Evaluating the Impact of Demand Side Management Techniques on Household Electricity Consumption, A real case

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ABSTRACT
Demand Side Management (DSM) is a very important tool that converts a consumer’s passive role to an active one by changing energy consumption and helps the energy utilities to decrease the peak demand and reshape the load curve. This paper presents a detailed analysis of the impacts of three of the most important DSM techniques which are energy efficiency, direct load control, and shifting load through two cases for one day in summer and one day in winter. The effectiveness of the three techniques is demonstrated on an average daily consumption of an Egyptian residential house in Shebin El-Kom, Menoufia Governorate. The desired objectives are reducing the energy consumption, electricity bill, and minimizing peak to average ratio (PAR). The obtained results confirm that applying DSM techniques has significant potential in terms of financial savings for the consumers and utility provider, and a cleaner environment without any impact on service quality or customer satisfaction.

Keywords: Demand Side Management (DSM), Energy Efficiency (EE), Direct Load Control (DLC), Load Shifting, and Peak to Average Ratio (PAR).

1. Introduction
In Egypt, electricity consumption is growing continuously because of increasing population and development needs [1-4]. Egypt’s energy sector faces challenges in facing electricity demand among all sectors (agriculture, industry, services, and residential), the rate of electricity consumption in Egypt has increased by 7% annually during the past three decades [4]. The residential sector was the largest energy consumption that was responsible for more than half of the total energy consumption in Egypt according to the last report from the Egyptian authority [5,6]. According to that increase in consumption, electricity production should be increased also. So, sources use more fossil fuels to generate electricity which in turn increases the level of carbon dioxide in the atmosphere. Moreover, the electrical system becomes unreliable during peak hours, the production and transmission capacity are insufficient to meet the increase in demand, and the infrastructure of the electricity system is outdated [1-4]. One of the solutions to solve the previous problems is to implement Demand Side Management (DSM) techniques [7,8].

DSM is done by planning, implementing, and developing activities to influence customer’s use of electricity, so as to produce the desired daily or seasonal load shapes [9-12]. For utility, DSM means avoiding or delaying the need to construct new generating units, reducing capital investments, and ensuring efficient operation in the generation, transmission, and distribution. For residential consumers, DSM means reduced bills. DSM is a set of interactive programs that give a customer a greater role in shifting its consumptions to off-peak periods, decreasing the total electricity bills while giving lower costs per kWh to utilities [12].

Mainly six techniques are popularly used for demand management to enhance the load shape which are load shifting, peak clipping, conservation, load building, valley filling, and flexible load shape [13,14]. These techniques are illustrated in Figure (1), which are different from one utility to another, depending on the number of customers, nature of the load type, the level of customers’ reaction or satisfaction with the applied technique, etc. [12].

In [11,15,16], rescheduling of the load curve of a consumer from the current load curve is performed as a DSM strategy. The former is done depend on a time-based pricing method that would reduce the PAR of the end-user. This scheduling is also dependent on categorizing the devices used by the consumer as shiftable and non-shiftable loads. In [2,4,8,17], the impact of the DSM strategy on load was investigated with renewable energy sources. The pricing model was presented as a more effective...
alternative. In [1,4,18], the ability of the energy-saving behavior as a DSM strategy has been explored in the reduction of developed economies. This study suggested that energy-saving behavior could reduce energy demand by a maximum of 21.9% and the energy efficiency strategy could reduce electricity demand in the residential sector by about 28.8%.

Figure 1-Demand Side Management Techniques

In this paper, the average load curve for a household load in Shebin El-Kom City, Menoufia Governorate is investigated. Then, applying DSM techniques such as energy efficiency, direct load control, and shifting load to reduce daily energy consumption, minimization of electricity cost, and peak to average ratio (PAR). The approaches of DSM are examined in section II, section III introduces the load categories, section IV focuses on the proposed DSM strategy, and the simulation results are discussed in section V. Finally, section VI summarizes the main conclusions.

2. Approach to DSM

DSM can be classified into two main parts as Energy Efficiency (EE), and Demand Response (DR). Demand response can be divided into a time of use, direct load control, and load shifting. Figure (2) shows the general classification of DSM [7,19,20]. Three techniques are used in this study which are energy efficiency, direct load control, and load shifting. Each technique is explained as follows:

2.1 Energy Efficiency

Energy efficiency technique is very important in power systems where it is required to decrease the overall energy consumption by replacing normal appliances with energy-efficient appliances [21, 22]. Energy-efficient appliances use less electricity to achieve the same level of performance as similar models with the same size or capacity. The more efficient the model, the less its energy consumption and its operating cost [23].

2.2 Direct load control

Direct load control technique is aimed at decreasing the demand during peak hours, especially if the installed capacity is not enough to cover the peak demand. Not all devices are suitable for direct load control. Devices like refrigeration load, heating, and cooling devices are suitable for direct load control technique. Maximum interruption is between 30 minutes to 1 hour that can be applied 2-3 times a day [7, 24].

2.3 Load Shifting

Load shifting is one of the best techniques used in Demand Side Management (DSM) by shifting the loads from peak hours to off peak hours. It does not make any change in the amount of consumed energy but reducing the peak loads in the network demand pattern [25, 26].
3. Load Categorization
According to the energy consumption pattern, operating time, and user preference, the appliances are categorized into three broad classes: regularly operated appliances, shiftable, and elastic appliances. Each category is explained as in [27,28]. The power consumption (E) of these appliances is represented as [29]:

\[
E = \sum_{t=1}^{T} \sum_{i \in ap} \rho_i \ v_s(t)
\]  
(1)

Where \(\rho_i\) is the power rating of each appliance, \(T\) represents total time slots, \(v_s(t)\) is the state of each appliance in particular time slot \(t\) which is given as:

\[
v_s(t) = \begin{cases} 
0 & \text{if appliance is OFF} \\
1 & \text{if appliance is ON}
\end{cases}
\]  
(2)

3.1 Regularly operated appliances
Regularly operated appliances or fixed appliances are those devices that must be run at the ideal times specified by the users. The energy consumption pattern and overall operation time of these devices cannot be changed [27].

3.2 Shift-able appliances
These are the loads that can perform their work at any instant of time but the operation should not be interrupted after starting, however, their runtime must be completed [27,29]. They are also named as burst load.

3.3 Elastic appliances
These loads are considered as flexible appliances, their time period and energy consumption profile are flexibly adjusted. These devices can be switched on at any time and can be cut off while they are running [27, 29].

4. Proposed DSM Strategy
This section introduces two subsections that described subsequently:

4.1 Household electricity consumption model
The total energy consumption and the total cost per day are computed as [27]:

\[
E_{A_n,T} = \sum_{t=1}^{T} \left( \sum_{i=1}^{A_n} P_{A_n}^f \ast \tau(t) \right)
\]  
(3)

\[
C_{A_n,T} = \sum_{t=1}^{T} \left( \sum_{i=1}^{A_n} P_{A_n}^f \ast \varepsilon(t) \ast \tau(t) \right)
\]  
(4)

Suppose \(A_n\) represents a set of appliances, while \(P_{A_n}^f\) is the power rating of appliances, \(E_{A_n,T}\) is the total energy consumption in a day where \(T\) equals 24 hours, and \(C_{A_n,T}\) is the total consumption cost per day.

Where \(\tau(t)\) is the number of appliances operating hours per day and \(\varepsilon(t)\) is the price of energy consumption kilowatt hour (L.E/kWh).

PAR is defined as the ratio between peak load over average loads in a given time frame that can be written as follows [30]:

\[
PAR = \frac{\max_{t} (E_{A_n,T})}{1/T \sum_{t=1}^{T} E_{A_n,T}}
\]  
(5)

The high value of PAR threatens grid stability and increases electricity cost. While the reduction in PAR, simultaneously enhances the stability and reliability of the power grids and reduces the electricity bill of the consumers [15, 16].

4.2 Egyptian Household Energy Consumption
For our study, the average consumption of a real house in Stadium Street in Shebin El-Kom is analyzed through monthly bills and daily consumption in two cases namely one day in the summer and another day in the winter season.

According to the report of the Egyptian electricity company [5], the following electricity segment prices for the new fiscal year 2020/2021 are listed in Table (1).

<table>
<thead>
<tr>
<th>Monthly Consumption kWh/month</th>
<th>Tariff Egypt (L.E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KWh 50 – 0</td>
<td>0.38</td>
</tr>
<tr>
<td>KWh 100 – 51</td>
<td>0.48</td>
</tr>
<tr>
<td>KWh 200 – 0</td>
<td>0.65</td>
</tr>
<tr>
<td>KWh 350 – 201</td>
<td>0.96</td>
</tr>
<tr>
<td>KWh 650 – 351</td>
<td>1.18</td>
</tr>
<tr>
<td>to less than 1000 KWh 0</td>
<td>1.18</td>
</tr>
<tr>
<td>to more than 1000 KWh 0</td>
<td>1.45</td>
</tr>
</tbody>
</table>
Table (2) shows the most common household appliances that will be used in this study where household appliances differ from one house to another, from one residential area to another, from one standard of living to another, and from one season to another.

Table 2- The list of consumption of major home appliances

<table>
<thead>
<tr>
<th>eAppliance</th>
<th>Range of consumption (Watt) [5],[23]</th>
<th>Power consumption (Watt)</th>
<th>No. of Operation hours of appliances (Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent Lamp</td>
<td>60 - 20</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Energy saving bulbs</td>
<td>27 - 2</td>
<td>25</td>
<td>8</td>
</tr>
<tr>
<td>Television (TV)</td>
<td>250 - 100</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>800 - 56</td>
<td>350</td>
<td>24</td>
</tr>
<tr>
<td>Freezer</td>
<td>800 - 56</td>
<td>275</td>
<td>15</td>
</tr>
<tr>
<td>Microwave</td>
<td>- 800</td>
<td>1050</td>
<td>2</td>
</tr>
<tr>
<td>Electric heater</td>
<td>- 1000</td>
<td>1000</td>
<td>4</td>
</tr>
<tr>
<td>Washing machine</td>
<td>700 - 500</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>-1200</td>
<td>1200</td>
<td>1</td>
</tr>
<tr>
<td>Water heater</td>
<td>- 1000</td>
<td>1000</td>
<td>6</td>
</tr>
<tr>
<td>Computer (PC)</td>
<td>200 - 100</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>Air Conditioner (AC)</td>
<td>- 1000</td>
<td>1200</td>
<td>6</td>
</tr>
<tr>
<td>Fan</td>
<td>100 - 60</td>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>Iron</td>
<td>- 600</td>
<td>1000</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Two cases studied are presented as:

Case 1:
Figure (3) shows the average daily load curve in the pattern of using loads of a household in summer season where the average consumption is 983 kWh/month with an average load per day 32.75 KWh/day. From the load curve, it can be seen that the peak consumption occurs from 8:00 pm to 11:00 pm which is confirmed with the report of the Egyptian electricity company [5].

Figure 3- Daily average load curve for case 1

Case 2:
The average daily load curve in winter is presented in Figure (4) where the average consumption is 422 kWh/month with average load per day 14.1 KWh/day. From this curve, it can be seen that the peak consumption occurs during the period of 5:00 pm to 9 pm.

Figure 4- Daily average load curve for case 2
It is noticed that the consumption in the summer and holidays season differs from the consumption in the winter and school season. User habits of some appliances’ usage are quite similar in the summer and winter time, such as refrigerator, PC, some small kitchen appliances, hairdryer, TV, and others. The consumption falls in the middle of the day and in the evening consumption again increases when people return home after work. Some appliances are kept on all day long whereas some appliances are used for a limited period [20, 21]. Energy consumption due to air conditioners, refrigerators, and freezer turn out are the largest share in energy consumption in summer case while in winter case the water heater and the electric heater turns out are the largest share in energy consumption.

5. RESULTS and DISCUSSION
In each case, the impacts of energy efficiency, direct load control, and load shifting are analyzed on the average daily load curve, monthly consumption (KWh), electricity bill, and on the peak to average ratio (PAR) are presented and discussed.

5.1 Effect of Energy Efficiency (EE) Technique
In this technique, the refrigerator, light, and television loads are replaced by energy-saving loads as shown in Table (3) and the effect of these changes on the average daily load curve, thus on electricity consumption and the electricity bill is studied.

Table 3- Energy consumption of the replaced appliances

<table>
<thead>
<tr>
<th>Appliances</th>
<th>Energy consumption of old appliances (Watt)</th>
<th>Energy consumption of an efficient ones (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>Fluorescent lamp</td>
<td>40</td>
<td>LED tube light 18Watt</td>
</tr>
<tr>
<td>saving -Energy bulb</td>
<td>25</td>
<td>LED bulb light 12Watt</td>
</tr>
<tr>
<td>Fan</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>TV</td>
<td>100</td>
<td>48</td>
</tr>
</tbody>
</table>

Figures. (5) and (6) show the resulted load curve when replacing the mentioned appliances in Table (3) with an energy-efficient one for both cases. Table (4) illustrates the effect of energy efficiency for both cases. It can be observed that applying the energy efficiency technique increases the monthly consumption savings by 26 % and 29.3 % in the summer and winter seasons respectively. Also, the electricity bill savings are 25.5 % and 37 % in the summer and winter seasons respectively. The PAR factor is slightly decreased due to the reduction in both peak and average consumption.
Table 4- The obtained results of applying EE technique

<table>
<thead>
<tr>
<th></th>
<th>Before applied EE</th>
<th>After applied EE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly Consumption (KWh)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>983</td>
<td>727.3</td>
</tr>
<tr>
<td>Case 2</td>
<td>422</td>
<td>298.4</td>
</tr>
<tr>
<td>Electricity bill (L.E)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>1184.94</td>
<td>883.2</td>
</tr>
<tr>
<td>Case 2</td>
<td>373.96</td>
<td>235.46</td>
</tr>
<tr>
<td>Peak of consumption (Watt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>2160</td>
<td>1469</td>
</tr>
<tr>
<td>Case 2</td>
<td>757.5</td>
<td>520.5</td>
</tr>
<tr>
<td>Daily average of consumption (Watt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>682.3</td>
<td>495</td>
</tr>
<tr>
<td>Case 2</td>
<td>293</td>
<td>207.2</td>
</tr>
<tr>
<td>(%) PAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>3.16</td>
<td>2.97</td>
</tr>
<tr>
<td>Case 2</td>
<td>2.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

5.2 Effect of direct load control (DLC) Technique

According to the direct load control method, some particular loads are turned off for a limited time. By applying this DSM technique, some amount of energy can be saved every day. The summer and winter cases are studied as:

- In the summer case, the freezer is kept off from 8:30 pm to 9:00 pm. Air Conditioner (AC) is kept off from 8:00 pm - 8:30 pm and from 9:00 pm - 9:30 pm. Also, the water heater is kept off from 10:00 pm to 10:30 pm.

The resulted daily average load curve is shown in Figure (7) for the summer case. While, for winter day the appliances which are kept off are:

- The refrigerator is kept off from 7:00 pm to 7:30 pm, and the water heater is kept off from 7:00 pm to 7:30 pm and from 8:30 pm - 9:00 pm. The electric heater is kept off from 8:00 pm to 8:30 pm and from 9:30 pm to 10:00 pm.

The resulted daily average load curve is shown in Figure (8) and Table (5) illustrates the effect of the DLC technique for both cases. It can be concluded that the PAR ratio is decreased, the monthly consumption savings are increased by 5.4 % and 5.9 % also, the electricity bill savings are 5.3 % and 8.95 % in the summer and winter cases, respectively.
Table 5- The obtained results of applying DLC technique

<table>
<thead>
<tr>
<th></th>
<th>Before applied DLC</th>
<th>After applied DLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly Consumption (KWh)</td>
<td>Case 1</td>
<td>983</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>422</td>
</tr>
<tr>
<td>Electricity bill (L.E)</td>
<td>Case 1</td>
<td>1184.94</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>373.96</td>
</tr>
<tr>
<td>Peak of consumption (Watt)</td>
<td>Case 1</td>
<td>2160</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>757.5</td>
</tr>
<tr>
<td>Average of consumption (Watt)</td>
<td>Case 1</td>
<td>682.3</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>293</td>
</tr>
<tr>
<td>(%) PAR</td>
<td>Case 1</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Table 6- The obtained results of applying load shifting technique.

<table>
<thead>
<tr>
<th></th>
<th>Before applied load shifting</th>
<th>After applied load shifting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak of consumption (Watt)</td>
<td>Case 1</td>
<td>2160</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>757.5</td>
</tr>
<tr>
<td>(%) PAR</td>
<td>Case 1</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>2.6</td>
</tr>
</tbody>
</table>

5.3 Effect of Load shifting Technique

Water heater, washing machine, dish washer, microwave oven, and iron can be shifted from peak hour to off-peak hour.

- The load curve after shifting the water heater from (6 p.m-7 p.m.) to (12 a.m-1 p.m.), washing machine from (9 p.m-10 p.m.) to (6 a.m-7 a.m.) and iron from (9: 30 p.m-10 p.m.) to (12 a.m-12: 30 a.m.) is shown in Figure (9) for case 1.
- While for case 2, the water heater shifted from (7 p.m. - 7: 30 p.m.) to (3: 30 p.m. – 4 p.m.), washing machine shifted from (7 p.m. – 8 p.m.) to (12: 30 a.m-1: 30 p.m.), electric heater shifted from (8 p.m. - 8: 30 p.m.) to (4 p.m. - 4: 30 p.m.), and dryer shifted from (6 p.m. - 6: 30 p.m.) to (5 a.m. - 5: 30 a.m.).

Table (6) illustrates the effect of the load shifting technique in both cases, it concluded that:

- The consumption distribution throughout the day is almost uniform, so the average consumption is constant and the peak load demand is reduced.
- A large decrease in PAR value, which leads to enhancing the stability and reliability of power networks.

Figure 9- Daily load curve after applying load shifting for case 1
6. CONCLUSIONS
The electricity consumption of a residential house at Stadium Street in Shebin El-Kom, Menoufa Governorate when applying DSM based on energy efficiency, direct load control, and shifting load have been analyzed. The electricity consumption of two cases study have been obtained for one day in winter and other in summer. is concluded From the results, it:

- Noticeable amount of energy can be saved by replacing normal appliances with energy efficient appliances. So, this technique should be given priority to reduce energy consumption.
- The direct load control technique is not the best among the other two technologies in terms of reducing consumption and saving electricity bills.
- The load shifting technique displays a better result by reducing the PAR ratio where the reduction in PAR and enhances the stability and reliability of the power grids.

So, DSM can change the thinking of constructing a new plant to meet the demand and defers high investment to setup transmission and distribution networks.

6. REFERENCES


