Demand Side Management in Power Distribution Systems
Algorithmic Development for Peak Demand Shaving

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Abstract

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Overloading is one of the most significant challenges in the electric network. It causes abrasion and sometimes energy shortages. In the past, this problem used to be solved by suppliers of electricity. Over the last decade, researchers have been working on new technological advancements within the realm of “smart grid”, where electricity customers and consumers are offered a more active role than they used to have earlier, and they are able to manage their loads and electricity consumptions. This opportunity is called demand side management (DSM). This system is suitable for residential houses or commercial buildings. With demand-side management, systems become more intelligent, and both supplier and consumer sides become active. Demand-side manager works as a time manager, where it controls all loads and decides which load to be active in different time periods.

This thesis is focused on development of a demand-side management control algorithm in a residential house, aiming at the creation of higher flexibility in demand and a better integration of the renewable technologies locally. To make a decent algorithm applicable to real world scenarios, physical models of appliances within a house are developed and several different scenarios are investigated, where customer comfort and local limits are taken into consideration.

Keywords:
Home energy management system (EMS), demand limits, non-critical loads, load priority, real-Time Pricing
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## Nomenclatures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{wall}$</td>
<td>Area of wall</td>
<td>ft²</td>
</tr>
<tr>
<td>$A_{ceiling}$</td>
<td>Area of ceiling</td>
<td>ft²</td>
</tr>
<tr>
<td>$A_{window}$</td>
<td>Area of house windows</td>
<td>ft²</td>
</tr>
<tr>
<td>$A_{windowsouth}$</td>
<td>Area of the windows facing south</td>
<td>ft²</td>
</tr>
<tr>
<td>$A_{tank}$</td>
<td>Surface area of the tank</td>
<td>ft²</td>
</tr>
<tr>
<td>$C_{air}$</td>
<td>The specific heat capacity of air for a typical room condition</td>
<td>Btu/°F.ft³</td>
</tr>
<tr>
<td>$C_{battery}$</td>
<td>Rated capacity of the battery</td>
<td>kWh</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Air sensible heat factor</td>
<td>Btu/°F.ft³</td>
</tr>
<tr>
<td>$D_{AC,i}$</td>
<td>Demand response control signal for AC unit at time slot $i$</td>
<td></td>
</tr>
<tr>
<td>$D_{WH,i}$</td>
<td>Demand response control signal for WH unit at time slot $i$</td>
<td></td>
</tr>
<tr>
<td>$D_{CD,i}$</td>
<td>Demand response control signal for CD unit at time slot $i$</td>
<td></td>
</tr>
<tr>
<td>$D_{EV,i}$</td>
<td>Demand response control signal for EV unit at time slot $i$</td>
<td></td>
</tr>
<tr>
<td>$E_{dr}$</td>
<td>Energy used in driving</td>
<td>kWh</td>
</tr>
<tr>
<td>$f_{ri}$</td>
<td>Hot water flow rate at time slot $i$</td>
<td>gpm</td>
</tr>
<tr>
<td>$G_i$</td>
<td>Heat gain rate of the house during time slot $i$</td>
<td>Btu/h</td>
</tr>
<tr>
<td>$H_p$</td>
<td>Heat gain from one-person</td>
<td>Btu/h</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>$H_{solar}$</td>
<td>Solar radiation power</td>
<td>W/m²</td>
</tr>
<tr>
<td>$M$</td>
<td>Total number of drying levels</td>
<td></td>
</tr>
<tr>
<td>$n_p$</td>
<td>Number of households</td>
<td></td>
</tr>
<tr>
<td>$P_{AC}$</td>
<td>Rated power of the AC unit</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{AC,i}$</td>
<td>Power consumption of the AC unit at time slot $i$</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{WH}$</td>
<td>Rated power of the WH unit</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{WH,i}$</td>
<td>Power consumption of the WH unit at time slot $i$</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{CD}$</td>
<td>Rated power of the CD unit</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{CD,i}$</td>
<td>Power consumption of the CD unit at time slot $i$</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{EV}$</td>
<td>Rated power of the EV unit</td>
<td>kW</td>
</tr>
<tr>
<td>$P_{EV,i}$</td>
<td>Power consumption of the EV unit in time slot $i$</td>
<td>kW</td>
</tr>
<tr>
<td>$R_{tank}$</td>
<td>Heat resistance of water heater tank</td>
<td>°F.ft².h/Btu</td>
</tr>
<tr>
<td>$R_{ceiling}$</td>
<td>Heat resistance of ceiling</td>
<td>°F.ft².h/Btu</td>
</tr>
<tr>
<td>$R_{wall}$</td>
<td>Heat resistance of house wall</td>
<td>°F.ft².h/Btu</td>
</tr>
<tr>
<td>$R_{window}$</td>
<td>Heat resistance of house windows</td>
<td>°F.ft².h/Btu</td>
</tr>
<tr>
<td>$SHGC$</td>
<td>Solar heat gain coefficient of windows</td>
<td></td>
</tr>
<tr>
<td>$SOC_i$</td>
<td>State of charge for the battery at time slot $i$</td>
<td></td>
</tr>
<tr>
<td>$SOC_{max}$</td>
<td>Maximum state of the battery at fully charged</td>
<td></td>
</tr>
<tr>
<td>$SOC_0$</td>
<td>Initial charge state of battery</td>
<td></td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature</td>
<td>°F</td>
</tr>
<tr>
<td>$T_{accumilaited}$</td>
<td>Accumulated time of the drying operation</td>
<td>minutes</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Room temperature at time slot $i$</td>
<td>°F</td>
</tr>
</tbody>
</table>
\( T_{\text{inlet}} \)  \hspace{2em} \text{Inlet water temperature}  \hspace{2em} ^\circ\text{F}

\( T_{\text{required}} \)  \hspace{2em} \text{Required time for drying operation}  \hspace{2em} \text{minutes}

\( T_{\text{out},i} \)  \hspace{2em} \text{Outdoor temperature at time slot } i  \hspace{2em} ^\circ\text{F}

\( T_{\text{outlet},i} \)  \hspace{2em} \text{Outlet temperature in the water heater tank}  \hspace{2em} \text{ft}^3

\( V_{\text{house}} \)  \hspace{2em} \text{Volume of the house}  \hspace{2em} \text{ft}^3

\( V_{\text{tank}} \)  \hspace{2em} \text{Volume of the tank}  \hspace{2em} \text{ft}^3

\( W_{\text{AC},i} \)  \hspace{2em} \text{On-Off status of the AC unit in time slot } i

\( W_{\text{WH},i} \)  \hspace{2em} \text{On-Off status of the WH unit in time slot } i

\( W_{\text{CD},i} \)  \hspace{2em} \text{On-Off status of the CD unit in time slot } i

\( W_{\text{EV},i} \)  \hspace{2em} \text{On-Off status of the EV unit in time slot } i

**Abbreviations**

- \text{AC} \hspace{2em} \text{Air Conditioner}
- \text{WH} \hspace{2em} \text{Water Heater}
- \text{CD} \hspace{2em} \text{Clothes Dryer}
- \text{EV} \hspace{2em} \text{Electric Vehicle}
- \text{DL} \hspace{2em} \text{Demand Limit}
- \text{DR} \hspace{2em} \text{Demand Response}
- \text{EMS} \hspace{2em} \text{Energy Management System}
Chapter 1: Introduction

This chapter introduces the concept of demand-side management (DSM) and describes its development practices. Subsequently, modelling the house physical devices are accomplished and a demand-side management algorithm will be introduced. Finally, peak shaving method will be applied during peak hours and the results will be evaluated.

1.1 Problem Description

Power system operators are continuously seeking solutions that ensure adequate generation is available to meet the projected demand in future. Traditionally this requirement is met through controlling the supply side (i.e., generators) in power systems and limited priority was placed on involving the demand side. However, increased investment in development of a “Smart Grid” [1] is driving new opportunities for the demand side to take a more active role in power system planning and operations. Demand Side Management (DSM), also referred to often as Demand Response (DR), is a class of programs that are designed to motivate end-use customers to modify their electricity usage. This could be realized through shifting of electricity usage to another time slots (e.g., off-peak hours).

This project develops an algorithm that can automatically control some loads in a house-hold setting to reduce the total power consumption at peak demand periods without
violating consumer’ comfort levels. Among its advantages is that it can save energy and money without any customer comfort violation. Residential loads are classified into the following load types: space cooling/heating, water heating, clothes drying, cooking, refrigeration, freezer, lighting, and others. In this study, these load types are classified into two broad categories: controllable and critical. Water heater, air conditioner, clothes dryer and electric vehicle are employed as the controllable set of loads in this project.

To prevent the consumers’ comfort violation, every load is assigned a certain priority level that is determined by the consumers. Also, minimum power consumption is determined by evaluating the reasonable energy levels. Too low or high limits negatively affects the comfort limits. When house power consumption reaches the peak demand, the algorithm keeps that consumption below a certain level which is determined earlier. The algorithm can compare the priority levels and automatically shift the operational time of individual devices/appliances.

The world’s population is increasing. Today, the world population has reached 7.5 billion people. It is estimated that this population will be around 8.5 billion people by 2030.
Figure 1.1: Global energy demand in the world by 2030 [2]

Such a drastic change in population has a significant impact on the global energy demand. Figure 1.1 illustrates that this energy demand is on the rise. We will be needing additional generation sources to meet this increasing demand. However, the available energy resources are not endless. Besides, resources such as coal, oil and natural gas cause negative greenhouse effect that should be carefully managed to prevent a violation of the environmental concerns. Clean sources of energy is one of the best solutions to reduce CO$_2$ emissions and generate additional electricity more cost-effectively.

Renewable energy industry has grown in the past decade. Scenarios show renewables providing 57% of world electricity by 2050. Investments have reached nearly $286 billion, more than six times in 2004. Producers can take advantages to prefer renewable energy, because sources are endless and plant locations are flexible. Second, renewable energy is a good way to decrease CO$_2$ emissions. In 2015, nearly 200 countries signed up to the 17 goals of the 2030 Agenda for the Paris Climate Change Agreement. Renewable resources are vital to reduce CO$_2$ emissions and DSM has an important role to
integrate old systems with new technology. Wind power could save as much as 1.5 billion tons of CO₂ every year by 2020. California utility found that its investments in grid and renewables would result in benefits to society worth USD 391 million to USD 1.32 billion and avoid emission of 7.7 million tons of carbon dioxide [3]. On the other hand, renewable energy systems have not yet reached their maximum efficiency. Thus, solutions have to be sought on paving this transition period more effectively.

![Electricity sales by sector (2010-40)](image)

According to Figure 1.2, industrial, commercial, residential and transportation sectors have shared the biggest portion of energy consumption in the world. Electricity use in residential sector accounts for significant portion of this total energy consumption both in developing and the western world. From Figure 1.3, one can understand that the hourly electricity consumption follows a pattern that changes at each hour. The load curve is not
straight and linear, but fluctuates over time. It reaches its maximum and minimum point in different hours of the day. High points are known as *peak demand* that occurs mostly during evening hours when the people get back home.

![Graph showing residential energy demand in a 24-hour period](image)

**Figure 1.3**: Residential energy demand in a 24-hour period [5]

Diurnal hours are divided into the *on-peak* period between 17:00-22:00, the *off-peak* period between 22:00-06:00 and the *mid-peak* period between 06:00-17:00. These time periods reflect the level of electricity demand to be served in the electricity network. During off-peak period, electricity prices will be cheaper than that at other times intervals. The role of load control is to change the load curve shape in such a way that the energy consumption peak decreases, while the total consumption for a specific household is remained unchanged.
Residential consumption varies depending on the type of the loads. Controllable loads are defined as the loads that can be controlled without noticeable impacts on the consumer's life-style. Loads in this category can include space cooling, space heating, water heater, and clothes dryer loads. The other category contains loads that are either very important (critical loads) or those that cannot be controlled [7].

The peak demand point in the grid occurs for a short period. To meet the peak demand, high-cost generating stations are needed. Adding more generation was the solution strategy followed in the recent past to meet the rising electricity demand while extra demand affects the grid operation negatively. As a result, suppliers address this challenge by reflecting it through an additional price to consumers. Most people are not aware of the higher electricity price at peak hours. Researchers are working on reducing the peak energy demand through demand side management. Loads and electricity usage through some appliances can be delayed, controlled or shifted with DSM techniques [8].
A demand side management system plays a vital role in residential demand response (DR) applications in a smart grid environment. Its position includes the ability to manage electrical energy (kWh) and demand (kW) based on the utility signals, load priorities and customer preference without consumer’ comfort violation. The system is designed to effectively interact with new technologies such as renewable energy or electric vehicles. Moreover, all this process can be accomplished in a more sustainable and safe manner thanks to the advanced software programs already available or yet to be developed.

1.2 Thesis Outline

This thesis is organized in five chapters. The first chapter provided a general background on the smart grid and energy management systems, where the problem definition was explored.

Chapter 2 provides a literature review on the topic, exploring the challenges that have been researched so far and the solution technologies proposed by the researchers.

In Chapter 3, non-critical loads are introduced, mathematical formulations and customer-related limits are proposed, and though the critical customer comfort levels, all physical load models are developed.

Chapter 4 presents the proposed home energy management algorithm where the impacts on the loads are investigated.

Chapter 5 is focused on the numerical results where the solutions are studied with and without the home energy management systems. The simulation results for the developed load models are presented and fully discussed. Different electricity pricing mechanisms in the electricity market are applied and the performance of the developed
algorithm in the electricity billing systems is explored. The impact of the solar panel systems on the electricity prices is also investigated.

Chapter 6 presents the concluding remakes and introduces the future research avenues. Appendix A, B, C and D are devoted to the data utilized in this study, and the developed MATLAB codes for the simulations are also attached.
Chapter 2: Literature Review

A smart grid is an autonomous electricity environment able to deliver electricity in a controlled and smart way from points of generation to consumers. These consumers are considered an integral part of a smart grid as they can alter their purchasing patterns and behaviors based on the received signals and information, incentives, and dis-incentives realizing a two-way communication [9]. A smart grid environment engenders an improved system reliability performance, customers’ responsiveness, and encourages more efficient decisions by the customers and the utility provider [10]. Smart grids play a critical role in transforming the traditional power grid into a user-oriented service that provides high-security, high-quality, and efficient energy grids. Despite the significant advantages of smart grids, maintaining their sustainability requires the total capacity of installed generation in the system to be larger than the maximum load demand as well as additional control mechanisms in order to respond to emergencies; this ensures the security of supply in the face of various uncertainties (e.g. generation breakdowns and interruptions to primary fuel sources) and variations in generation and demand due to changing weather conditions [11]. Hence, DSM is found to be an efficient way to increase the power grid reliability and resiliency.

Demand side management refers to a modification of normal consumption patterns of electrical usage by end-use customers in response to changes in the price of energy or to customer pay incentives in order to reduce electricity price and usage in periods with a high wholesale market price or lack of energy supply [12]-[14]. The idea of managing demand side resources has been discussed since 1890’s, as described in detail in [15]. However, it was not well addressed until the restructuring and deregulation era of electric
utilities in the 1990’s and subsequent issues that began to arise in the new wholesale electricity markets when a concerted effort was made to include DSM as an essential aspect of such new market developments [16]. In support of this, the United States government has issued a number of policies in an effort to remove impending barriers to DSM participants [17]-[20]. These programs have been identified with the potential to provide a wide ranging benefits to both power system operators and the end-use consumers [21]-[23].

In order to levelize the peak demand, three common load management strategies are frequently used: (i) load shifting, (ii) peak clipping and (iii) valley filling.

Figure 2.1: Load management strategies: peak clipping, load shifting and valley filling

**Peak Clipping:** Reduction of load during short usage peaks is known as peak clipping. Generally peak clipping is done through direct load control. In this method, the utility directly disconnects consumer appliances when a critical operational situation occurs. This direct control can be used to reduce capacity requirements, operating costs, and dependence on critical fuel [24].
Valley Filling: Building loads during off-peak periods is known as valley filling. This will help to reduce the average price of electricity. One of the most promising methods of valley filling is off-peak industrial production, which displaces the loads served by fossil fuels with electricity [24].

Load Shifting: Load shifting moves peak loads to off-peak time periods without necessarily changing the overall consumption. This method combines the benefits of peak clipping and valley filling by moving the existing loads from on-peak to off-peak hours [24].

All these approaches provide some possible benefits that include:

- *Reduction in grid demand during peak hours and subsequent reduction in the reliance on expensive peaking units* [25]. In the United States, DSM potential is estimated to be between 38GW and 188GW power by 2019 [21]. Peak reduction also has the added potential to defer the transmission system infrastructure upgrades that may otherwise be required to expand system capacity [26].

- *Reduction in wholesale energy prices and decreased price volatility*. Even a small increase in the demand elasticity can offset the extreme increase in generation cost at high demand levels [16], [27].

- *Increased system reliability*. DSM resources can be scheduled in the ancillary services market for regulation, spinning reserve, or to support the integration of renewable resources [28]-[32].

- *Reduced electricity costs and new revenue opportunities through the local electricity market operator for the end-user.*
Chapter 3

3.1 Development of Physics-Enabled Residential Load Models

In this section, controllable loads are identified and models for physical devices are developed. Four loads are chosen to be managed through the DSM approach with special consideration to some critical loads. Critical loads are not controllable, but they have a significant impact on the total power consumption. All power intensive non-critical loads are developed in accordance with [33].

3.2 Air Conditioning Load Model

AC unit keeps the room temperature between certain limits. Every time slots depend on one step earlier. The air conditioning model with its inputs, outputs and corresponding parameters are demonstrated in Figure 3.1 [33].

![Figure 3.1: AC unit load model [33]](image-url)
In the beginning, the AC system is off. The system will evaluate the room temperature at first and then compares it with respect to its set points. If the temperature is lower than the maximum set point, it is tolerable, and the AC can keep being off. When the room temperature exceeds the desirable set point, the AC system is sent a signal to switch on. The system keeps working until temperature drops below the set point. The status of the AC system remains unchanged if it is within the allowable range. The air conditioning system is defined as follows:

\[
W_{AC,i} = \begin{cases} 
0, & Ti < Ts - \Delta T \\
1, & Ti \geq Ts - \Delta T 
\end{cases} \quad (3.1)
\]

\[
W_{AC,i} = W_{AC,i-1} \quad Ti - \Delta T \leq Ti \leq Ts + \Delta T
\]

These conditions are same for the heating system (3.2). The heating system works when the room temperature goes down below the desired set point. It keeps working until the room temperature reaches the tolerable limits.

\[
W_{AC,i} = \begin{cases} 
0, & Ti > Ts - \Delta T \\
1, & Ti < Ts + \Delta T 
\end{cases} \quad (3.2)
\]

\[
W_{AC,i} = W_{AC,i-1} \quad Ts - \Delta T \leq Ti \leq Ts + \Delta T
\]

\[W_{AC,i}\]  the status of the space cooling/space heating unit at time slot \(i\)

\(Ti\)  room temperature data at time slot \(i\)

\(Ts\)  thermostat set point

\(\Delta T\)  dead band of AC unit

For this project, our set point (\(Ts\)) is determined as:

- Maximum room temperature: 74 °F
- Minimum room temperature: 68 °F
3.2.1 Power Demand of the AC Unit
AC system has two conditions: either on or off status. It consumes power only when it turns on. The energy consumption of the AC unit is calculated as follows:
\[ P_{AC,i} = P_{AC} \cdot W_{AC,i} \]  

\( P_{AC,i} \)  The demand for electricity of the space cooling/space heating at time slot \( i \)
\( P_{AC} \)  The rated power of the space cooling/space heating system
\( W_{AC,i} \)  On-off status of the space cooling/space heating unit at time slot \( i \)

3.2.2 Room Temperature Determination
The room temperature at time slot \( i \) depends on many parameters. Every time slot has a direct correlation with the one step earlier [33]. Equation (3.4) is employed to calculate the room temperature by taking such important factors into consideration.
\[ T_{i+1} = T_i + \Delta t \cdot \frac{C_{HV,AC}}{\Delta c} \cdot W_{AC,i} \]  

\( T_i \)  Room temperature at time slot \( i \)
\( \Delta t \)  Length of time slot \( i \)
\( C_{HV,AC} \)  Cooling/ heating capacity, positive for heating and negative for cooling
\( \Delta c \)  Energy needed to change 1 °F temperature in the room
\( W_{AC,i} \)  On-off status of the AC unit at time slot \( i \)

Heat Gain (\( G_i \)) is also dependent to several parameters and should be calculated separately as follows [33].
\[ G_i = \left( \frac{A_{\text{wall}}}{R_{\text{wall}}} + \frac{A_{\text{ceiling}}}{R_{\text{ceiling}}} + \frac{A_{\text{window}}}{R_{\text{window}}} + \frac{11.77 \text{ Btu}}{F \times ft^3} \times n_{\text{ac}} \times V_{\text{house}} \right) \times (T_{\text{out,}i} - T_i) + \text{SHGC} \times A_{\text{windowsouth}} \times H_{\text{solar}} \times \frac{3.412 \text{ Btu}}{10.76 ft^2} + H_p \] (3.5)

\( G_i \)  Heat gain rate of the house at time slot \( i \), positive value results in an increase in room temperature and negative value results in a decrease in room temperature

\( A_{\text{wall}} \)  Area of the wall

\( A_{\text{ceiling}} \)  Area of ceiling

\( A_{\text{window}} \)  Area of house windows

\( A_{\text{windowsouth}} \)  Area of the windows facing south

\( R_{\text{wall}} \)  Heat resistance of wall

\( R_{\text{ceiling}} \)  Heat resistance of ceiling

\( R_{\text{window}} \)  Heat resistance of house windows

\( n_{\text{ac}} \)  Number of air conditioners in each time slot

\( V_{\text{house}} \)  House volume

\( T_{\text{out,}i} \)  Outdoor temperature at time slot \( i \)

\( \text{SHGC} \)  Solar heat gain coefficient of windows

\( H_{\text{solar}} \)  Solar radiation heat power

\( H_p \)  Heat gain from one-person

Energy required to change the house temperature by 1 °F, is calculated as below.

\[ \Delta c = C_{\text{air}} \times V_{\text{house}} \] (3.6)
Δc  Energy needed to change the temperature in the room by 1 °F

$C_{air}$  Specific heat capacity of air for a typical room condition

$V_{house}$  House volume

### 3.2.3 Model Development

In this project, the data for the air conditioner model in a typical house is utilized and programmed with the granularity resolution of 1 minute intervals. Table 3.1 summarizes the data corresponding to the air conditioner. The system is designed for a typical summer day. AC unit characteristics are borrowed from the ASHRAE handbook in [34].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δt</td>
<td>1/60 hours</td>
</tr>
<tr>
<td>$C_{HV, AC}$</td>
<td>33000 Btu/h</td>
</tr>
<tr>
<td>$A_{wall}$</td>
<td>1564 ft$^2$</td>
</tr>
<tr>
<td>$A_{ceiling}$</td>
<td>2664 ft$^2$</td>
</tr>
<tr>
<td>$A_{window}$</td>
<td>228 ft$^2$</td>
</tr>
<tr>
<td>$R_{wall}$</td>
<td>12 °F·ft·h/Btu</td>
</tr>
<tr>
<td>$R_{ceiling}$</td>
<td>32 °F·ft$^2$·h/Btu</td>
</tr>
<tr>
<td>$R_{window}$</td>
<td>2 °F·ft$^2$·h/Btu</td>
</tr>
<tr>
<td>$C_s$</td>
<td>1.177 Btu/°F·ft$^2$</td>
</tr>
<tr>
<td>ACH</td>
<td>0.5 changes/h</td>
</tr>
<tr>
<td>$V_{house}$</td>
<td>21312 ft$^2$</td>
</tr>
<tr>
<td>$T_{out, air}$</td>
<td>93 °F</td>
</tr>
<tr>
<td>SHGC</td>
<td>0.67</td>
</tr>
<tr>
<td>$A_{windowsouth}$</td>
<td>32 ft$^2$</td>
</tr>
<tr>
<td>$H_{solar}$</td>
<td>Appendix A</td>
</tr>
</tbody>
</table>

16
In this section, the model adopted for the water heater is developed to determine the hot water temperature. Similar to the Ac system, the water heater is also assigned desirable limits. The main goal is to keep the water temperature within certain limits. The water heater model is generally illustrated in Figure 3.2.

![Water Heater Load Model](image)

Figure 3.2: Water Heater (WH) unit load model [33]

If the water temperature is above the set point, the system does not operate. When the water temperature drops to a certain limit, the heat coil starts working until the hot
water temperature reaches the upper limit. The status of the WH remains unchanged if it is within the allowable range.

This situation is formulated and expressed as follows:

\[
W_{wh,i} = \begin{cases} 
0, & \text{Outlet, } i > Tf \\
1, & \text{Outlet, } i < Tf + \Delta Tw
\end{cases}
\]  

\[W_{wh,i} = W_{wh,i-1} \quad Tf - \Delta Tw \leq \text{Outlet, } i \leq Tf\]  

\(W_{wh,i}\) Mixed water temperature in the tank at time slot \(i\)

\(Tf\) Hot water temperature set point

\(\Delta Tw\) Lower tolerance

\(W_{wh,i}\) On-off status of the water heater at time slot \(i\)

### 3.3.1 Power Demand of the Water Heater

Power consumption of the water heater depends on its status over time. Power consumption is calculated only when the water heater is on and is expressed blow [33]:

\[P_{wh,i} = W_{wh,i} \cdot P_{wh} \cdot n_{wh}\]  

\(P_{wh}\) Rated power of the water heater

\(n_{wh}\) Efficiency factor;

\(W_{wh,i}\) On-off status of the water heater at time slot \(i\)

For this project, the set point (\(Tf\)) is determined as follows:

Maximum water temperature: 118 °F
Minimum water temperature: 108°F
3.3.2 Determination of Water Temperature of the Tank

Water temperature of the tank is affected by the outdoor temperature, shape of the tank and so on. The temperature is determined via the following formulation.

\[
T_{\text{outlet},i+1} = T_{\text{outlet}} - \frac{V_{\text{tank}}}{V_{\text{tank}}} f_{ri} \cdot \Delta t + \frac{T_{\text{inlet},i} - f_{ri} \cdot \Delta t}{V_{\text{tank}}} \left( \frac{1}{8.34 \text{ lb}} \times \left[ \frac{p_{\text{wh},i}}{V_{\text{tank}}} \times \frac{3412 \text{ Btu}}{kWh} \right] \right) - \left( \frac{A_{\text{tank}} \times (T_{\text{outlet},i} - T_a)}{R_{\text{tank}}} \right) \times \Delta t \text{ min} \times \frac{1}{60 \text{ h}} \times \frac{1}{V_{\text{tank}}}
\]

(3.9)

\[ T_{\text{outlet}} \quad \text{Outdoor temperature in the tank} \]

\[ T_{\text{inlet}} \quad \text{Temperature of inlet water} \]

\[ T_a \quad \text{Room temperature} \]

\[ f_{ri} \quad \text{Hot water flow rate at time slot } i \]

\[ A_{\text{tank}} \quad \text{Surface area of the tank} \]

\[ V_{\text{tank}} \quad \text{Volume of the tank} \]

\[ R_{\text{tank}} \quad \text{Heat resistance of the tank} \]

\[ \Delta t \quad \text{Duration of each time slot} \]

3.3.3 Model Development

In this project, the data for the water heater model in a typical house is utilized and programmed with the granularity resolution of 1 minute intervals. Table 3.2 summarizes the data for the modeled water heater. The ambient temperature is taken the same as the room temperature.
Table 3.2: Parameters of the WH unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$</td>
<td>1 minute</td>
</tr>
<tr>
<td>$T_{outlet}$</td>
<td>118 °F</td>
</tr>
<tr>
<td>$T_{inlet}$</td>
<td>68 °F</td>
</tr>
<tr>
<td>$T_a$</td>
<td>$T_i$</td>
</tr>
<tr>
<td>$f_{ri}$</td>
<td>Appendix B</td>
</tr>
<tr>
<td>$A_{tank}$</td>
<td>14 ft$^2$</td>
</tr>
<tr>
<td>$V_{tank}$</td>
<td>80 gallons</td>
</tr>
<tr>
<td>$R_{tank}$</td>
<td>16 °F ft$^2$.h/Btu</td>
</tr>
<tr>
<td>$P_{AC}$</td>
<td>4 kW</td>
</tr>
<tr>
<td>$n_{wh}$</td>
<td>0.85</td>
</tr>
</tbody>
</table>

2.4 Clothes Dryer Load Model

The inputs, outputs and the built-in parameters for the clothes dryer (CD) model [33] are illustrated in Figure 3.3.

![Cloth Dryer Load Model](image)

Figure 3.3: The CD unit load model [33]

Starting time and durations are the most critical parameters for a clothes dryer. Starting time is appointed by the consumers. The clothes dryer operates until the accumulated time is less than the required duration and is modeled as follows.
\[ W_{CD,i} = \begin{cases} 0, & \text{otherwise} \\ 1, & T_{\text{accumulated}} \geq T_{\text{required}} \end{cases} \]  

\( W_{CD,i} \) On-off status of the clothes dryer at time slot \( i \)

\( T_{\text{accumulated}} \) Accumulated time of the drying operation

\( T_{\text{required}} \) Required time/duration of the drying operation

### 3.4.1 Power Demand of the Clothes Dryer

The clothes dryer has two types of parameters: those related to the heating coil and those corresponding to the motor part. The latter consumes tolerable power, and so, it works continuously; the heating coil, however, should be managed. Main power demand is calculated as:

\[ P_{CD,i} = k \cdot P_h \cdot W_{CD,i} + P_m \cdot W_{CD,i} \]  

\( P_{CD,i} \) The electricity demand of the CD at time slot \( i \)

\( P_h \) Rated power of clothes-dryer heating coil

\( k \) Drying level (\( k=1/M, 2/M, \ldots M/M \))

\( M \) Total number of drying levels

\( P_m \) Power consumption of the dryer’s motor

\( W_{CD,i} \) On-off status of the clothes-dryer’s heating coils at time slot \( i \)

### 3.4.2 Model Development

A typical clothes dryer with total power consumption of 4 kW has been selected in this study and Table 3.3 summarizes the data used in the clothes dryer model.
Table 3.3: Parameters of CD unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$</td>
<td>1 minute</td>
</tr>
<tr>
<td>$P_{hc}$</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>M</td>
<td>5</td>
</tr>
<tr>
<td>$P_m$</td>
<td>0.3 kW</td>
</tr>
<tr>
<td>Start time</td>
<td>6 p.m.</td>
</tr>
<tr>
<td>Duration</td>
<td>90 minutes</td>
</tr>
</tbody>
</table>

3.5 Electric Vehicle Load Model

Electric vehicles operation is mainly dependent to three primary conditions: starting time, battery state of charge (SOC) and the rated power. The system works until it is fully discharged. The electric vehicle model, its inputs, outputs and built-in parameters are illustrated in Figure 3.5.

![Electric Vehicle Load Model](image)

Figure 3.5: Electric vehicle load model [33]

The status of the electric vehicle is determined as follows:
\[ W_{EV,i} = \begin{cases} 0, & SOC_i \geq SOC_{max} \\ 1 & SOC_i < SOC_{max} \end{cases} \]  

\( W_{CD,i} \) Status of the electric vehicle at time slot \( i \)

\( SOC_i \) Charge state of the battery at time slot \( i \)

\( SOC_{max} \) Charge state of the battery at the fully-charged condition

SOC primarily depends on the earlier time slot, used energy, and capacity of the battery.

\[ SOC_0 = 1 - \frac{E_{dr}}{C_{batt}} \]  

\[ SOC_i = SOC_{i-1} + P_{EV} \cdot \frac{\Delta t}{C_{batt}} \]

\( SOC_0 \) SOC when EV is plugged in

\( \Delta t \) Length of time slot

\( E_{dr} \) Energy used for driving

\( C_{batt} \) Battery rated capacity

### 3.5.1 Power Demand of Electric Vehicle

Electric vehicles’ power demand is calculated as follows:

\[ P_{EV,i} = P_{EV} \cdot S_{EV,i} \cdot W_{EV,i} \]

\( P_{EV,i} \) EV charging power at time slot \( i \)

\( P_{EV} \) EV rated power

\( S_{EV,i} \) EV connectivity status in time slot \( i \), 0 if the EV is not physically connected to the outlet and 1 if EV is connected;
\[ W_{EV,i} \] Uncontrolled EV charging status in time slot \( i \) which depends on the battery SOC, 0 if EV is not being charged and 1 if EV is being charged;

### 3.5.2 Model Development

A typical electric vehicle model with total power consumption of 3.6 kW has been selected in this study and table 3.4 summarizes the data used in the considered electric vehicle model. The energy used for driving is assumed as 15 kW and the initial charge state of battery is obtained as 37.5% for the considered case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta t )</td>
<td>1 minute</td>
</tr>
<tr>
<td>( C_{batt} )</td>
<td>24 kW</td>
</tr>
<tr>
<td>( P_{EV} )</td>
<td>3.6</td>
</tr>
<tr>
<td>Start time</td>
<td>6 p.m.</td>
</tr>
</tbody>
</table>

### 3.6 Critical Loads

The aggregated load profile of critical loads is created based on the historical data of the industry-accepted database, i.e., RELOAD database. As critical loads will be kept as they are during the demand response periods, the average model will work in the distribution network. Critical loads are referred to those that should work without any interruption. This group of loads includes the lighting, coffee machine, freezing, cooking and so on. Our critical loads range from 1 kW to 2 kW. These loads reach the peak around 5 p.m. because residents come back home in a daily routine. After midnight, the peak demand reduces again.
Figure 3.6: Daily chart of critical load model in a residential house
Chapter 4

4.1 Home Energy Management System Algorithm

Our primary goal in this study is to develop an algorithm that keeps the total power under an absolute limit, during the peak hours. Thanks to the loads time shifting characteristics, there would not be extra burden on the electricity grid. Consumers assign demand and comfort limits. Such limits can vary at every time slot. The home energy management system (HEMS) would control only four loads as mentioned before and these loads may be increased or decreased. This system is designed for a one-occupant house here, but is generic enough to be adapted to an apartment or neighborhood loads.

According to the developed system, two loads work during the day and two loads start after a certain time period. When all loads begin working together, the system considers consumer’s comfort level and load’s priority. In order to develop the HEMS, the priorities of the appliances must be identified. Priorities of the controllable loads are given in table 4.1. Figure 4.1 gives a general step-by-step model of the HEMS algorithm.

Table 4.1: Controllable load priorities selected for the developed HEMS

<table>
<thead>
<tr>
<th>Load</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Priority</td>
<td>1</td>
</tr>
<tr>
<td>WH Priority</td>
<td>2</td>
</tr>
<tr>
<td>CD Priority</td>
<td>3</td>
</tr>
<tr>
<td>EV Priority</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 4.1: HEMS algorithm flow chart

W_x  Request to change status of non-critical appliance, x

THD  Total Household Demand

DL   Demand Limit

P_{r,x} Priority of the non-critical appliance, x

D_x  EMS control signal to non-critical appliance, x
4.2. Demand Response for AC Unit

The AC system requirement is examined in the previous section. If the AC system should work, it sends a signal to the management system. Then the system controls all the loads and the total power and the system then decides on the on-off status of the AC. The AC has the highest priority, so it has to be open after a received signal. This process is formulated below:

\[ P_{AC,i} = P_{AC} \cdot W_{AC,i} \cdot D_{AC,i} \]  

\[ D_{AC,i} = \begin{cases} 1, & \text{If EMS decide to open the AC unit} \\ 0, & \text{If EMS decide to open the AC unit} \end{cases} \]

- \( P_{AC,i} \) electricity demand for the space cooling/space heating at time slot \( i \)
- \( P_{AC} \) rated power of the space cooling/space heating system
- \( W_{AC,i} \) on-off status of the space cooling/space heating unit at time slot \( i \)
- \( D_{AC,i} \) control signal received from the HEMS at time slot \( i \)

4.3 Demand Response for WH Unit

The water heater is assigned the second highest priority. The system should keep the water temperature within certain limits. When the water heater sends a signal to the system, the system checks the total power consumption and loads the status. If the total power consumption is higher than the demand limit, it reflects that the system starts to close the load that has the lowest priority and it continues until power consumption is reduced lower than the demand limit. As soon as the total household power becomes less than the limit, the HEMS decides to turn the water heater on and sends the corresponding
control signal. The demand response enabled load model for the water heater is represented as follows.

\[ P_{wh,i} = W_{wh,i} \cdot P_{wh} \cdot n_{wh} \cdot D_{WH,i} \]  
(4.2)

\[ D_{WH,i} = \begin{cases} 1, & \text{If EMS decide to open WH unit} \\ 0, & \text{If EMS decide to open WH unit} \end{cases} \]

- \( P_{wh} \): Rated power of the water heater
- \( n_{wh} \): Efficiency factor;
- \( W_{wh,i} \): On-off status of the water heater at time slot \( i \)
- \( D_{WH,i} \): DR control signal for water heater at time slot \( i \)

### 4.4 Demand Response for CD Unit

The clothes dryer has more flexibility than other loads and does not have certain limitations. In the clothes dryer model, only the heating coils are controlled by the HEMS control signal. It is assumed that the motor is not controlled by the EMS as it cannot be turned on without human intervention once it is turned off. If the clothes dryer is switched on, the motor will continuously operate until the job is completely accomplished. As the motor consumes less power compared to the heating coils, the effect of not controlling the motor does not significantly impact the total household power demand. The modified demand response enabled clothes dryer model is as follows.

\[ P_{CD,i} = k \cdot P_h \cdot W_{CD,i} \cdot D_{CD,i} + P_m \cdot W_{CD,i} \]  
(4.3)
\[ D_{CD,i} = \begin{cases} 1, & \text{If EMS decide to open CD unit} \\ 0, & \text{If EMS decide to close CD unit} \end{cases} \]

\[ P_{CD,i} \quad \text{The CD demand for electricity at time slot } i \]

\[ P_h \quad \text{Rated power of clothes-dryer heating coil} \]

\[ k \quad \text{Drying level (k=1/M, 2/M, … M/M)} \]

\[ M \quad \text{Total number of drying levels} \]

\[ P_m \quad \text{Power consumption of the dryer’s motor} \]

\[ W_{CD,i} \quad \text{On-off status of the clothes-dryer’s heating coils at time slot } i \]

**4.5 Demand Response for Electric Vehicle**

The home energy management system will control charging of the electric vehicle, and the modified demand response with enabled electric vehicle power demand is modeled as follows. If the system realizes there will be no enough time to charge the EV, then the EV priority will be the highest.

\[ P_{EV,i} = P_{EV} \cdot S_{EV,i} \cdot W_{EV,i} \cdot D_{EV,i} \quad (4.4) \]

\[ D_{EV,i} = \begin{cases} 1, & \text{If EMS decide to open EV unit} \\ 0, & \text{If EMS decide to close EV unit} \end{cases} \]

\[ P_{EV,i} \quad \text{EV charging power at time slot } i \]

\[ P_{EV} \quad \text{EV rated power} \]

\[ S_{EV,i} \quad \text{EV connectivity status at time slot } i, \ 0 \text{ if EV is not physically connected to the outlet and 1 if EV is connected} \]
\( W_{EV,i} \)  
uncontrolled EV charging status at time slot \( i \) which depends on the battery SOC, 0 if EV is not being charged and 1 if EV is being charged

\( D_{EV,i} \)  
DR control signal for EV at time slot \( i \)
Chapter 5: Numerical Case Studies

5.1 Load Management without HEMS

5.1.1 AC Unit

Power consumption of the AC unit is managed by regulating the temperature. The 24-hour operation of the AC unit for the maximum and minimum limits of the temperature is considered and the typical operation of the AC unit for the time period from 6 a.m. - 6 a.m. is given in Figure 5.1, where the red lines represent the limit values.

![Figure 5.1: Room temperature within the limits by AC unit](image)

Figure 5.1: Room temperature within the limits by AC unit

Figure 5.2 illustrates the power consumption of the AC unit. One can see from this figure that power consumption and on-off signal follow the same pattern as expected.
5.1.2 WH Unit

The water heater temperature drops under the specified limit five times during a day and it means the heater should work at these points. The temperature changes in the morning and night hours due to (i) people taking shower before leaving home or after coming home and (ii) some people do the dishes around these time period. The red lines represent the limit values.
Figure 5.3: Outlet water temperature within the desired limit during day by water heater

Figure 5.4 shows the power consumption of the WH unit. The power consumption and on-off signal indicate that the algorithm works reliable and the performance is stable.

Figure 5.4 Power consumption of WH unit
5.1.3 CD Unit

In this study, it is assumed that the homeowner operates the clothes dryer at 6 p.m. The clothes dryer needs 90 minutes to finish its duty. Figure 5.5 shows the on-off signal and power consumption for the clothes dryer where the motor part and the heating coil work together.

![Figure 5.5: Status of clothes dryer](image)

5.1.4 Electric Vehicles

In this study, it is considered that the electric vehicle is plugged in at 5 p.m. assuming that it has an initial state of charge (SOC) of 37.5%. The electric vehicle load curve with its charging profile is illustrated in Figure 5.6.
It can be seen from Figure 5.6, that it has taken 4 hours and 10 minutes to fully charge the electric vehicle with 37.5% initial state of charge. In Figure 5.6, the power demand of the electric vehicle at each time interval is indicated in blue and the state of charge is shown in pink.
Figure 5.7 illustrate the power consumption of the electric vehicle. Power consumption starts 17.00 pm and there is no interruption during charging period. On-off signal and power consumption fallow same pattern as expected.

5.1.5 Total Household Load Profile without HEMS

The total load curve for the household which includes the critical and non-critical loads without EMS is shown in Figure 5.8.
Figure 5.8: Total power consumption without HEMS

After 5.00 p.m. all loads become active and the grid reach its peak point at around 15 kW. This is the highest point during the day when the electricity price is higher in this time period.

5.2 Loads Operation with HEMS

The operations of the non-critical loads which are controlled by the developed HEMS with the demand limits are discussed in the next section. The demand limit is selected randomly. If it is selected too low, it will be unreasonable and hard to control with many loads.

The demand limit is determined:
Between 06.00- 18.00= 6 kW

Between 18.00- 06.00= 8 kW

**5.2.1 AC Unit**

Figure 5.9: Room temperature within the limits by AC unit with HEMS

The operation of the AC unit with the demand limits enforced in HEMS algorithm is given in Figure 5.9. It shows the on and off operation of the AC unit and the temperature variation managed within the desired temperature limits.
Between 07.00 a.m. and 08.00 a.m. critical loads, the AC system and the water heater units are working together. HEMS controls all three loads in order to keep the demand limit. Thus, the AC unit alternates between on-off position as depicted in Figure 5.10.
5.2.2 WH Unit

Figure 5.11: Outlet water temperature within limit during day by water heater with HEMS

The operation of the WH unit when the demand limits are enforced in the HEMS algorithm is demonstrated in Figure 5.11. It reflects the on and off operation of the WH unit and the temperature variation which is managed within the desired temperature limits.

Figure 5.12: Power Consumption of WH with HEMS
Between 07.00 a.m. and 08.00 a.m. critical load, the AC system and the water heater are working together. The HEM system controls all three loads in order to maintain the demand limit. Thus, the water heater unit alternates between the on-off statuses as can be seen in Figure 5.12.

5.2.3 CD Unit

The operation of the CD unit with the enforced demand limits is illustrated in Figure 5.13. The starting time of the clothes dryer changes with HEMS. It delays around 3 hours. During the waiting period, motor part is working continuously, and heating coil starts after 3 hours.

Figure 5.13: Status of clothes dryer with HEMS
5.2.4 Electric Vehicle

The operation of the EV unit with the demand limits enforced is given in Figure 5.14. Even if the EV sends a signal to the management system, the system shifts the EV operation time until the total power drops under the demand limit. The EV has to wait 3 hours to be fully charged. Also, its total charging time has increased.

![Figure 5.14: Status of electric vehicles and state of charge change with HEMS](image)

Figure 5.14: Status of electric vehicles and state of charge change with HEMS
Figure 5.15: Status of electric vehicles and state of charge change with HEMS

5.2.5 Total Household Load Profile with HEMS

Figure 5.16: Total power consumption with HEMS
The daily load curves with and without demand limits are given in Figure 5.16. The demand limits for different time periods are also given in this figure. It is observed that when the demand limits are enforced in the EMS algorithm, the operation of the non-critical loads are scheduled in such a way that the total household load is always lower than the demand limits during the corresponding time period. Hence, the peak load of the household has been reduced from 14.65 kW to 7.75 kW. Note that in both cases, the daily energy consumption is the same.

5.3 Dynamic Pricing Model

Amongst the various techniques and strategies developed for managing the peak demand, user defined pattern modification of electricity usage is the most popular technique utilized [35]. The development of customer cost-rate plans can be subdivided into (i) Developing the Critical Peak Pricing with Time-Of-Use (TOU) Rate; (ii) TOU Rate; (iii) Peak-Time Rebate (PTR); and (iv) Real Time Pricing (RTP) [36]. A smart grid communication network permits automatic meter reading at scheduled intervals during which the utilities can provide time- and demand-based pricing including:

- TOU – specific time intervals correspond to different pricing tiers (i.e. off-peak and on-peak) [11].
- CPP – a process of identifying spikes in peak demand and communicating price changes with end users to provoke shifts in energy consumption [37].
- PTR – customers are provided with rebates for reducing their electricity consumption during peak periods or during high price time periods [38].
• RTP – the ability to not only change energy prices based on fluctuations in the cost of generation but also to notify consumers (and consumer devices) to integrate demand-side applications to participate in load-shifting decisions [39].

Dynamic retail pricing, especially RTP, has been identified as one of the main tenets for providing DR in electricity markets. Dynamic pricing includes calculating the total load for a given area while determining the cost of electricity in real-time. As the load increases, the cost of electricity consumption increases. Hourly electricity pricing is one mechanism for stimulating price-responsive demand. Presently, utilities are providing standard or default services to evaluate the effect of RTP, often at a capped or administratively determined rate [40]. DR programs, which offer explicit payments to customers for load reductions represent a different and potentially complementary type of approach. The direct effect of RTP is a function of the amount of load remaining on the rate and the price responsiveness of the customers [41].

According to Virginia energy supplier, summer period price rate is given in Figure 5.17. This figure shows that between 13.00 p.m. and 19.00 p.m. the electricity price is at its peak.
5.17: Summer pricing guide in Virginia [42]

In order to compare the price between 16.00 - 22.00, the average power consumption is created. According to Fig. 5.18, the average power consumption reaches to 12 kW without HEMS algorithm. This average power consumption decreases in Figure 5.19 to 7 kW if HEMS algorithm is applied.
5.18: Average hourly power consumption without HEM

5.19: Average hourly power consumption with HEM
The total energy cost during 16.00 p.m. and 22.00 p.m. is calculated as follows:

With Demand Limit: 314.6660 (cent/ kW)
Without Demand Limit: 388.6753 (cent/ kW)

HEMS will save around 20% of the total cost.

4.4 Integrating Solar Panel System

In this project, solar system is chosen to evaluate the difference in power consumption. HEM system helps to reduce the peak point and the solar system helps to reduce total power consumption. A daily solar power output is given in [43] with the solar panel input given Appendix D. Figure 5.20 and Figure 5.21 show the difference in the total power without and with the demand limit.

Figure 5.20: Comparing total power output by adding solar panel without HEMS
Figure 5.21: Comparing total power output by adding solar panel with HEMS

Energy prices are calculated again between 16.00 p.m. and 22.00 p.m. Table 5.1 presents all the scenarios.

Table 5.1: Energy prices in four different scenarios

<table>
<thead>
<tr>
<th>Total Energy Cost (16.00 pm-22.00 pm)</th>
<th>Only Grid (cent/kW)</th>
<th>With Solar Panel (cent/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without HEM</td>
<td>388.6753</td>
<td>361.0825</td>
</tr>
<tr>
<td>With HEM</td>
<td>314.6660</td>
<td>291.0051</td>
</tr>
</tbody>
</table>

From Table 5.1, it can be seen that the energy cost for the same household load profile is less when the developed HEMS is deployed in the household for managing the
non-critical loads. The saving which a consumer can obtain by using this HEMS with the considered demand limits is around 20% per day and it should be noted that consumer comfort has not been violated in reaching this electricity cost saving. Besides, total saving can be increased by integrating solar panel systems.
6.1 Conclusion

Demand side management in the domestic sector can play an essential role in reducing the peak demand in power distribution networks. Eventually, it can help in reducing overloading and the stress on transmission and distribution lines. Many enhanced programs have been created and applied in the industrial and commercial sector. These programs show serious success regarding pricing and efficiency. However, this situation is unequal for domestic sector. Power cut and price raising is used to reduce the peak demand which cause violation of the customer comfort. In contrast, load shifting comes with a new proposal. It will be in favor of both supplier and customer.

In order to develop a demand response project, every load should consider its technical parameters. For creating controllable loads, every parameter should be given real and certain values. Every step affects one step later and every load has impact on the others. These load models are created for controlling non-critical loads. With smart grid system, these load models will extend, and the system will be more developed.

It is essential to manage the demand of power intensive domestic loads to reduce the peak demand of the household. Loads can be defined as critical loads and non-critical loads. In this work, power intensive non-critical loads are managed through advanced EMS algorithm, and these loads include the water heater, AC unit, clothes dryer and electric vehicle. The highlight of the presented EMS algorithm for home energy management is its capability to control the operation of non-critical loads to maintain the total household
demand below specified peak demand limits by considering consumer behavior or priorities and giving customers more flexibility in their operational time.

Our results show that it is possible to control the operation time of the loads. At this point, EMS is used only to non-critical loads, but it could be developed for critical loads to further increase the system efficiency. Suppliers use all this information to make the system more reliable and sustainable. Applying EMS algorithm, peak demand has reduced from 14.65 kW to 7.75 kW. Also, it can be seen that between 16.00 pm to 22.00 pm, the total energy cost has reduced around %20. During this time period, the comfort violation is prevented. It is possible to decrease the peak demand even further with the expense of customer comfort violations.

6.2 Scope for Future Works

While this project focused only on one residential house, this system can be applied to a multi-building neighborhood or a city. The proposed EMS can also be studied to build a platform for the integrated renewable energy system with/without energy storage. Besides, the load models can be developed by considering time changing technical advancements and user behaviors in the future works.
References

Appendix A-Critical Load Profile

A typical load profile for the critical loads in the household is selected for this work.

<table>
<thead>
<tr>
<th>Time</th>
<th>Power Demand (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 a.m. - 7 a.m.</td>
<td>1.6</td>
</tr>
<tr>
<td>7 a.m. - 8 a.m.</td>
<td>1.3</td>
</tr>
<tr>
<td>8 a.m. - 9 a.m.</td>
<td>1.3</td>
</tr>
<tr>
<td>9 a.m. - 10 a.m.</td>
<td>1.1</td>
</tr>
<tr>
<td>10 a.m. - 11 a.m.</td>
<td>1</td>
</tr>
<tr>
<td>11 a.m. - 12 noon</td>
<td>1.2</td>
</tr>
<tr>
<td>12 noon - 1 p.m.</td>
<td>1</td>
</tr>
<tr>
<td>1 p.m. - 2 p.m.</td>
<td>1</td>
</tr>
<tr>
<td>2 p.m. - 3 p.m.</td>
<td>1.3</td>
</tr>
<tr>
<td>3 p.m. - 4 p.m.</td>
<td>1.3</td>
</tr>
<tr>
<td>4 p.m. - 5 p.m.</td>
<td>1.6</td>
</tr>
<tr>
<td>5 p.m. - 6 p.m.</td>
<td>2</td>
</tr>
<tr>
<td>6 p.m. - 7 p.m.</td>
<td>1.6</td>
</tr>
<tr>
<td>7 p.m. - 8 p.m.</td>
<td>1.5</td>
</tr>
<tr>
<td>8 p.m. - 9 p.m.</td>
<td>1.5</td>
</tr>
<tr>
<td>9 p.m. - 10 p.m.</td>
<td>1.5</td>
</tr>
<tr>
<td>10 p.m. - 11 p.m.</td>
<td>1.2</td>
</tr>
<tr>
<td>11 p.m. - 12 midnight</td>
<td>1</td>
</tr>
<tr>
<td>12 midnight - 1 a.m.</td>
<td>1</td>
</tr>
<tr>
<td>1 a.m. - 2 a.m.</td>
<td>1.1</td>
</tr>
<tr>
<td>2 a.m. - 3 a.m.</td>
<td>1</td>
</tr>
<tr>
<td>3 a.m. - 4 a.m.</td>
<td>1.2</td>
</tr>
<tr>
<td>4 a.m. - 5 a.m.</td>
<td>1.2</td>
</tr>
<tr>
<td>5 a.m. - 6 a.m.</td>
<td>1.4</td>
</tr>
</tbody>
</table>
## Appendix B - Solar Radiation Data

Hourly variation of solar irradiation data in Atlanta, US for hot summer day is considered. Corresponding solar irradiation data are extracted from ASHRAE handbook.

<table>
<thead>
<tr>
<th>Time</th>
<th>Solar Radiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 a.m. - 7 a.m.</td>
<td>115</td>
</tr>
<tr>
<td>7 a.m. - 8 a.m.</td>
<td>320</td>
</tr>
<tr>
<td>8 a.m. - 9 a.m.</td>
<td>528</td>
</tr>
<tr>
<td>9 a.m. - 10 a.m.</td>
<td>702</td>
</tr>
<tr>
<td>10 a.m. - 11 a.m.</td>
<td>838</td>
</tr>
<tr>
<td>11 a.m. - 12 noon</td>
<td>922</td>
</tr>
<tr>
<td>12 noon - 1 p.m.</td>
<td>949</td>
</tr>
<tr>
<td>1 p.m. - 2 p.m.</td>
<td>922</td>
</tr>
<tr>
<td>2 p.m. - 3 p.m.</td>
<td>838</td>
</tr>
<tr>
<td>3 p.m. - 4 p.m.</td>
<td>702</td>
</tr>
<tr>
<td>4 p.m. - 5 p.m.</td>
<td>528</td>
</tr>
<tr>
<td>5 p.m. - 6 p.m.</td>
<td>320</td>
</tr>
<tr>
<td>6 p.m. - 7 p.m.</td>
<td>1</td>
</tr>
<tr>
<td>7 p.m. - 8 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>8 p.m. - 9 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>9 p.m. - 10 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>10 p.m. - 11 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>11 p.m. - 12 midnight</td>
<td>0</td>
</tr>
<tr>
<td>12 midnight - 1 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>1 a.m. - 2 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>2 a.m. - 3 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>3 a.m. - 4 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>4 a.m. - 5 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>5 a.m. - 6 a.m.</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix C-Water Usage Profile

A typical hot water usage profile is considered assuming that there are three people in the house. The hot water usage for shower, bath and cooking are considered.

<table>
<thead>
<tr>
<th>Time</th>
<th>Flow rate of water (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 a.m. - 7 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>7 a.m. - 7.10 a.m.</td>
<td>2</td>
</tr>
<tr>
<td>7.20 a.m. - 7.30 a.m.</td>
<td>2</td>
</tr>
<tr>
<td>8 a.m. - 9 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>9 a.m. - 10 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>10 a.m. - 11 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>11 a.m. - 12 noon</td>
<td>0</td>
</tr>
<tr>
<td>12 noon - 1 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>1 p.m. - 2 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>2 p.m. - 3 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>3 p.m. - 4 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>4 p.m. - 5 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>5 p.m. - 6 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>6 p.m. - 6.15 p.m.</td>
<td>5</td>
</tr>
<tr>
<td>6.20 p.m. - 7.30 p.m.</td>
<td>3</td>
</tr>
<tr>
<td>7.30 p.m. - 8 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>8 p.m. - 8.15 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>8.15 p.m. - 9 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>9 p.m. - 9.15 p.m.</td>
<td>5</td>
</tr>
<tr>
<td>9.15 p.m. - 10 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>10 p.m. - 12 midnight</td>
<td>0</td>
</tr>
<tr>
<td>12 midnight - 6 a.m.</td>
<td>0</td>
</tr>
</tbody>
</table>
## Appendix D-Solar Panel Power Output

<table>
<thead>
<tr>
<th>Time</th>
<th>Generated power (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 a.m. - 7 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>7 a.m. - 8 a.m.</td>
<td>0.057</td>
</tr>
<tr>
<td>8 a.m. - 9 a.m.</td>
<td>0.215</td>
</tr>
<tr>
<td>9 a.m. - 10 a.m.</td>
<td>0.346</td>
</tr>
<tr>
<td>10 a.m. - 11 a.m.</td>
<td>0.703</td>
</tr>
<tr>
<td>11 a.m. - 12 noon</td>
<td>0.956</td>
</tr>
<tr>
<td>12 noon - 1 p.m.</td>
<td>1.045</td>
</tr>
<tr>
<td>1 p.m. - 2 p.m.</td>
<td>0.988</td>
</tr>
<tr>
<td>2 p.m. - 3 p.m.</td>
<td>0.948</td>
</tr>
<tr>
<td>3 p.m. - 4 p.m.</td>
<td>0.898</td>
</tr>
<tr>
<td>4 p.m. - 5 p.m.</td>
<td>0.788</td>
</tr>
<tr>
<td>5 p.m. - 6 p.m.</td>
<td>0.580</td>
</tr>
<tr>
<td>6 p.m. - 7 p.m.</td>
<td>0.351</td>
</tr>
<tr>
<td>7 p.m. - 8 p.m.</td>
<td>0.076</td>
</tr>
<tr>
<td>8 p.m. - 9 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>9 p.m. - 10 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>10 p.m. - 11 p.m.</td>
<td>0</td>
</tr>
<tr>
<td>11 p.m. - 12 midnight</td>
<td>0</td>
</tr>
<tr>
<td>12 midnight - 1 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>1 a.m. - 2 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>2 a.m. - 3 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>3 a.m. - 4 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>4 a.m. - 5 a.m.</td>
<td>0</td>
</tr>
<tr>
<td>5 a.m. - 6 a.m.</td>
<td>0</td>
</tr>
</tbody>
</table>