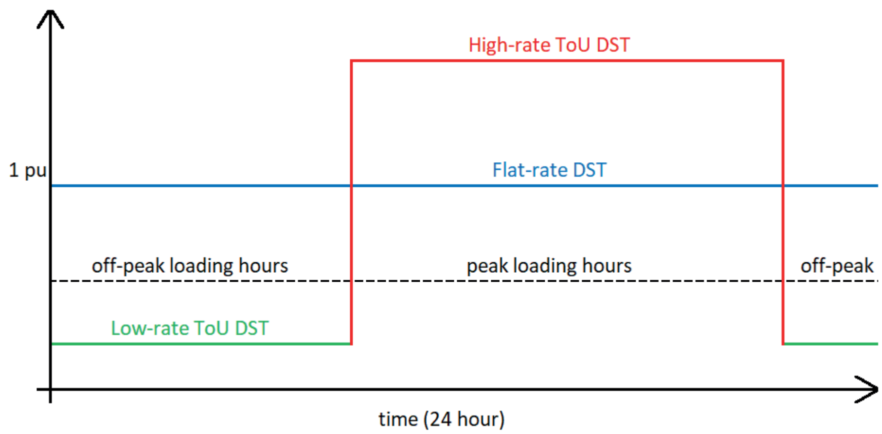

Figure 3. Schematic representation of high- and low-rate ToU-based DSTs.

Typical daily load curves of DisCOs are publicly available in Turkey for a typical weekday, Saturday, and Sunday for each season separately. As an example, the typical daily load curve of residential consumers at the pilot Kartal HV substation (AYEDAS DisCO) are presented in Figure 4 for a typical weekday in winter, along with ToU-based high- and low-rate DST intervals. The high-rate DST is proposed to be implemented between 10:00 and 22:00 given the increase of residential load in that interval. Similarly, ToU-based high- and low-rate DST intervals are determined for industrial consumers, as illustrated in Figure 5. The high-rate DST is proposed to be applied between 09:00 and 20:00, which spans the peak loading interval of industrial loads.

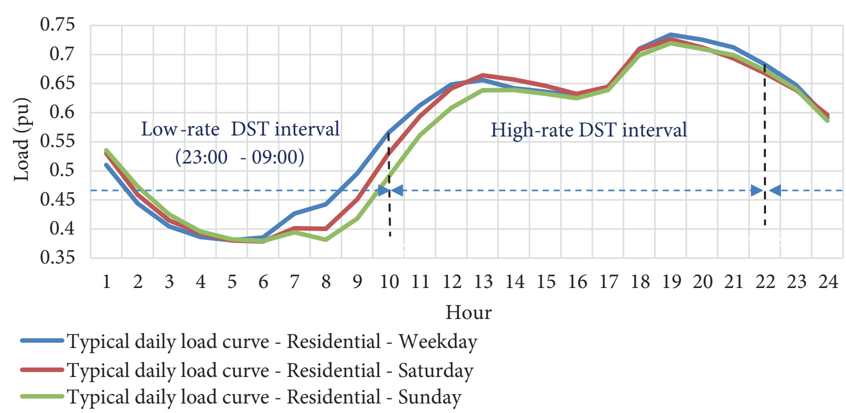

Figure 4. Typical daily load curves of residential consumers at pilot Kartal HV SS (AYEDAS DisCO) during winter season.

It is also assumed that electricity bills of those consumers that do not change their consumption will not change after implementing the ToU-based DSTs. This ensures rationality of the ToU-based DSTs in terms of those consumers that do not respond to the ToU-based DST. Exact values of the high- and low-rate DSTs under the aforementioned assumptions are determined by an iterative process as illustrated in Figure 6. Details of the methodology are described in the following subsections.

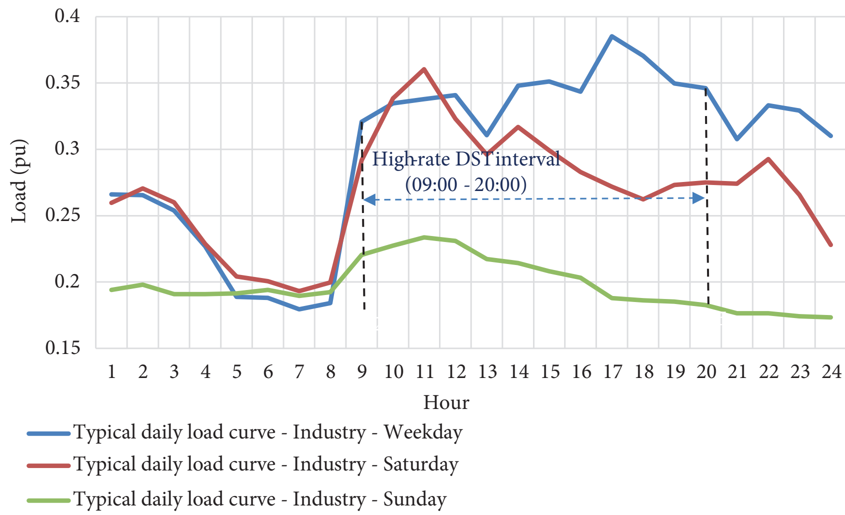

Figure 5. Typical daily load curves of industrial consumers at pilot Kartal HV SS (AYEDAS DisCO) during winter season.

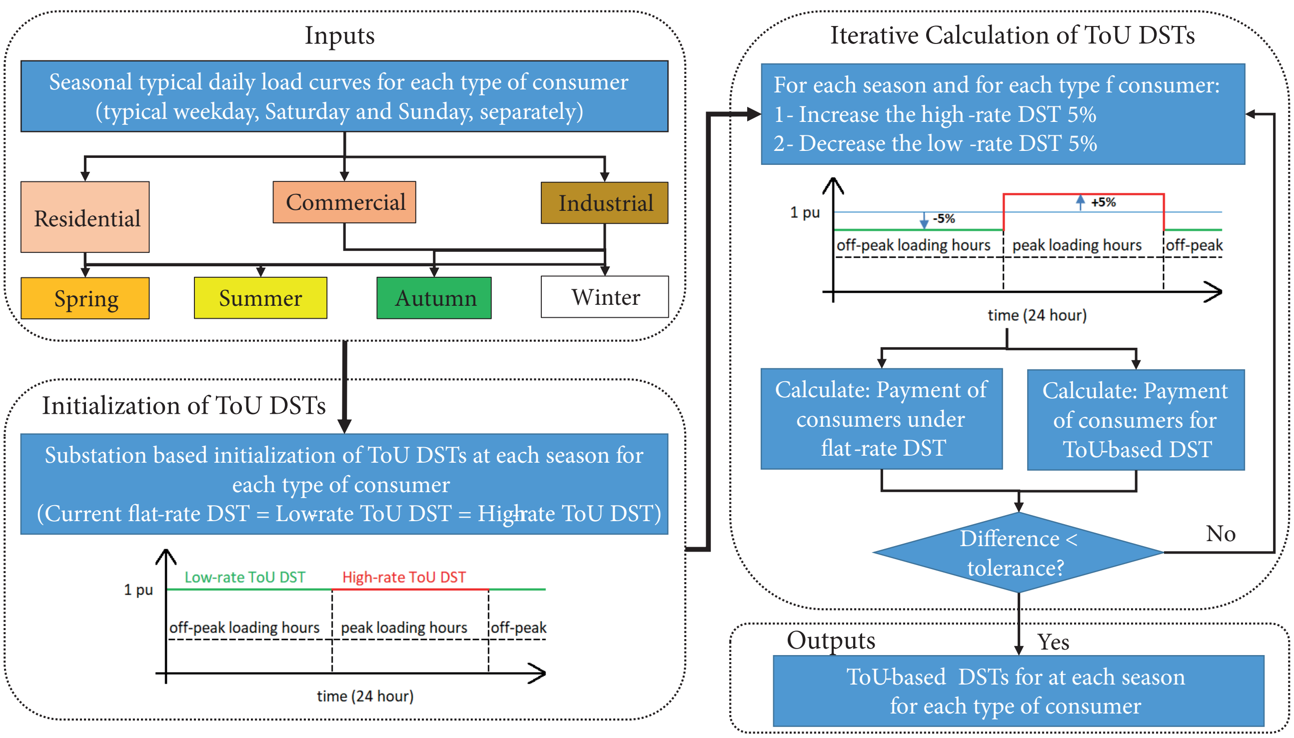

Figure 6. Flowchart of determining exact values of high- and low-rate DSTs.

3.1.1. Inputs of the methodology

Typical daily load curves of each type of consumer (residential, commercial, and industrial) are taken as inputs for each season (spring, summer, autumn, and winter) separately, as illustrated in Figure 6. For example, Figure

4 depicts typical daily load curves of residential consumers at pilot Kartal HV SS in winter. Another input is the current flat-rate DSTs of each type of consumer.

3.1.2. Initialization of the ToU-based DSTs

Initial values of ToU-based DSTs are assumed to be equal to current flat-rate DSTs for each type of consumer along typical days (i.e. gap between current flat-rate DSTs and ToU-based DSTS is zero). This requires identification of peak and off-peak loading hours at each pilot region (i.e. substation-based). To do so, typical days are separated into two time intervals, off-peak loading hours and peak loading hours, for each pilot region separately based on actual loading hours of the substations. As an example, the peak loading period of pilot Kartal HV SS in winter is 09:00–20:00, as illustrated in Figure 4.

3.1.3. Iterative calculation of ToU-based DSTs

The aim is to determine high- and low-rate values of ToU-based DSTs in such a way that total payments to consumers from current flat-rate DSTs and ToU-based DSTs are equal under constant typical load curves (i.e. price elasticity is zero). To do so, high- and low-rate ToU-based DSTs are determined by increasing the gap between high- and low-rate ToU-based DSTs gradually (5% of the flat-rate DST) in an iterative manner. This is done by gradually increasing and decreasing the high- and low-rate ToU-based DSTs, respectively. In every iteration, total payments to consumers from current flat-rate DSTs and iteratively calculated ToU-based DSTs are determined and compared for each type of consumer (each typical day and each season), separately. This process continues until total payments to consumers in flat-rate DST and ToU-based DST cases converge, as illustrated in Figure 6. A summary of the calculated ToU-based DSTs for the pilot Kartal HV SS of AYEDAS DisCO is presented in Table 3.

Table 3. ToU-based DSTs at pilot Kartal HV SS (urban region at AYEDAS DisCO).

Consumer type	**Season**	**High-rate interval**	**Low-rate interval**	**High-rate DST (pu)**	**Low-rate DST (pu)**
Residential	Winter	10:00 – 22:00	23:00 – 09:00	1.30	0.65
	Summer	10:00 – 22:00	23:00 – 09:00	1.15	0.82
	Spring	10:00 – 22:00	23:00 – 09:00	1.15	0.82
	Autumn	10:00 – 22:00	23:00 – 09:00	1.15	0.65
Industrial	Winter	09:00 – 20:00	21:00 – 08:00	1.30	0.70
	Summer	09:00 – 20:00	21:00 – 08:00	1.30	0.70
	Spring	09:00 – 20:00	21:00 – 08:00	1.30	0.82
	Autumn	09:00 – 20:00	21:00 – 08:00	1.30	0.70
Commercial	Winter	10:00 – 22:00	23:00 – 09:00	1.20	0.76
	Summer	10:00 – 22:00	23:00 – 09:00	1.30	0.65
	Spring	10:00 – 22:00	23:00 – 09:00	1.15	0.70
	Autumn	10:00 – 22:00	23:00 – 09:00	1.15	0.76

3.2. Modeling and formulation of consumers' elasticity to DSTs

Elasticity of consumers to price is defined with an elasticity constant (EC) as denoted by (1):

$$\text{Elasticity constant (EC)} = \frac{\text{Change in demand (\%)}}{\text{Change in total price (\%)}}. \tag{1}$$

EC is inversely proportional to change in the total price of electricity including retail tariff and DST. Table 4 presents the ECs considered for different types of consumers in Turkey [4]. Elasticity levels of consumers are investigated in three different levels as presented in the table. Essentially, industrial consumers have the maximum elasticity constant while the residential consumers have the minimum in all levels.

Table 4. Elasticity constants considered in the study [4].

Consumer type	**Elasticity constant**		
	Low-level	**Medium-level**	**High-level**
Residential	-0.20	-0.25	-0.30
Commercial	-0.28	-0.35	-0.42
Industrial	-0.30	-0.38	-0.46
Irrigation	-0.26	-0.33	-0.40

The objective function of consumers is to minimize electricity bills under the presumed ECs presented in Table 4 and ToU-based DTSs (2). Mathematically speaking, the objective function is:

$$Min\ EP_{td}^{ct} = \sum_{t=1}^{24} D_t^{ct} \times \left(RT_t^{ct} + DST_t^{ct}\right) \qquad \forall ct,\, \forall td, \tag{2}$$

where t is time index ($t = 1, 2, , 24$); ct is consumer type index ($ct \in \{Residential, Commercial, Industrial\}$); td is typical day index ($td \in \{typical; weekday, Saturday, and Sunday for each season\}$); EP_{td}^{ct} is payment of electricity for consumer type ct at typical day td; D_t^{ct} is demand of consumer type ct at time t of typical day td; RT_t^{ct} is retail energy tariff of consumer type ct at time t of typical day td; and DST_t^{ct} is the ToU-based DST of consumer type ct at time t of typical day td.

Elasticities of consumers are subjected to the following constraints independent of the EC:

- Comfort constraint: residential and commercial consumers cannot increase their consumption between 01:00 and 04:00, which is formulated as in (3):

$$D_t^{ct} \le TD_t^{ct} \;\; ct \in \{Residential,\ Commercial\}, \forall td,\ t = 1,\ 2,\ 3,\ 4. \tag{3}$$

- Capacity constraint: maximum demand of consumers is limited with their maximum demand under flat-rate DST for all types of consumers. This constraint is represented by (4):

$$D_t^{ct} \le \max(TD_t^{ct}) \qquad \forall ct, \forall td. \tag{4}$$

Moreover, ToU-based DST upper and lower limits of elasticity should be considered for a residential consumer as in (5)–(7), which are illustrated in Figure 7:

$$LL_t^{ct} \le D_t^{ct} \le UL_t^{ct} \qquad \forall ct, \forall td, \tag{5}$$

$$UL_t^{ct} = TD_t^{ct} \times \left(1 + |EC^{ct}| \times \left[\frac{(RT_t^{ct} + DST_t^{ct} - FT^{ct})}{FT^{ct}}\right]\right), \tag{6}$$

$$LL_t^{ct} = TD_t^{ct} \times \left(1 - |EC^{ct}| \times \left[\frac{(RT_t^{ct} + DST_t^{ct} - FT^{ct})}{FT^{ct}}\right]\right), \tag{7}$$

where TD_t^{ct} is demand of consumer type ct at time t of typical day td; LL_t^{ct} is the lower limit of demand of consumer type ct at time t of typical day td; UL_t^{ct} is the upper limit of demand of consumer type ct at time t of typical day td; EC^{ct} is the elasticity constant of consumer type ct; and FT^{ct} is the flat-rate DST of consumer type ct.

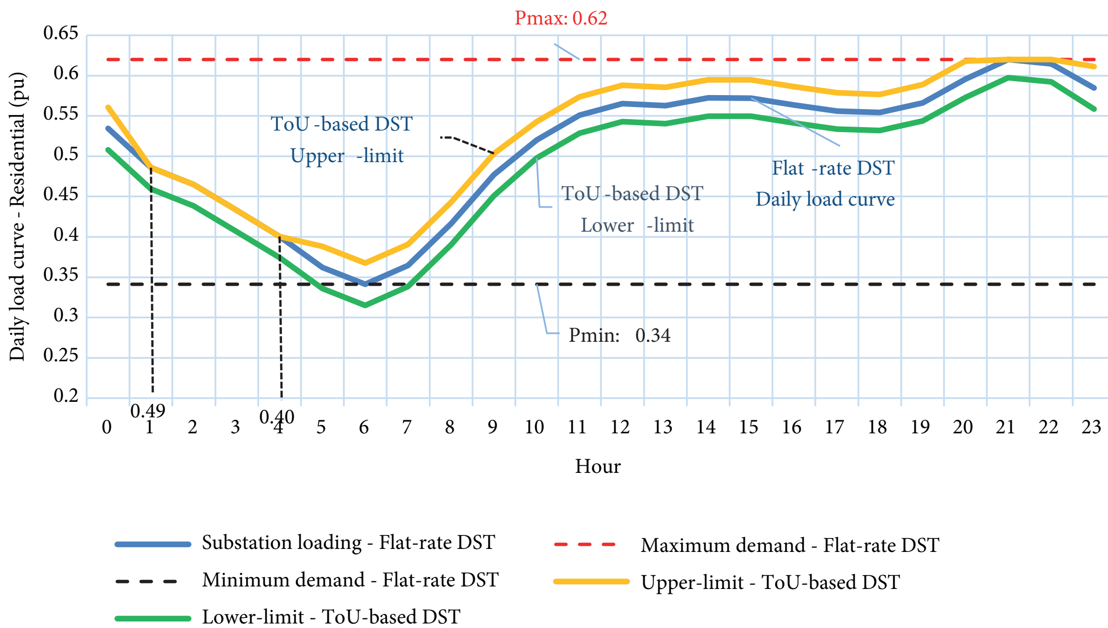

Figure 7. ToU-based DST upper and lower limits of residential consumer elasticity under comfort and capacity limits.

The optimization model formulated through objective function of (2) subject to (3)–(7) has a nonlinear optimization nature, which is tackled by the fmincon solver. Figure 8 depicts the optimization process to find out the optimal demand at each hour considering the ToU-based DST.

According to Figure 8, the customer type, load curves associated with each type of consumer, season under study, comfort coefficients of the customer for calculating (4), and maximum demand of the customer for calculating (3) are the main inputs for defining optimal demand at each hour considering the ToU-based DST. By the inputs in place, the ToU-based DST for each type of customer is defined with daily and seasonal specifications (as depicted in Figure 6). Next is the calculation of elasticity constants, which are used to calculate lower and upper limits of demand of consumer type ct at time t of typical day td in (6) and (7). The output of elasticity and ToU-based DST calculations are used in optimizing the hourly demand of the customer. For optimization, first the objective function and constraints are reshaped to the format defined by the fmincon solver, and then they are solved by the fmincon algorithm. The details of fmincon can be found in [15].

Elasticity of the consumers is modeled for the following cases:

Case 1: Total demand of the consumers along the day is constant for the flat-rate DST and ToU-based DST approaches (8). Case 1 represents the shifting of electricity consumption at peak hours to off-peak hours.

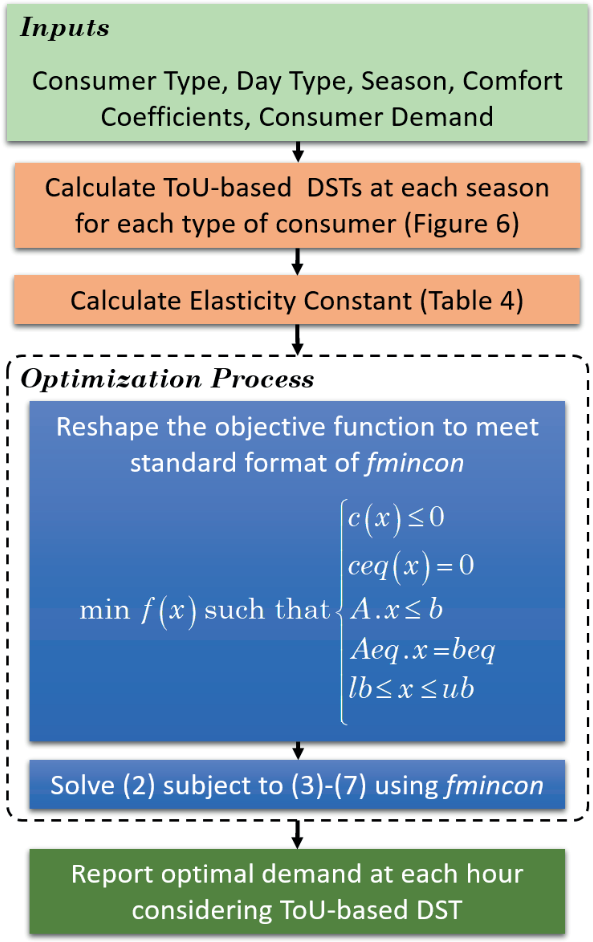

Figure 8. The optimization process to define optimal demand at each hour considering ToU-based DST.

Energy constraint (only for Case 1):

$$\sum_{t=1}^{24} D_t^{ct} = \sum_{t=1}^{24} TD_t^{ct} \quad \forall ct,\ \forall td. \tag{8}$$

Case 2: Total demand in the ToU-based DST approach is less than that of the flat-rate DST approach. Case 2 represents reduction of total electricity consumption of consumers at peak-loading hours to save more money if compared to Case 1.

4. Simulation studies

This section studies the effectiveness of the proposed method in peak shaving and technical loss reduction issues. In this respect, the grid modeling and the assumptions made in this study are discussed. Next, results of simulation studies for consumers' responses to ToU-based DSTs are investigated. Finally, grid simulation studies are carried out and effects of ToU-based pricing of DST are outlined. Results of time-independent (i.e. flat-rate) and time-dependent (i.e. ToU based) DSTs are compared in terms of grid and consumer perspectives.

Results of time-independent (i.e. flat rate) and time-dependent (i.e. ToU-based) DSTs are compared in terms of grid and consumer perspectives.

4.1. Modeling of distribution grid for grid analysis simulations

Distribution grids of pilot regions are modeled for grid analysis to compare the following parameters between the ToU-based DST and flat-rate DST approaches: 1) peak-shaving in the grid (%); 2) technical losses in the grid (%).

LV grids of the pilot regions are modeled in addition to MV grids in order to simulate technical losses. HV grid models of the pilot distribution regions are extracted from the Geographical Information System (GIS) database. In addition, LV grids are modeled through typical LV grid models for urban and rural LV grids separately. For example, the grid model of an urban pilot region is presented in Figure 9.

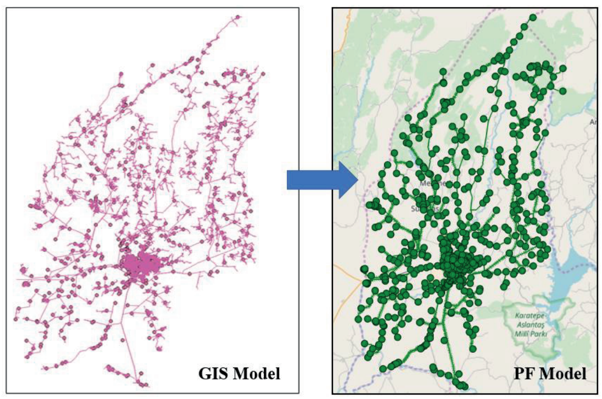

Figure 9. Grid model of a pilot region (urban pilot region - Kadirli HV substation).

Typical LV grid models include following type of consumers; i) Residential; ii) Commercial; iii) Industrial; and iv) Irrigation. Typical daily load curves are utilized for each consumer type, separately. Exact loading amounts are calculated by scaling the MV feeder loads, which are taken from meters, down to transformers with respect to transformer capacity. It is assumed that load ratio of each consumer type at the regional level is same in all MV/LV transformers. Key parameters of the typical LV grid model is presented in Table 5.

Table 5. Representative LV grid model considered in the study.

LV conductor type	Total line length (m)
ASTER (A)	281
PANSY (P)	821
ROSE (R)	1,016

4.2. Results of consumers' responses to ToU-based DSTs

Responses of consumers to ToU-based DSTs are presented in this section. Objective function (2) is evaluated for each type of consumer for each typical day in four seasons separately. Each season is represented by a typical weekday and typical weekend days (i.e. one year is represented by eight typical days). Typical daily load curves are utilized for each consumer type separately. For example, the calculated ToU-based DSTs for residential consumers at the pilot Kartal HV substation are illustrated in Figure 10.

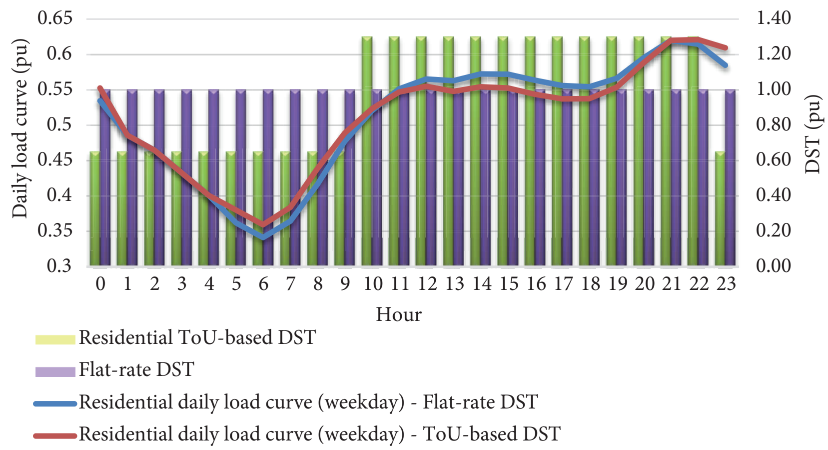

Figure 10. Residential ToU-based DSTs and response of residential consumers on typical summer weekday (Kartal HV SS – AYEDAS DisCO).

4.3. Grid simulation results

Grid simulations are performed using DigSilent PowerFactory simulation software. Peak loads of MV feeders and distribution transformers are calculated along with technical losses in the MV and LV grids. Simulations are performed for the current flat-rate DST case and the ToU-based DST case separately for the sake of comparison. Total electric bills of consumers (including retail tariff and DST) and total amount of money collected from the DST by the DisCO are also calculated for each case separately. Load flow simulations are performed for the low-, medium-, and high-elasticity scenarios (see Table 4). Responses of consumers to ToU-based DSTs are addressed quantitatively in terms of peak shaving and technical loss minimization at the pilot distribution grids.

4.3.1. Case 1 – Total demand of the consumers along the day is constant

In Case 1, total demand of the consumers along the day is assumed to be constant for the flat-rate DST and ToU-based DST approaches (8). It represents shifting of electricity consumption at peak hours to off-peak hours.

A. Peak shaving at pilot distribution grids: A summary of peak shaving results is presented in Figure 11. The figure illustrates the maximum peak shaving in each HV substation within a year. Average values of the peak shaving are 4.43% and 4.87% for urban and rural pilot regions, respectively. Maximum attained peak shaving is 6.3% at the pilot Kadirli HV substation (rural). Peak shaving results for the pilot rural region of the Beypazari HV substation (Baskent DisCO) are provided in Figure 12 for typical winter days. Essentially, peak shaving increases along with the consumer elasticity level (see Figure 11 and Figure 12). The vertical axis in Figure 11 shows the amount of peak shaving in pilot regions if the consumers are subjected to ToU-based DSTs instead of current flat-rate DSTs under high elasticity. The computational time of the proposed method is 256 s using a personal computer with Intel Core i7 CPU @3 GHz and 12 GB RAM.

B. Technical losses at pilot distribution grids: The results of simulation for reducing technical losses are summarized in Figure 13. Technical loss reduction results for the pilot rural region of the Kartal HV

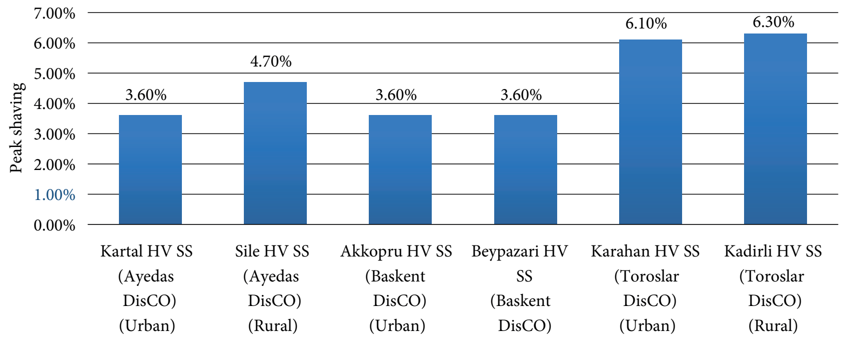

Figure 11. Summary of maximum peak shaving results along the year (time-independent flat-rate DSTs vs. ToU-based DSTs - high elasticity).

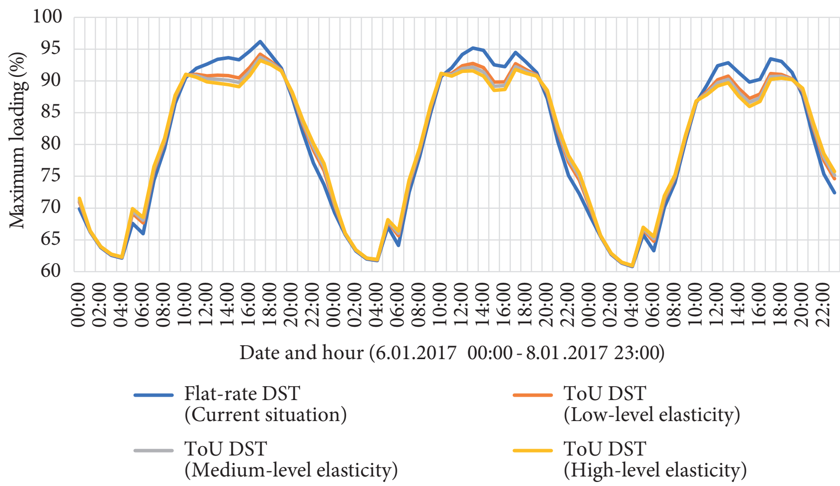

Figure 12. Maximum loading on typical winter days (Beypazarı HV SS – Baskent DisCO – Rural) (time-independent flat-rate DSTs vs. ToU-based DSTs).

substation (Baskent DisCO) are provided in Figure 14 for typical summer days. As can be seen, total amount of technical loss reduction increases along with the consumer elasticity level.

C. Financial results at pilot distribution grids: Financial results are investigated in terms of cost reduction due to decrement in technical losses and annual savings of the consumers by switching from flat-rate DSTs to ToU-based DSTs. The results of investigations from a financial point of view are summarized in Figure 15 and Figure 16. In both figures, the zero level of the vertical axis corresponds to the flat-rate DST case (i.e. time-independent) and values on the vertical axis show the quantitative benefits from ToU-based DTS (i.e. time-dependent) for different levels of consumer elasticity. DisCOs benefit from cost reduction due to decrease in technical losses. The range of this benefit is between 10,000 TL/year and 85,000 TL/year, depending on the region and level of consumer elasticity, as presented in Figure 15. Annual savings range for the consumers by switching from flat-rate DSTs to ToU-based DSTs is between 500,000 TL/year and 7,000,000 TL/year depending on the region and level of consumer elasticity, as presented in Figure 16. This savings corresponds to the annual loss of money collected by the DisCOs from the consumers. The amount of this loss is less than the annual cost reduction of DisCOs in all regions. That is, peak shaving and technical loss reduction benefits of DisCOs occur

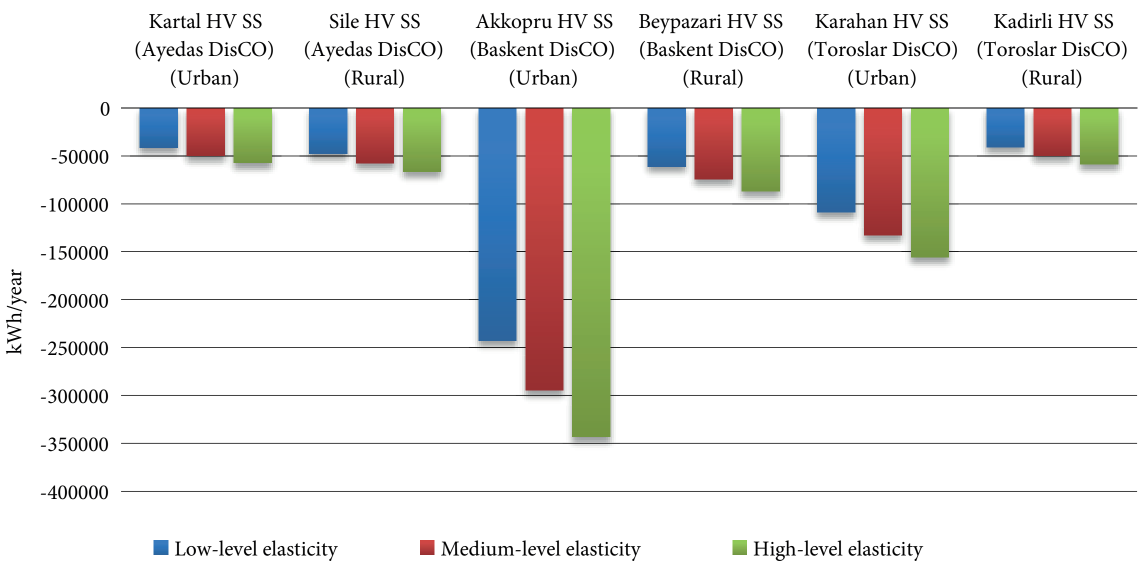

Figure 13. Amount of technical loss reductions at the pilot distribution grids (time-independent flat-rate DST vs. ToU-based DST - high elasticity).

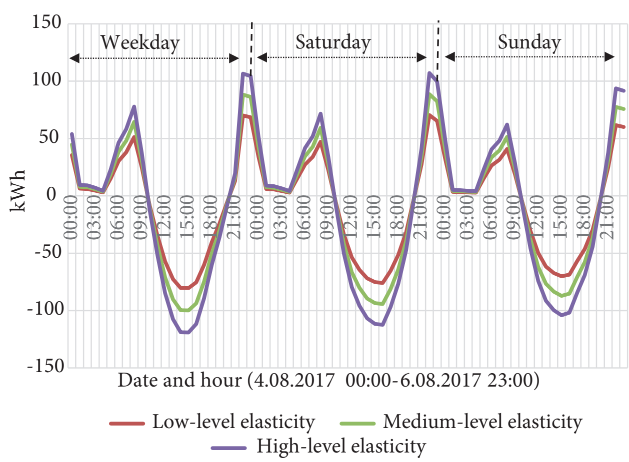

Figure 14. Technical loss reductions on typical summer days (Kartal HV SS – Ayedas DisCO – Urban).

at the expense of reduction in the total payment by the consumers. Activities of DisCOs are regulated by the energy market regulatory authorities given their monopoly in the business, and therefore, revenue requirements of DisCOs are compensated by DSTs, which are subjected to regulatory authority approval. The gap in the collected money from the ToU-based DSTs and revenue requirements could be compensated by identifying the DSTs for the following years.

4.3.2. Case 2 – Total demand of the consumers along the day is not constant

The energy constraint (8) is excluded in Case 2, which represents reduction of total electricity consumption of consumers at peak loading hours to save more money compared to Case 1. Excluding the energy constraint (8) results in increment of consumers' loads in low-rate DSTs. This increment is limited by the elasticity constants

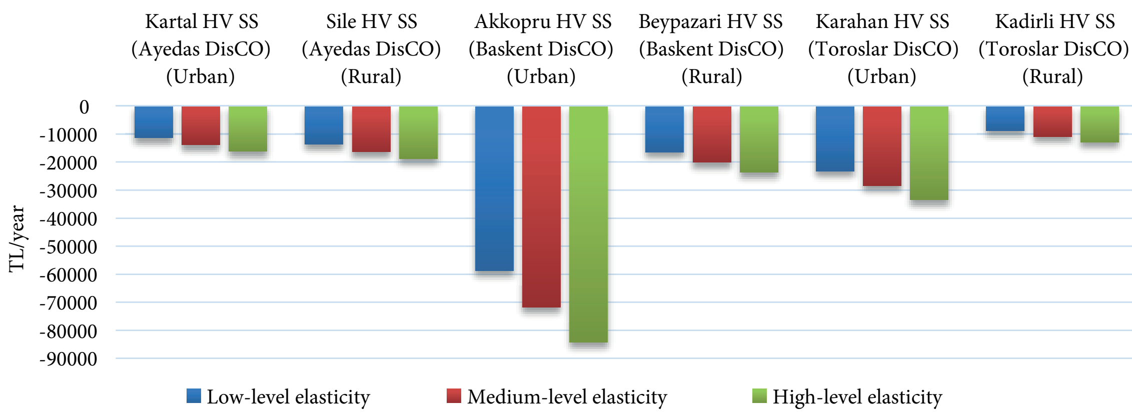

Figure 15. Annual cost reduction of DisCOs with respect to flat-rate DSTs due to decrease in technical losses effect.

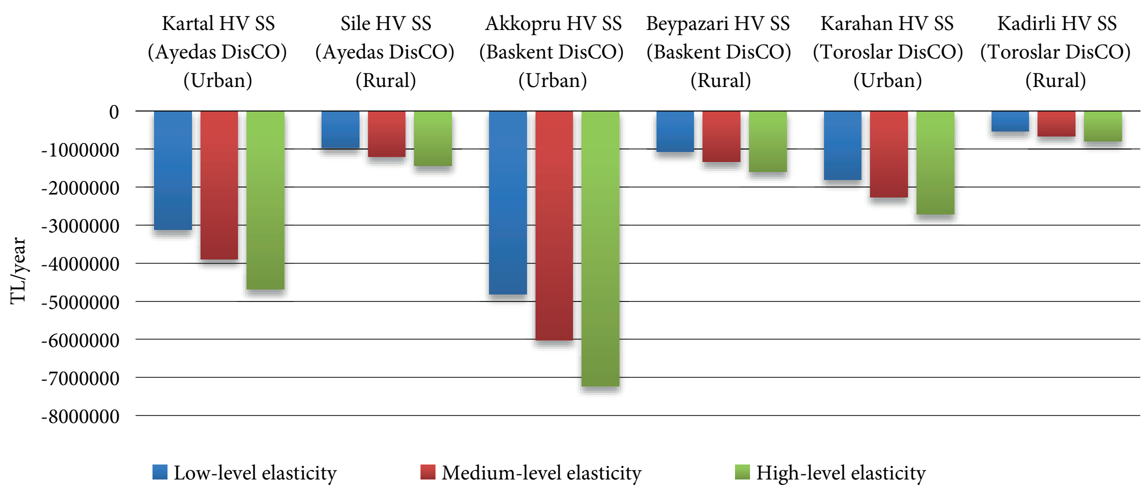

Figure 16. Annual savings of consumers by switching from flat-rate DSTs to ToU-based DSTs.

of the consumers. A summary of simulation results is presented in Figure 17, which compares the results of Case 1 and Case 2. Savings of consumers for electricity bills and savings of DisCOs from technical loss reduction increase essentially if compared to Case 1, as illustrated in Figure 18. Zero level in the vertical axis of Figure 18 corresponds to the case of the current time-independent flat-rate DST.

5. Conclusions

This study presented a methodology to address ToU-based pricing of DSTs to incentivize distribution consumers to shift their loads from peak loading times to off-peak. Responses of consumers to ToU-based DSTs were modeled by elasticity constants. Comfort constraints, capacity constraints, and energy constraints were considered in formulating the minimization of electricity bills of consumers. Responses of consumers to ToU-based DSTs were addressed quantitatively in terms of peak shaving and technical loss minimization in the pilot regions. Each season along a year is represented by a typical weekday and typical weekend days. Typical daily load curves are utilized for each consumer type (residential, commercial, and industrial) separately. The simulations concluded that adapting the DST to the time of use can contribute to peak shaving and technical loss reduction.

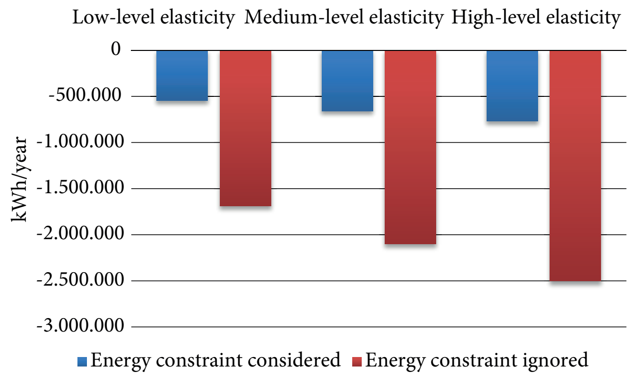

Figure 17. Summary of results (Case 1 vs. Case 2) - Amount of total technical loss reductions (total in all pilot regions).

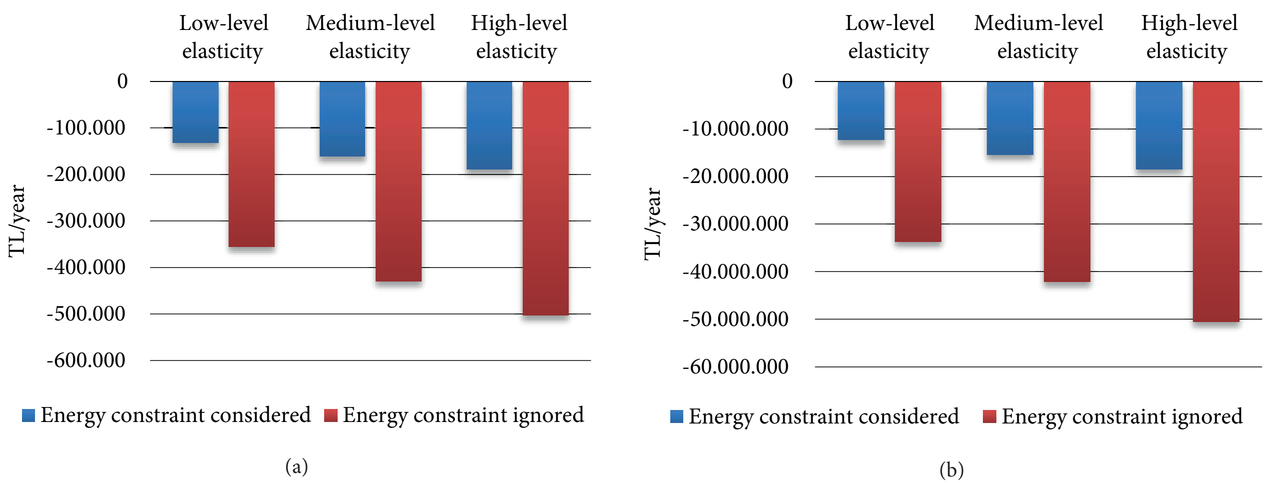

Figure 18. Case 1 vs. Case 2 - a) Total amount of annual cost reduction of DisCOs due to decrease in technical losses; b) annual savings of consumers by switching from flat-rate DSTs to ToU-based DSTs.

For the pilot regions, the technical loss reductions at the pilot distribution grids can reach 350000 kwh per year. Second, depending on the region and level of consumer elasticity, consumers can benefit from more annual savings by switching from flat-rate DSTs. For the pilot regions, the savings range for consumers by switching from flat-rate DSTs to ToU-based DSTs is between 500,000 TL/year and 7,000,000 TL/year depending on the region and level of consumer elasticity. Third, by excluding the energy constraint, i.e. when the total demand of the consumers along the day is not constant, more savings can be achieved by the customers.

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