An Evaluation of Demand Side Management in a Grid-Connected PV System in Istanbul, Turkey

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Abstract—The application of renewable energy in electric power system is growing fast. There is an increasing need for economic evaluation to inform the photovoltaic (PV) allocation decisions of a range of decision-makers. For economical operation and control purposes, electric power users with PV systems are interested in the availability and the effects of these systems. This paper presents an evaluation of the solar PV systems that would be installed in Istanbul-Turkey. In addition to the technical and commercial parameters, the measurements are also used to carry out the evaluation. The effect of the solar PV on demand side management is also studied.

I. INTRODUCTION

With the availability of solar photovoltaic (PV)/Battery systems, it is now possible to manage demand to control the energy consumption on the customer’s side. Although PV systems are an expensive option of generating electricity when compared to other systems; this technology has been supported due to its potential benefits, which can be classified as customer-related benefits, electric utility-related benefits and environmental benefits. Earning revenue by selling PV electricity can be given as an example for the customer-related benefits. The examples for the electric utility-related benefits are; reduced transmission and distribution costs and losses, peak shaving, and meeting peak demand. CO2 savings, NOx and SO2 savings can be listed as the environmental benefits of PV systems [1].

The demand for electricity in each area is different and therefore depends on numerous factors, such as the price of electricity, the weather conditions, the time of day, the type of day and the season. The load profiles describe the variation of the electricity demand with time. The hourly load profile provides crucial information on how electricity is used, and thus on where and what demand side management strategies could be potentially effective. Demand Side Management (DSM) is the process of managing the consumption of energy to optimize available and planned generation resources. The most widely accepted definition of demand-side management is the following: “Demand side management is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility’s load shape, i.e., changes in the time pattern and magnitude of a utility’s load” [2].

There are six generic load shape objectives that can be considered during demand-side management planning, namely peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [2]. The desired changes in the load shape can be obtained by shifting load to a less expensive time period, or by substituting another resource for delivered electricity such as solar PV/Battery systems.

The integration of the user demand and local PV generation patterns can help us achieve optimal use of PV electricity. The combination of DSM with PV systems that are grid-connected-type with small-scale electricity storage provides an Active Demand Side Management (ADSM). In this concept, both PV systems operators and consumers connected to the same grid can profit through cooperative strategies [3].

An important part of the demand-side management process involves the evaluation of demand-side to supply-side alternatives and vice versa [4]. The objective of this paper is to evaluate demand side management in the grid-connected solar PV/Battery systems in Istanbul, one of Turkey’s most populated cities with rapid economic growth. The geographical location of the city and the locations of the major power plants are shown in Figure 1.
Both the hourly load data gathered from electricity provider in Istanbul and the solar radiation data collected using the experimental setup in the Technical University of Istanbul are used for the evaluation of DSM, since such information is essential for an informative DSM study.

II. THE DATA ACQUISITION SYSTEM FOR SOLAR SYSTEM DATA COLLECTION

The solar radiation data is very important in figuring out the amount of electricity generated by PV modules. The solar radiation is typically generated by the solar radiation model based on the meteorological data. Several approaches to model solar radiation and to forecast solar irradiance are given in literature [5-6]. The models do not feature real-world effects such as heat, dirt and dust, DC-to-AC inverter conversion efficiency, wiring, weather conditions, etc. In this study, instead of applying the solar radiation models, the power output (i.e. current and voltage) and temperature signals collected from the PV modules are used to obtain real operating conditions for the evaluation of the solar system.

The PV system that charges a lead-acid battery storage system was installed in 2002. The stored energy is used to illuminate a parking lot. The data acquisition system in Figure 2 used in the experiments was developed at our Department of Electrical Engineering and it has been used to collect data since 2002. The photovoltaic panels that generate 2 kW are oriented due south at an angle of 35° from horizontal. The latitude/longitude locations of the panels are 41° 6.3’ N. Latitude, 29° 1.46’ E. Longitude.

In this study, the data obtained in 2009 are to be used for the evaluation. The data are presented in the form of graphs and the results are normalized, since the energy value generated by a solar PV system is a function of the PV array’s size and efficiency, and the availability of the solar resource.

The power output from the solar PV system varies throughout the day, and the patterns and peak values vary depending on the seasons. The variations of the hourly collected power outputs can be seen in Figure 3. The variations of the peak power outputs of solar modules are also given in Figure 4. It can be inferred from these figures that weather conditions affect the power outputs, and the profiles vary from moment to moment. The daily output profile is higher in the summer because there are more hours of sunlight and the angle of the sun is higher during the day.

III. EVALUATION OF DEMAND SIDE MANAGEMENT

The detailed load profiling gives electricity planners crucial information regarding the demand. Such information has been used for demand-side management, system planning, and tariff design. By knowing the load profile, distribution companies and/or customers can plan the improvements and
future investment scenarios [7-8]. In this study, the load profile data obtained with the support of Bosphorus Electricity Distribution Company (BEDAS) are used for the evaluation of the solar PV systems which would be installed in Istanbul-Turkey. Intelligent meters were used to measure the real and reactive power consumption of customers in intervals of 15 minutes. A total of 365 days (a year) of measurements were collected from the distribution transformer, located near the PV modules. The evaluation was performed over a period of one year from Jan 1, 2009 to Dec 31, 2009. It was assumed that 1000 customers, each having a 500 W PV system, were supplied by a 2 MVA transformer. The total surface area of a 500W monocrystalline solar panel is approximately 5 m².

A normalization, which is the conversion of demand values in kW to per-unit values to obtain homogeneous curves, is performed by dividing all measured values by the peak power of the measured load profiles. This process also converts the original measurements to unitless variables [9]. The peak power of the measured load profiles was 1066 kW. An example of a daily load profile obtained on Wednesday, January 21, 2009 is illustrated in Figure 5. It is found that the peak loading for customers occurs from 1:00 pm to midnight. Figure 6 shows the daily load profile obtained on a summer day, Wednesday, July 1, 2009. The demand reaches a peak at 1:00 pm, while the off peak loading is occurred at 6:00 am. In Figure 6, it is found that the power consumption mainly occurs after 10:00 am during the summer.

The contribution of PV system on the demand savings can also be seen from the figures. The area filled with a hatch pattern in the figures shows the demand saving obtained via using PV system. Although this contribution is limited in the winter (Figure 7), the peak summer load coincides with maximum PV output, and the demand savings reach maximum. The amount of energy derived from non-renewable sources drops almost to zero at weekend afternoons (Figure 8).

IV. COST ANALYSIS IN EVALUATION

Electric utilities employ a number of tariffs for electricity pricing, and these tariffs vary from country to country. Depending on the tariffs offered by the utilities, the customers can reduce energy costs in a variety of ways such as using solar PV systems. Turkish Distribution System BEDAS offers two tariffs that are available to residential customers on a voluntary basis. One of the tariffs applies a fixed rate, another applies time-of-use (TOU) rates that provide an incentive for the customers who can distribute loads to lower-cost times of day and thereby reduce their energy bill. The time periods are defined as follows:
Peak: 5:00 p.m. to 10:00 p.m.
Partial-Peak: 6:00 a.m. to 5:00 p.m.
Off-Peak: All other times (10:00 p.m. to 6:00 a.m.)

The cost function for TOU tariff can be given as:

\[
C_{(kWh)} = \begin{cases} 
0.5 \times c \times kWh & \text{if } 10:00 \text{pm} \leq t < 6:00 \text{am} \\
0.95 \times c \times kWh & \text{if } 6:00 \text{am} \leq t < 5:00 \text{pm} \\
1.5 \times c \times kWh & \text{if } 5:00 \text{pm} \leq t < 10:00 \text{pm}
\end{cases}
\]

where \(c\) is the cost of electricity per kWh for the fixed rate tariff. The average cost of residential electricity for the fixed rate tariff was 13.5 ¢/kWh in Turkey in 2009.

The power balance equation for the system with PV can be given as:

\[
\sum_{i=1}^{n} P_{D,i} + \sum_{i=1}^{n} P_{PV,i} = \sum_{i=1}^{n} P_{L,i}
\]

(2)

where,
- \(P_{D,i}\) is the net demand of \(i\) th customer
- \(P_{PV,i}\) is the generated power by \(i\) th customer’s PV system
- \(P_{L,i}\) is the load of \(i\) th customer,
- \(n\) is the number of customers.

Using the total demand, the hourly total energy demand from the utility grid can be calculated. The overall daily energy consumption cost is calculated using:

\[
C_{\text{total}} = \sum_{i=1}^{24} C_{(kWh)} \times W_{D,\text{total}}
\]

(3)

where,
- \(C_{\text{total}}\) is the total daily energy consumption cost
- \(W_{D,\text{total}}\) is the hourly total energy demand from the utility grid

V. CASE STUDY

To evaluate the economic benefits of the solar PV system which would be installed in Istanbul-Turkey, the overall annual energy consumption costs for different cases are calculated using the measurements, and the results are presented in the tables. The tariffs used in the calculations are:

- Tariff 1 which applies a fixed rate,
- Tariff 2 which applies time-of-use (TOU) rates

Feed-in-Tariff (FiT), in which the customers can acquire an income for every kilowatt hour of electricity they generate and sell back to the grid, is also considered for the systems with solar PV. The energy benefit of the solar PV system is calculated for differently sized PV panels (0.5 kW, 1 kW, 2 kW) along the annual load duration curve, bearing in mind the corresponding solar PV system output along this curve. The total annual energy consumption costs for the system without any solar PV are also calculated for both tariffs, and given in the tables. The PV system helps the customers to make money for generating their own energy, since they purchase much less electricity. When they cannot generate enough electricity for their own needs, they can still purchase electricity from the utility. The customers can improve their benefits by selling electricity back to the grid. The overall annual energy consumption costs for both of these cases, namely selling electricity back to the grid or not selling back, are also given in the tables.

<table>
<thead>
<tr>
<th>Case</th>
<th>Tariff 1</th>
<th>Tariff 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without sell-back</td>
<td>With sell-back</td>
</tr>
<tr>
<td>no PV</td>
<td>393,729</td>
<td>393,729</td>
</tr>
<tr>
<td>with PV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 kW</td>
<td>353,997</td>
<td>353,712</td>
</tr>
<tr>
<td>1 kW</td>
<td>317,396</td>
<td>313,694</td>
</tr>
<tr>
<td>2 kW</td>
<td>280,866</td>
<td>233,658</td>
</tr>
</tbody>
</table>

Using the annual load profile, the total energy consumption is calculated to be 2,916,513 kWh/year. As seen from the Table 1, the total energy consumption cost is $393,729 in the case that the customers don’t have any PV systems, and that they all use Tariff 1. The cost is calculated to be $366,753 if all the customers prefer to use Tariff 2. The solar PV systems help the customers to reduce their energy usage costs. With a 2kW solar PV system, the total energy consumption cost is reduced to $280,866 in Tariff 1. If the customers can sell the electricity back, the annual energy benefit value ($/year) will be $160,071, and this amounts to 40.6% off the total cost. In tariff 2, the magnitude of the decrease is 44.3%.

Table 2 shows the total energy consumption cost in July 2009. The total energy consumption is calculated to be 247,360 kWh for this month. The monthly energy benefit value ($/month) reaches a maximum value in July since there are more hours of sunlight. If the customers can sell the electricity back, and use Tariff 2, the cost can be reduced from $30,914 to $4,735. Thus a cost decrease of 85% can be reached.

<table>
<thead>
<tr>
<th>Case</th>
<th>Tariff 1</th>
<th>Tariff 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without sell-back</td>
<td>With sell-back</td>
</tr>
<tr>
<td>no PV</td>
<td>33,394</td>
<td>33,394</td>
</tr>
<tr>
<td>with PV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 kW</td>
<td>27,106</td>
<td>27,106</td>
</tr>
<tr>
<td>1 kW</td>
<td>21,643</td>
<td>20,818</td>
</tr>
<tr>
<td>2 kW</td>
<td>17,844</td>
<td>8,243</td>
</tr>
</tbody>
</table>

To see the potential benefits of a single customer having a solar PV system, the total costs per customer were also calculated, assuming the number of customers supplied by transformer is 1000. Both of the results for the year 2009 and for the month July are given in Table 3 and Table 4, respectively.
Table 3 shows the average monthly energy consumption costs per customer. According to the results, the average cost for 243 kWh/month energy consumption is calculated to be $17 by using a feed-in-tariff and 2kW solar PV panels. In July, the customer’s electricity bill can be reduced to below $5.

**TABLE III. THE AVERAGE ENERGY CONSUMPTION COSTS PER CUSTOMER**

<table>
<thead>
<tr>
<th>Case</th>
<th>Tariff 1</th>
<th>Tariff 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without sell-back</td>
<td>With sell-back</td>
</tr>
<tr>
<td>no PV</td>
<td>32.81</td>
<td>32.81</td>
</tr>
<tr>
<td>with PV</td>
<td>0.5 kW</td>
<td>29.50</td>
</tr>
<tr>
<td></td>
<td>2 kW</td>
<td>20.88</td>
</tr>
</tbody>
</table>

**TABLE IV. THE TOTAL COSTS PER CUSTOMER IN JULY, 2009**

<table>
<thead>
<tr>
<th>Case</th>
<th>Tariff 1</th>
<th>Tariff 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without sell-back</td>
<td>With sell-back</td>
</tr>
<tr>
<td>no PV</td>
<td>33.39</td>
<td>33.39</td>
</tr>
<tr>
<td>with PV</td>
<td>0.5 kW</td>
<td>27.11</td>
</tr>
<tr>
<td></td>
<td>0.5 kW</td>
<td>21.64</td>
</tr>
<tr>
<td></td>
<td>2 kW</td>
<td>17.84</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

There is an increasing need for economic evaluation to inform the photovoltaic (PV) allocation decisions of a range of decision-makers. An evaluation of the solar PV systems that would be installed in Istanbul-Turkey is presented in this paper. Signals such as power outputs, collected from the PV modules and substations as a part of an ongoing project, have been used for the evaluation. The different tariffs such as time-of-use and feed-in-tariff were also taken into consideration, and the effects of the using solar PV systems on the annual cost were obtained. The results show that the customers can reduce the electricity payments by more than 40% by installing solar PV systems.

The study will be extended to estimate solar power production, since forecast information on the expected solar power production is necessary for demand side management. Other future works will feature power system design and operation optimization problems such as the minimization of costs using grid connected Battery Storage PV systems.

VII. REFERENCES


