Smart Meter Based Tools to Enhance Feedback Oriented DSM with Time of Use Rates

N. Athula Kulatunga, R. Loetscher, and S. Kuruppu

Abstract—Time of day electric utility rates (TOU) are unavoidable. Consumers have no idea how TOU rates will impact their energy bills. Studies have shown that TOU accompanies by real-time feedback help reducing energy consumption and shifting loads to off-peak hours. Soon, smart meters with wireless communication capabilities will be in every household. Using the capabilities of smart meters, detailed usage of appliances can be provided to consumers via web applications. By allowing consumers to apply and test the impact of different rates, effectiveness of feedback based DSM can be enhances. Features and capabilities of web application are presented with a real world example.

Index Terms—Smart Grid, Smart Meters, Demand Side Management, Time of Use Rates, Feedback Utility

I. NOMENCLATURE

TOU: time of use
DSM: demand-side management
SM: Smart Meter

II. INTRODUCTION

Smart meters come with variety of features to make electric utility grid smarter. The U.S. Department of Energy identified seven defining traits of a smarter grid:

1. Optimize asset utilization and operating efficiency.
2. Accommodate all generation and storage options.
3. Provide power quality for the range of needs in a digital economy.
4. Anticipate and respond to system disturbances in a self-healing manner.
5. Operate resiliently against physical and cyber attacks and natural disasters.
6. Enable active participation by consumers.
7. Enable new products, services, and markets.

An Advanced Metering Infrastructure (AMI) and visualization technologies must be in place to implement most of the traits described above [1]. In the coming years, electric utility companies in the U.S. will have to replace about 150 million old meters with smart meters with wireless communication capabilities. Those meters are expected to last twenty years or more. Therefore, there is room for new inventions and innovations around smart meters. This paper describes how features of smart meters can be used to enhance consumer participation and utility benefits. Special attention is given to TOU rate structures with real-time feedback.

III. FEEDBACK MECHANISMS

Feedback about the user’s energy consumption can be provided in different forms to the electricity consumers. This can range from a monthly electricity bill in paper form to real-time feedback through a sophisticated in-home-display. Figure 1 [2] shows these distinct feedback methods. The methods can be divided into two main feedback categories and into six different subcategories. The first four categories show “indirect” feedback provided after consumption occurs, and the last two categories represent “direct” feedback provided through in-home-displays. The last two categories requires real time or near real time feedback, which is possible through modern wireless communication based SMs.

![Feedback delivery mechanism spectrum](image)

Fig. 1. Feedback delivery mechanism spectrum

A. Real-time Feedback

Feedback is provided through in-home displays that show the user on a near real-time basis energy consumption-level and the corresponding cost. Some of these devices also show CO2 emissions and indicate the power demand by changing the display color. The in-home display has two preset thresholds: if the power demand passes a certain threshold, the display changes color from green to yellow and red. Green
indicates low power demand, yellow increased demand, and red a high demand. Displaying the home’s power demand by color provides simple feedback to all users. The user does not need any specific knowledge or training to read the information from the display. The in-home display receives information periodically from the smart meter.

B. Real-time Plus Feedback

Real-time Plus category is similar to the previously described category, but shows disaggregated consumption of the individual appliances. A home area network (HAN) is required to monitor all major appliances in real-time. Real-time Plus provides the most sophisticated display and analysis of the user’s energy consumption. Since most appliances in households will not be replaced in the next 10-15 years [3], the appliance’s power demand will be measured by separate meter devices, sending the appliance’s electricity consumption through radio signals or over a wired network to the receiver. The received data can be accessed through the internet, laptop, and handheld devices. Until smart appliances are not widely used, the relatively high costs for the network components and the meter devices will limit wide application of this system. There are also factors which influence the effectiveness of the six categories. The next items show the most important and considerable points for displaying data to the user for obtaining height energy conservation and demand reduction.

- Data is provided frequently, as soon after the consumption behavior as possible.
- It is clearly and simply presented.
- It is customized to the household’s specific circumstances.
- It is provided relative to a meaningful standard of comparison.
- It is provided over an extended period of time.
- It includes appliance-specific consumption breakdown (some studies).
- It is interactive (some studies [4] [5]).

Table 1 delineates the previously described categories and the potential energy savings. The percentage values are average energy savings from 31 studies published between 1980 and 2005. The average energy conservations are based on category one ‘Standard Billing’ [2].

### TABLE 1
**AVERAGE POTENTIAL ENERGY CONSERVATION EFFECTS OF SEVERAL STUDIES**

<table>
<thead>
<tr>
<th>Feedback Category</th>
<th>Avg. Energy Conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat. 1 Standard Billing</td>
<td>0%</td>
</tr>
<tr>
<td>Cat. 2 Enhanced Billing</td>
<td>9%</td>
</tr>
<tr>
<td>Cat. 3 Estimated Feedback</td>
<td>4%</td>
</tr>
<tr>
<td>Cat. 4 Daily/Weekly Feedback</td>
<td>8%</td>
</tr>
<tr>
<td>Cat. 5 Real-Time Feedback</td>
<td>7%</td>
</tr>
<tr>
<td>Cat. 6 Real-time Plus</td>
<td>12%</td>
</tr>
</tbody>
</table>

It appears that the biggest savings can be obtained with category five. However, applying this mechanism requires additional equipment and consumer education, which would increase the implementation costs. In order to maximize energy conservation, providing category five with more detailed information (disaggregated consumption) might have similar high conservation effects. The major difference between mechanism five and six is the disaggregating of the individual appliances. The approach in breaking up the electricity usage of the different appliances and giving the user this information in addition to the in-home displays (mechanism five) might be as effective as category six.

A contemporary study from Hydro One Networks reveals similar results [6]. This study involving 486 participants (residential, farm, and small general service) demonstrates that 153 of its pilot participants responsive to the TOU, instead of Regulated Price Plan (RPP), rates were able to significantly shift their loads and conserve energy. Load-shifting impact averaged 3.7% and conservation impact averaged 3.3%. Participants on TOU rates provided with in-home-displays (IHD) could shift their loads even more. This study also found that “on a normal summer day, the load-shifting impact averaged 5.5%, while the conservation impact averaged 7.6%.

On a hot summer day (over 30°C), the load-shifting impact was even more pronounced at 8.5%.” (Similar results in Table 1). As already mentioned, demand peaks in the grid especially occur during hot summer days. Therefore, this demand reduction is very desirable for unloading the stressed grid and for increasing capacity margins. Table 2 abridges the major findings of the study.

### TABLE 2
**DEMAND REDUCTION AND ENERGY SAVINGS OF HYDRO ONE STUDY**

<table>
<thead>
<tr>
<th>Groups</th>
<th>Demand reduction/shifting</th>
<th>Energy conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPP TOU rates with IHD</td>
<td>-5.5% (-8.5% on a hot summer day)</td>
<td>-7.6%</td>
</tr>
<tr>
<td>RPP TOU rates w/o IHD</td>
<td>-3.7%</td>
<td>-3.3%</td>
</tr>
<tr>
<td>Regular RPP with IHD</td>
<td>n.A</td>
<td>-6.7%</td>
</tr>
<tr>
<td>Regular RPP w/o IHD</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

It is also mentionable that 76% of the study’s participants lowered their electricity bill, compared to the other participants remaining on standard rates. The participants simply shifted their loads for reducing their electricity costs. These participants lowered their electricity bill on average of about $72 per year. By contrast, participants that did shift their loads had a higher bill on average of $24 per year. The study also shows that “72% of the participants indicated that they would like to remain on the RPP TOU rates, and 87% claimed they changed their behavior during the pilot. Only 4% found the changes in their daily activities in response to the RPP TOU rates to be inconvenient.” This high acceptance of TOU rates and the customer’s willingness to change their behavior point out the promising potential of demand reduction and energy conservation for developing feedback software as a web application. The next section provides more details about this software.
IV. NOVEL APPROACH

In-home displays are relatively inexpensive and easy to install. Some manufacturers offer in-home displays which require no installation. These in-home displays receive their information about the current energy consumption through radio signals.

Developing software, which provides data disaggregated for each appliance, could also provide this additional information for customers with in-home displays (category five of Table 1). The data should be accessible as described in the real-time plus category. The software should also be capable of offering the users easily accessible information about their electricity consumption or even provide energy saving tips.

A. Impacts of TOU Rates: Example

This section shows how TOU price schedules applied in two different homes may affect their energy bill. These calculations were performed with the aid of a developed software program. Some of the software features are discussed in this section as well.

To calculate and compare a home’s energy bill using constant vs. TOU price, data from two actual homes located in Indiana were obtained in the month of February. The data was recorded with data-loggers, recording on 10 channels every 8 seconds for one day and each minute during one week. Each measurement contains temperature, current, and Date/Time of the record. For each, daily and weekly measurements, about 140,000 data values were obtained. For the two households, daily and weekly data were recorded (total 560,000 data points for both households).

The electricity-usage of all major electricity consumers were measured and recorded in the electric distribution panel. The recorded data was then saved in a tab delimited text-files. The large amount of data posed a problem, because it first needs to be processed and then graphically presented. The requirement for data-processing software was the ability to compute more than 11,000 rows and more than 140,000 elements in a table per household. The software should also be easy to use (user-friendly graphical user interface GUI) and should not require any proprietary software. For this purpose, software which can process, manipulate, calculate, simulate, and present the tab delimited text-files has been developed.

The program displays graphs and computed numbers to the user. Some of these charts are shown in the next section. Figure 1 depicts the data flow diagram of the developed software.

B. Software Development

The coded program is written in C#, which is a modern object oriented programming language based on C and used primary for professional software developers. The textbook: ‘An Information System Approach to Object-Oriented Programming’ describes the advantages of C# as follow: “C# combines the elegance of C++ with the productivity enhancements offered by Visual Basic through the use of its integrated development environment.” The integrated development environment (IDE), which is part of Visual Studio, allows the development of powerful Windows applications with graphical user interface. The .Net framework offers reusable object classes, organized into a hierarchical namespaces. Developing software with C# allows for the creation of applications on other operating systems, Linux, Apple iPhone and Mac OS X, among others.

C. Software Features

The primary goal of the developed software is to display recorded data in a user-friendly way and to simulate load shifting of appliances. The software can be executed simply by double-clicking on its executable file. It then loads prerecorded data from two Indiana households. The user can also open its own file and name all desired channel names. Figure 3 shows a screen-shot of the entry tab to either open prerecorded data or open your own data.
The user can then display any data of any desired channel by selecting the appropriate radio button on the right side of the user interface. The graph also provides some interactive functionality for zooming as shown in Figure 4.

This interactive functionality is an especially powerful feature if large data quantities are displayed. For example, for weekly, monthly, or even annual data, the program allows the user to easily zoom into a specific date and to show only a few data points of the entire data collection.

The program also shows total energy consumption during the reported time and consumption categorized by appliance. See Figure 5. Energy consumption is further compared to the other recorded appliances and displayed in a pie-chart. Similar to the appliance’s energy consumption, CO2 production of the home is also calculated and graphically shown. In Figure 12 are CO2 production of each appliance, CO2 production for an average Indiana home, and annual CO2 production of the sample home. On the right side of the user interface, the user’s carbon “footprint” is displayed. The size of the carbon footprint in the back relates to the CO2 emissions of an average Indiana home.
D. Applying TOU Rates to the Example

The program allows user to enter TOU rates dictated by user’s area utilities. The daily electricity costs of two homes (under TOU and standard rates) were calculated and compared. The two homes with different load patterns are from the same town. Figure 7 shows the assumed TOU rates for determining the electricity costs of both homes. The Peak electricity price during on-peak times is three times higher than during off-peak times. The mid-range cost is 0.25$/kWh during 7-11am and 5-8pm. The standard rate is 18.75 cents per kWh and was computed by averaging the TOU rates.

Figure 8 and Figure 10 show these two typical load patterns of two homes. Note that these load patterns also include the major appliances (washer, dryer and dishwasher) within a 24 hour period. The stacked hourly demand bars of these two sample days show averaged electricity demands from the recorded data. The total electricity costs \( C_{E,\text{day}} \) during a 24 hour period can be calculated by using Equation 1. The hourly demand is denoted by \( P_{\text{hour}} \) and the variable cost for TOU rates by \( C_i \).

\[
C_{E,\text{day}} = \sum_{i=1}^{24} P_{\text{hour}} i * C_i
\]

Figure 8 shows the load pattern of an Indiana home with two adults and one child. Washer, Dryer and Dishwasher were used during this day. Total electricity consumption is 9.4 kWh.

For this sample day, total energy costs of both applied rates are approximately the same. See Figure 9. The energy costs of the standard rates are 176 cents per day, 2.3 percent higher than the costs for TOU rates. Applied TOU rates result in electricity costs of 172 cents for the sample day. These calculations represent a day in February without any air conditioning running. In a hot summer day, TOU prices may have a considerable influence on the energy bill, especially as demand for room conditioning and the on-peak rates timely coincide.
Figure 10 shows the load pattern of the second Indiana home with two adults and two children. Washer and Dishwasher were also used during this day. Total electricity consumption is 5.3 kWh.

The energy costs for the second home are also about the same for both applied rates. Energy costs of 99 cents result for standard rates and 96 cents for TOU rates. Costs for standard rates are 3.1 percent higher than for TOU rates. The hourly power demand in the previous graph shows that the home was not occupied during the day. Consumers with low demand during on-peak times are good candidates for TOU rates and may consider signing up, even if TOU rates are not mandatory.

TOU rates can significantly influence air conditioning costs of a home. Assume that the electricity costs for air conditioning account for about 12% [7]. As the need for air conditioning rises during the morning, TOU prices also increase. In the early afternoon, air conditioning demand reaches its peak which coincides with the TOU on-peak rate. In the late afternoon and evening when demand for air conditioning decreases, the TOU rates decrease as well. Assuming that 60% of the electricity is consumed during on-peak times and 40% during mid-peak times, TOU rates could raise air conditioning costs by 39%. Based on the 12% A/C cost, the total electricity cost of an average US home increases by 4.6%, due to applied TOU rates for air conditioning.

\[
\left( \frac{30}{18.75} \times 60\% + \frac{20}{18.75} \times 40\% \right) - 100\% = 39\%
\]

V. AUTOMATIC METER READING (AMR) PORTAL

The software tool described above needs data. This data can be collected via current clamps connected to the electrical distribution panel at the service entry point or they can be downloaded from a smart meter. The catch is that SMs are designed to measure current through the feeder conductors. However, the above software can be expanded to determine to guess usage pattern by asking consumers to perform certain tasks and monitoring change of currents when different appliances are turned on and off. The details will be presented in a separate paper.

All decision makers such as controllers, in-home displays, automatic thermostats, etc. must have some automatic meter reading (AMR) capabilities. All meter manufacturers provide circuit developers needed information to read data from tables located in smart meter memory.

Figures 12, 13, and 14 depict screen captures of AMR application developed at Smart Meter Integration Lab. It reads data every second from a SM and display energy profile and cost calculation according to a selected rate structure. Consumer can a predetermine rate structure or consumer’s own rate structure.
The energy portal was developed by using Visual Basic and it communicates to the SM via Zigbee wireless communication adapter. The rate input window shown in Figure 13 allows consumer to set rates or select pre made rate schedules. This feature also helps industrial consumers and utilities to experiment with different TOU rates.

VI. CONCLUSIONS

In summary, consumers will be able to better understand and manage their electrical energy usage when appropriate tools are available to them. If the TOU rates are available to consumers, residential, commercial, and industrial, the developed tool allows them to analyze the energy use under different circumstances. By integrating above tools with almost real time capabilities of newer smart meters, it is possible to successfully implement Real Time and Real Time Plus direct feedback response to consumers, which has shown more than 10% of energy saving capabilities.

VII. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Tom Martin and Landis+Gyr corporation for providing necessary development tools and background information.
VIII. REFERENCES


IX. BIOGRAPHIES

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