DEMAND RESPONSE POTENTIAL IN AGGREGATED HOUSES USING GRIDLAB-D

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

Ward Jewell, Committee Chair

Vinod Namboodiri, Committee Member

Ikram Ahmed, Committee Member

DEDICATION

To my parents and brother.

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ABSTRACT

Electrical power consumption or demand varies very significantly from region to region. There are various factors which affect the demand for a particular location; higher the electrical demand higher is the wholesale electrical charge as well. These higher prices included the cost incurred to operate a peaking power plant; these power plants are commissioned to supply peak demands, and the capital cost to establish such a plant is very high; furthermore these plants are left idle for most part of the year. This is an inefficient process but it has to be commissioned to meet the basic criteria to supply uninterrupted power supply to the consumers. However, with the advance in technology, demand response is now progressing as a preferable alternative for peak load reductions, thereby reducing the dependencies on the peak load power plants. Some loads on the customer's side can be effectively controlled and shut off for short durations during the peak load times. These controllable devices can be used in such a way that there is no significant impact on the consumer's lifestyle or comfort.

This research analyzes the potential of demand response for a small area or a community having residential houses in the United States. Different population sizes and properties of the residential sectors have been simulated with and without demand response for few days in the typical summer period June through September using GridLAB-D software. Potential savings in terms of demand reduction and energy consumption have been observed when demand response is coordinated with better thermal integration on residential houses. A correlated power consumption pattern has been observed for different population sizes, having same HVAC systems, thermal integration and different floor areas.

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LIST OF ABBREVATIONS

FERC	Federal Energy regulatory Commission
DR	Demand response
EPRI	Electric Power Research institute
DLC	Direct load Control
BGE	Baltimore Gas and Electric
PLR	Peak Load reduction
NYISO	New York Independent System Operator
USEPA	United States Environmental Protection Agency
PJM	PJM Interconnection LLC
LBMP	Location Based Marginal Price
RTM	Real Time Market
NREL	National Renewable Energy Laboratory
ISO	Independent System operator
RTO	Regional Transmission Organization
US DOE	United States Department of Energy
ETP	Equivalent Thermal Parameters
TRIAC	Triode for Alternating Current
BTU	British Thermal Unit
TMY	Typical Meteorological Year
GLM	Grid Lab Model
CSV	Comma Separated Values
HVAC	Heating Ventilation and Air Conditioning
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers

PARAMETER NOTATIONS

W	Watts is defined as joule per second
kW	Kilo Watts, the kilowatt is equal to one thousand (10^3) watts
MW	Mega Watts is equal to one million (10^6) watts
GW	Giga Watts is equal to one billion (10^9) watts
R-Roof	Roof's resistance to heat flow
R-Floor	Floor's resistance to heat flow
R-Window	Window's resistance to heat flow
R-Wall	Wall's resistance to heat flow
R-Door	Door's resistance to heat flow

CHAPTER 1

INTRODUCTION

The Federal Energy Regulatory Commission (FERC) of the United States defines Demand Response as [1]:

"Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

Demand response can otherwise be understood as a program that is implemented to reduce the peak load demand to a demand that can be easily handled with the already running power generating resources without the need of pressing in other generating stations and thereby avoiding high wholesale prices.

Implementing demand response is a very complex structure [2], this involves a lot of planning and research before it can actually be implemented. It requires various levels of decision making ranging from demand response target group, range, time, incentive etc. Some of the most important steps that need to be involved while implementing demand response are calculating if this program is cost effective alternative for present situation or not and there should be minimal or no customer dissatisfaction [2]. Apart from these the nature of electrical demand, customer's lifestyle, and climatic conditions prevailing are some of the factors that also affect demand response program [3].

Residential demand response has been the choice of many aggregator companies because of the potential benefits it has in store for the future and also in the present scenario in the United States [4]. Demand response can best be analyzed by aggregating a population of residential houses and then applying the demand response, this gives a significant figure of demand reduction in that geographical area [5]. This aggregated demand reduction now becomes a virtual power plant for the peak load period. Critical power consuming devices like residential air-conditioners are the target loads that need to be controlled during demand response to shave the extra demand for that period of time. Other appliances like water heater, space heater, electrical vehicle charging, dishwasher and clothes dryer can also be included in the demand response program, but that involves a lot more control over customer appliances and it requires finer research and calculations to figure out the application of demand response in such cases.

1.1 PROBLEM STATEMENT

Since the generation side of the electric power sector is slow to react towards changes in the grid and peaking power plants are inherently inefficient, management from the demand side proves more effective and can play an important role in the future to securely and reliably manage the electric grid.

Maintaining the state of equilibrium in power systems is one of the most important factors to keep the system running reliably. This has urged many to use the demand response programs to understand when the load shedding needs to be applied and how effectively it can be applied to maintain the stability and reliability of the grid system. The demand response program is as old as 1980 when it was first used by homeostasis control concept [6], where the load was shifted per the frequency deviations in the grid and also per the real time price of the electricity.

Demand response has many variants each having its own importance in the real world scenario. The ones that are prevailing in the market for residential customers are dynamic pricing without enabling technology, dynamic pricing with enabling technology, direct load control, interruptible tariffs and other demand response programs which are primarily based for commercial and industrial consumers.

The best peak reduction can be achieved by combining energy efficiency with demand response [7]. EPRI estimates that by 2030 the potential reduce in summer peak demand would be around 157GW to 218 GW when the energy efficiency and demand response are combined [7].

This research discusses how a cluster of houses, when aggregated and controlled for demand response during peak hours, becomes a virtual power plant during those hours. Direct load control method is used in this paper as a demand response program to control the load on the customers end and it is used to control the air-conditioner only. Large populations of houses are simulated to get a significant demand reduction. This research also discusses how improved thermal efficiency of a house in addition to demand response can be beneficial, not only to the utility but also to an individual consumer. This research however, does not recommend a particular demand response program, but it is left to the companies who provide electric power to the consumers to research and choose the best option per requirement. Demand response not only involves demand reduction but also consumer comfort. This research also focuses on how demand response can be implemented in residential sector without causing any discomfort to the customer.

1.2 OBJECTIVES

The goal of this research is to analyze the potential power reduction from a population of houses when demand response program is applied. It also analyzes how demand changes when residential energy efficiency is combined with demand response. The operation of air-conditioning devices at the consumer end is controlled by Direct Load Control program to achieve the demand reduction.

The following are the tasks performed to understand and provide an estimate of the power consumption reductions in different scenarios.

- The electrical power consumption patterns for different population sizes are simulated to understand and co-relate the houses varying in floor area and air-conditioning sizes.
- Simulate houses with all the default appliances in place and then apply the demand response to see how they affect the peak load.
- Simulate similar energy profile houses while applying demand response to understand the savings from these particular groups of houses.
- Compare the simulation results from different energy profile houses when demand response is in place and analyze how residential energy efficiency and demand response can effect peak load reduction.

1.3 DEMAND RESPONSE POTENTIAL IN UNITED STATES

The FERC report states that summer peak demand in U.S was about 810 GW in 2009 and reaches 950 GW by 2019 at an average growth rate of 1.7 percent [8]. It also states that there could be a zero percent peak demand growth by 2019 if full participation in the demand response program is expected, and it would also be 188 GW less than the predicted peak demand if there was no demand response in place.

FERC report 2012 [9], states that the potential peak reduction in just the residential sector has grown by 13 percent from 2010 to 2013. The peak reduction was reported 7189 MW in 2010 and in 2012 peak reduction was reported to be 8134 MW. Seventy percent of the entire peak load reduction was recorded from Direct Load Control (DLC) and time based rates program provided to the customers. Significant increase in the peak load reductions by DLC in residential sector from 2010 to 2013 was reported by Baltimore Gas and Electric (BGE), they recorded 763 MW PLR in 2012 against 272 MW PLR in 2010 [9].

The National Forum's Estimation Tools and Methods Working Group have identified immediate and anticipated demand response needs [10]; their study indicated that the existing analytical capabilities are sufficient to address many demand response needs. However it recognized that more research needs to be done in the area of forecasting and validating, end user settlement tools, electric distribution companies' program implementation tools and impact assessment tools. Some of these concerns are partly addressed in this paper. However, these results need to be expanded and complimented with other real time data to get an estimated peak load reduction.

CHAPTER 2

DEMAND RESPONSE

2.1 MOTIVATION

Demand response has become an important part of today's Power Suppliers, not because it has to be implemented but because it is an economical and effective method to avoid the economically higher alternative of using peaking power plants during peak demand times. To get an understanding about the need for demand reduction, a power demand curve would be needful.

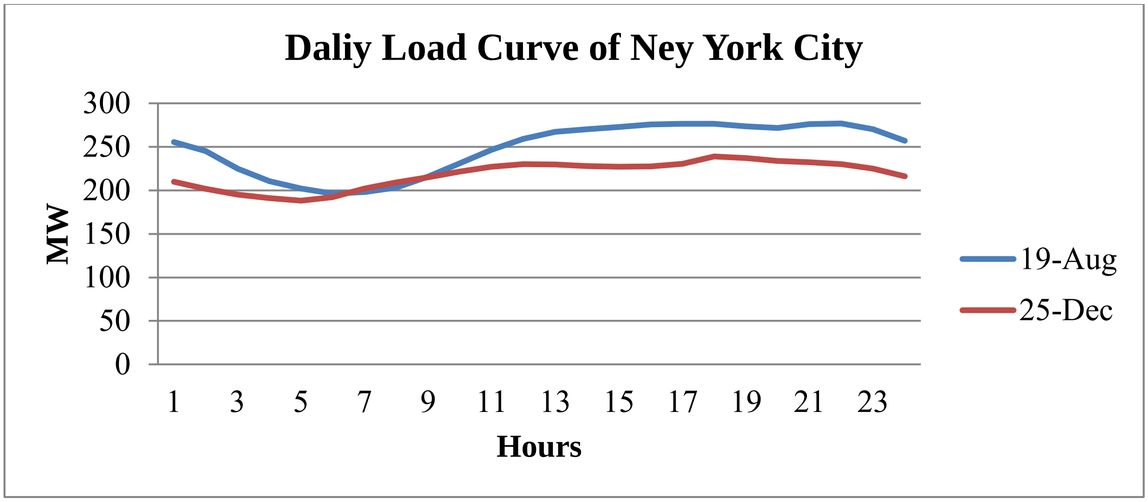


Figure 2.1.1: Summer and Winter Load profiles of New York City.

Figure 2.1.1 shows the real time load curve for New York City on a hot summer day 19th August 2012, and a cool winter day 25th December 2013 derived using data from New York Independent System Operator's (NYISO) daily reports [11].

Figure 2.1.1 clearly shows that the summer electrical demand is higher than the winter electrical demand. A report prepared for USEPA shows that a 2 degree Fahrenheit increase in the outdoor temperature raised an electrical demand by 4.6 percent in the regions that were supplied by the PJM [12]. In other words we can assume that there is a direct co-relation between outdoor air temperature and electrical load demand.

To maintain highest standards and reliable power supply to its consumers, power supplying utilities have to be equipped with power systems sized for highest load demand possible. These peak loads appear for a very minimum period ranging from few days in a year to sometimes few weeks in a year. Due to the increase in electrical demand during the peak summer season, investment for supplying this extra load will be very high, also the wholesale electricity price for that season will be comparatively higher. The peaking power plants that are commissioned to supply this extra demand become operational only during the peaking season and are shut down during other times of the year, making it an even more expensive solution. Alternatively if the demand side load management is applied, it could turn out to be beneficial to both consumers and the utility companies.

The Location Based Marginal Pricing (LBMP) data for August 19th 2011 was collected for New York City from NYISO's Real-Time Market LBMP [11]. In New York, for August 19th 2011 when the electric demand was highest on that day at 03:35 PM the real time market price was $1509.48/MWh and at 03:40 PM it was $785.27/MWhr compared to $47.85/MWh at11:35 AM, when the electrical load demand was comparatively lower. This extremely high pricing during peak times which creates an economic impact on the end user creates a motivation to move towards demand response. Some user end appliances like Air-Conditioners which become a major contributor of the electric load from a user end could be controlled to turn off or set to a higher set point value for a short duration of time; this would save a lot of energy and would be economically beneficial to customers and the utility companies.

A report prepared for NREL [13], finds that the greatest available potential in terms of peak load reduction for the Colorado Test System, and Capacity during the top 20 hours of greatest demand is the residential sector cooling at a mean of 10.9 MW topping all other available resources including residential water heating, commercial cooling, commercial heating etc.

2.2 DEMAND RESPONSE MODELS

There are a number of demand response models that are now used to manage the demand side power consumption. Following are the most commonly used models.

2.2.1 DEMAND RESPONSE USING DYNAMIC PRICING AND NOT ENABLING TECHNOLOGY

This program is based on real time pricing or prices announced one day before the event. The customers are offered time varying prices, which usually has high higher prices during peak demand hours and lower prices during non-peak hours. The prices are dynamic and change according to the events such as high demand hours, unexpected hot days etc. Customers are expected to respond to these price changes and react by turning off their air-conditioners, postpone their laundry schedule or charge their electrical vehicles at a later time when prices are lower.

2.2.2 DEMAND RESPONSE USING DYNAMIC PRICING AND ENABLING TECHNOLOGY

This program is similar to the DR using dynamic pricing and not enabling technology program where the customers are informed about the pricing on real time basis or a day ahead, but the communication is done using smart meters and their equipment is also equipped with devices; these devices can automatically sense the price changes and accordingly shut off the registered device or set the thermostat in case of air conditioners to a higher value to reduce the consumption. Some commercial and industrial consumers also make certain equipment's in their facility to react to these changes and reduce their consumption during those peak hours.

2.2.3 DEMAND RESPONSE USING DIRECT LOAD CONTROL

This is one of the popular methods that are practiced by many consumers in United States. Here the customer end appliances like air-conditioners, water heaters, space heaters etc. are directly controlled by the utility. The air-conditioners are either set to a higher set point or they are completely turned off per requirement during the demand response events. This method is usually applied when there is an operating reserve shortage. Some of the states in the U.S also include irrigation control in this method.

2.2.4 DEMAND RESPONSE USING INTERRUPTIBLE TARIFFS

This program is usually made available to large industries or commercial users who agree to reduce their consumption during the event of demand response and in turn they are offered with attractable incentives.

2.2.5 OTHER DEMAND RESPONSE PROGRAMS

There are other demand response programs, which are designed mainly for industrial and commercial users; these include demand or capacity bidding and other aggregator offers. The aggregator usually an ISO or RTO acts as a mediator between the utility and the consumer, they make offers available to customers to participate in the program and it's the responsibility of the aggregator to reduce the demand during specialty conditions or high peak load situations.

CHAPTER 3

GRIDLAB-D

GridLAB-D is a new power system modelling and simulation environment developed by the subsidiary of US Department of Energy (DOE) [14]. It is a flexible agent based open source software that can be used to simulate electrical distribution. It can be easily integrated with a number of third party data management and analysis tools. The advantage of using GridLAB-D is that its advanced algorithm can simultaneously co-ordinate with the state of millions of independent devices, which are described by multiple differential equations.

This software can handle unusual situations more accurately and time scales from sub-seconds to years [14]. This software becomes more essential to the industry and the government agencies to plan and design their electrical distribution, management and other programs more efficiently and effectively.

There are a range of areas that can be simulated using GridLAB-D; some of them are discussed below.

- Peak Load Management: There are a lot of programs that failed to deliver expected benefits while addressing the peak load shaving simulations. GridLAB-D has a flexibility to be calibrated to observe consumer behavior when a particular peak-shaving strategy is applied. More accurate forecast of the truly available resources can be determined.
- Distributed Automation Design: The design and analysis of a distributed automation technology can be easily done using GridLAB-D.
- Distributed Resources: By including the economic benefits of distributed energy resource technology, a utility manager can easily evaluate the cost benefit trade-off between distributed energy resource investments and expansion investments.
- Rate Structure Analysis: GridLAB-D provides the ability to build a model that can determine if a suit of rate offerings can succeed in response to multiple rate offerings.

3.1 GRIDLAB-D RESIDENTIAL END USER MODELLING

GridLAB-D uses Equivalent Thermal Parameters (ETP) to model residential and commercial end-uses. These models are solved for both state as a function of time and time as a function of state [14].

The following are the residential end uses from GridLAB-D. It simulates the power demand response for these appliances from a single family home and it includes the following

- Air-conditioners
- Space Heaters
- Plug loads
- Refrigerator
- Microwave Ovens
- Cooking range
- Dishwasher
- Water heater

3.1.1 MODELLING A WATER HEATER

A typical residential water heater sizes from 30 to 120 gallons, most of these fall in the range of 40 to 80 gallons. Hot water is usually drawn from the top of the tank and the cold water fills up simultaneously from the bottom of the tank, during this process a layer of cold water is present at the bottom of the tank.

These tanks are usually heated by two elements one placed at the bottom of the tank and the other at the top. Only one element is allowed to be operational at a given point of time and the element at the top has the highest priority. Most of the heating is done by the lower element and the top element only operates when the cold water has reached the upper level. This allows the rapid re-heating of the water above the top filament so as to allow full temperature water available during rapid depletion.

The commonly deployed water heaters have an element capacity anywhere from 1500 Watts to 6000 Watts and the most common being 4500 Watts.

The modelling assumptions made by the developers of GridLAB-D to make it computationally fast and reasonably accurate are

- The upper element maintains higher temperature than lower element
- Modelling of thermal stratification is not direct; either the water in the tank is considered to have a uniform temperature or lumped into two temperature regions namely hot and cold.
- Depending on the volumetric flow rate the cool water entering into the tank from the bottom is considered to mix up completely or not mixing at all.

Depending on the state of the tank at a given moment the water heater simulation uses two different models

- One Node Model: This model considers the temperature of the water to move between two specified points at any given time. This model applies when the tank state is full or depleted.
- Two Node Model: This model is applied when the tank state is partial, and assumes that the upper hot water is near the set point temperature of the heater and the lower cold region is at the inlet water temperature.

A detailed modelling approach is explained in [15].

3.1.2 MODELLING LIGHTS

Residential lighting is a mixture of several different types that is randomly distributed through the house across the two circuit phases. Apart from some outdoor lighting fixtures which are controlled by sensors, very sparsely residential indoor lighting is controlled by timers. The connected lighting power for each light fixture is represented in the residential model's lighting object.

Heat produced by the lighting fixtures can be either in the conditioned part of a residential house or in an unconditioned space like attic or outdoor lighting.

The following are the modelling assumptions made by the developers of GridLAB-D [15]

- Power factor of the lights depend on the type of light and an aggregate power factor of all the lights is assumed to be 0.95
- Installed capacity of each light is randomly chosen per the assumed power density being anywhere between 0.75 Watts per square feet to 1.25 Watts per square feet.
- The fraction of light that ends up as a heat in the house is assumed to be 90 percent.
- Each light has a constant power factor.

A detailed Modelling approach can be found at [15]

3.1.3 MODELLING A DISHWASHER

Dishwashers require a complex controlling model, each dishwasher available in the market have different specifications which run in several cycles from filling to drying. Some dishwashers also include water temperature boost which are usually energy intensive.

Some of the assumptions made by the developers of GridLAB-D [15] are

- Power factor is fixed to be a constant value at 0.95
- 50 percent of the washer consumption is assumed to become heat in the space, which presumes that half of the heat generated by the resistance heater and motor are flushed after transferring the heat to water.
- Washer capacity is randomly selected between 1000 Watts and 3000 Watts.

A detailed Modelling approach can be found at [15]

3.1.4 MODELLING A RANGE

Ranges are perfect examples for resistive loads and each burner is cycled on or off using a TRIAC device; however a user may during the process of cooking reset the knob setting multiple times. Thus, these loads vary by the number of burners installed and actively in use, the knob control by the user during use, and cycling by the TRIAC.

GridLAB-D developers [15] have simplified the process by making it identical to a plug load. The following are the assumption considered to model a range.

- The power factor is assumed to be constant at 0.95
- The heat generated by the range is assumed to be the heat transferred to the conditioned space.
- The installed capacity of the range is randomly selected between 2500 Watts and 4500 Watts.

A detailed Modelling approach can be found at [15]

3.1.5 MODELLING MICROWAVE OVEN

These devices are constant power consuming devices during normal operation, other modes of operation also consume the same power but in a cycled on or off method. These devices are typically in the range from 750 Watts and 1100 Watts and are usually 65 percent efficient, which means they use 65 percent of the energy to heat or cook food and the rest is released as heat to the conditioned space.

The following are the assumptions made by the developers of GridLAB-D [15]

- The power factor is fixed to be 0.95
- 25 percent of the energy consumed is converted as heat released to the conditioned space.
- The installed capacity is selected randomly anywhere between 700 Watts to 2000 Watts.

A detailed Modelling approach can be found at [15]

3.1.6 MODELLING A REFRIGERATOR

First principle models are used to estimate the thermal and electric loads on a refrigerator [15]. Thermal load is modeled as a function of lumped parameters like thermostat settings, internal gains due to adding and removing food items and ambient condition. The power consumption of compressor and fan is then calculated as electrical loads. This model is not accurate as a physical model but provides a reasonably accurate estimate of the energy consumption.

Following are the major heat gains contributed to the refrigerator thermal load:

- Conduction through refrigerator and freezer walls
- Heat gain due to addition of food and infiltration of ambient air when the refrigerator door is opened

Following are the assumptions made while modelling a refrigerator

- The power factor is assumed to be constant at 0.95
- Thermal conductance of the freezer and refrigerator compartments is assumed to be random normal in the range of 0.9 British thermal unit per square feet hour degree Fahrenheit to 1.1Btu per square feet hour degree Fahrenheit.
- The set point of the refrigerator is assumed to be between 35 degrees Fahrenheit and 39 degrees Fahrenheit.

A detailed Modelling approach can be found at [15]

3.1.7 MODELLING DUE TO INTERNAL GAINS

GridLAB-D has modelled each house to have two primary sources of internally generated heat. Firstly the heats given off by the devices that are modelled by GridLAB-D like the refrigerator. Secondly the devices that are not modelled by the GridLAB-D including electronic devices like television sets, hair dryers and other devices which can have a significant contribution towards internal heat gain.

Following are the assumptions that are considered while modelling internal gains

- All plug loads are consolidated to a single load and are split into one side of the home space or evenly distributed, which is selected randomly when houses are created.
- A random value of the installed capacity of plug load is set between 700 Watts and 2000 Watts.
- The fraction of load that contributes to heat in the house is set to 90 percent.
- The power factor of plug loads is assumed to be 0.95
- Power demand fraction is set to be anywhere between 0 and 0.1

A detailed Modelling approach can be found at [15]

3.1.8 MODELLING A HOUSE PARAMETRS

The residential house model considers four major heat gains or losses that compliment to heating and cooling loads

- Air infiltration
- Conduction through roofs, exteriors walls and fenestration
- Solar radiation
- Internal gains that include lighting, occupants, and other end use equipment's.

Assumptions made while modelling a house

- GridLAB-D assumes that the contribution to heating, ventilation and air-conditioning is from internal gains, solar gains through windows and envelop characteristics.
- Only heat pumps and air-conditioner sets are modeled.

A detailed modelling approach is given in [15]

CHAPTER 4

DEMAND RESPONSE CASE STUDY MODELLING

4.1 CLIMATE DATA

GridLAB-D software [16] usually comes bundled with TMY 2 [17] climate data, a user gets an option to both download and integrate it with the software or to decline and create own climate files.

The climate data that comes bundled with GridLAB-D software [16] has a data that updates every hour therefore any changes in the climate in between this hour is only updated in the next update cycle.

To get finer simulation results, archived climate data developed by the ARMP at NREL [18] from Lamont, Oklahoma are gathered and a new .CSV file is generated, that is then integrated with the GridLAB-D software through the simulation code. The uniqueness of the data that is gathered and built is that the climate data is updated every minute and thus making the simulations even more accurate and achieve finer load graphs.

Figures 4.1.1 and 4.1.2 shows the hourly updated and minutely updated weather data for Lamont, Oklahoma on August 19th, 2003 derived from [18]. Figure 4.1.3 shows the comparison of both the minutely updated weather data and hourly updated weather data. The graph in figure 4.1.2 clearly shows the smooth curve that updates the weather data every minute. This increases accuracy of all the components that depend on outdoor temperature like the indoor temperature and hence the load demand.

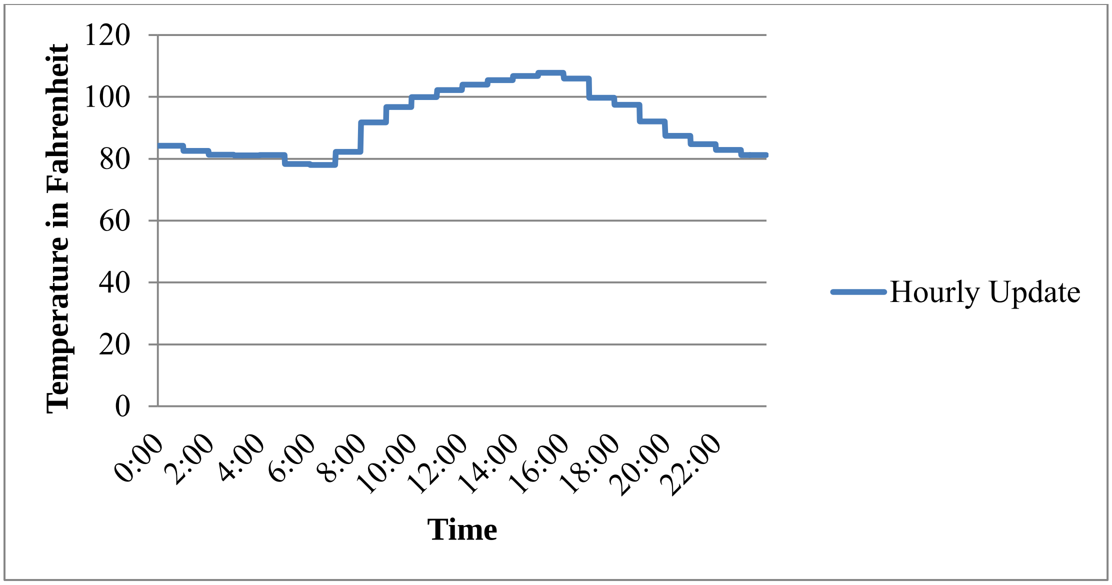


Figure 4.1.1 Hourly Updated Weather Data for August 19th, 2003

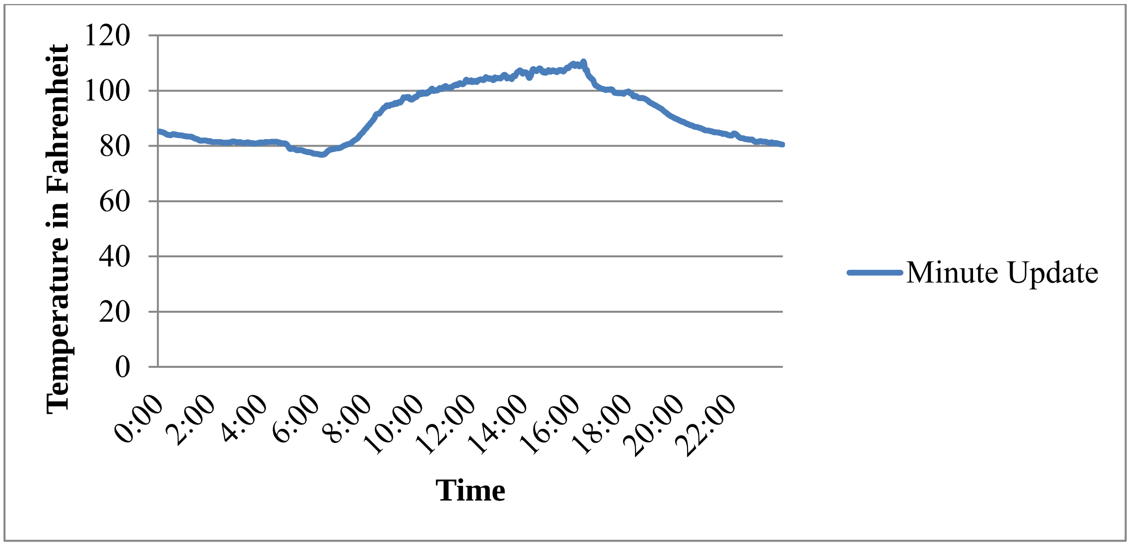


Figure 4.1.2 Minute To Minute Updated Weather Data for August 19th, 2013

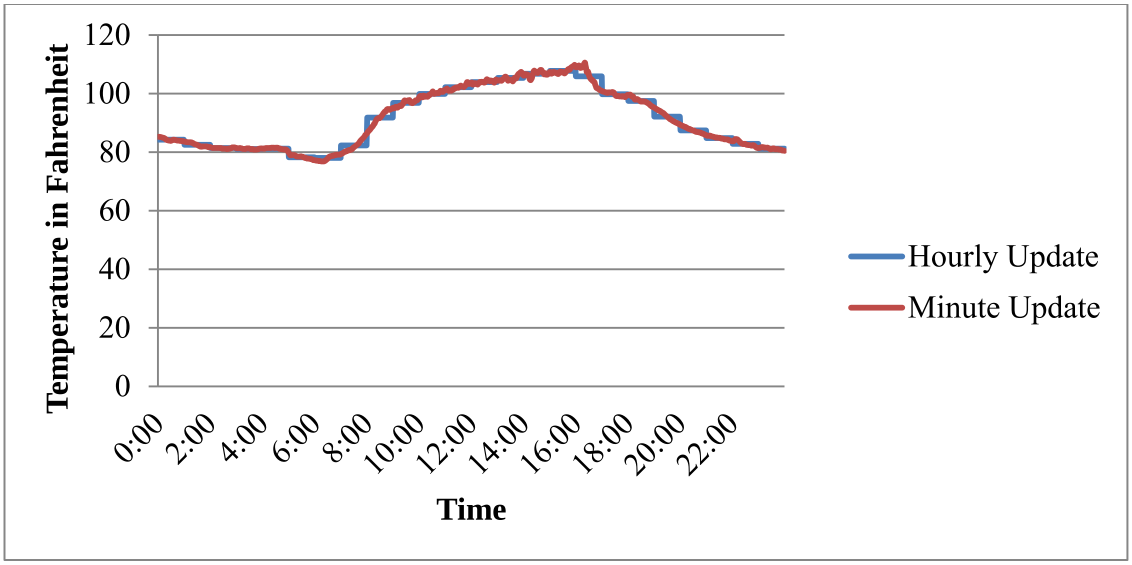


Figure 4.1.3 Comparison of Hourly Updated To Every Minute Updated Weather Data for August 19th, 2003

4.2 GRIDLAB-D CASE GENERATOR

GridLAB-D software recognizes only Grid Lab Model (GLM) files [16], to setup the desired configuration and then run the simulations. These GLM files are built by coding each component and sometimes setting it to a default value. Every component that we initiate must have a clear relationship with other components; each of these components must be explicitly defined to get accurate results. In case of large simulations where objects like houses need to be generated in large populations the code may become very complex and the GLM file becomes extremely large. This can be a cause of inconvenience to the programmer because the code may be vulnerable to many errors, and can take long time to fix the errors apart from wasting system resources.

To simplify this lengthy process a simple case generator is coded to generate any number of houses or objects. The input parameters like population size, air-conditioner size, floor area can be defined in the code generator to build a simple GLM file.

Another added advantage of using case generator code is that the parameters that need to be changed or varied for each house can be defined and can be assigned to random distributions like random normal distribution, random uniform distribution etc. A range of values can be declared and a random distribution be assigned to ensure that each object that is generated in that code is unique from others there by avoiding duplication.

4.3 THERMAL INTEGRITY LEVELS FROM GRIDLAB-D

Thermal integrity levels for residential houses made available by the GridLAB-D software [19] are “easy” to use parameters; they give reasonably default values for air exchange rates, R-values like R-roof, R-wall etc. to broadly represent generic building types.

GridLAB-D has made available eight different thermal integrity levels of residential houses [19].

- House with very little thermal integrity level
- House with little integrity level
- House with below normal integrity level
- House with normal integrity level
- House with above normal integrity level
- House with good integrity level
- House with very good integrity level
- House with unknown or user specified values.

Each house defined in the code is associated with one of these thermal integrity levels and if none of the above is specified by the user software sets it to unknown.

4.3.1 HOUSE WITH VERY LITTLE THERMAL INTEGRITY LEVEL

These houses are assumed to be old and extremely uninsulated. The energy consumption by HVAC in these houses is the highest than the other houses.

The following are the default R-values and air exchange values [19]

- R-Roof : 11 degF.sf.h/Btu
- R-Floor: 4 degF.sf.h/Btu
- R-Wall : 4 degF.sf.h/Btu
- R-Doors: 3 degF.sf.h/Btu
- R-window : 1/1.27 degF.sf.h/Btu
- Air change per hour : 1.5

4.3.2 HOUSE WITH LITTLE THERMAL INTEGRITY LEVEL

These houses are considered to be old but have insulation on them. The energy consumption by HVAC in these houses are little better than very little thermal integrity houses.

The following are the default R-values and air exchange values [19]

- R-Roof : 19 degF.sf.h/Btu
- R-Wall : 11 degF.sf.h/Btu
- R-Floor: 4 degF.sf.h/Btu
- R-Doors: 3 degF.sf.h/Btu
- R-window : 1/0.81 degF.sf.h/Btu
- Air change per hour : 1.5

4.3.3 HOUSE WITH BELOW NORMAL THERMAL INTEGRITY LEVEL

These houses are old and weatherized and have better insulation than the previous group of houses. The HVAC energy consumption on these houses is better but they can be improved for better savings.

The following are the default R-values and air exchange values [19]

- R-Roof : 19 degF.sf.h/Btu
- R-Wall : 11 degF.sf.h/Btu
- R-Floor: 11 degF.sf.h/Btu
- R-Doors: 3 degF.sf.h/Btu
- R-window : 1/0.81 degF.sf.h/Btu
- Air change per hour : 1.0

4.3.4 HOUSE WITH NORMAL THERMAL INTEGRITY LEVEL

These houses are old and are retrofitted with better insulation than the previous groups the HVAC power consumption is also comparable to the above group of old houses.

The following are the default R-values and air exchange values [19]

- R-Roof : 30 degF.sf.h/Btu
- R-Wall : 11 degF.sf.h/Btu
- R-Floor: 19 degF.sf.h/Btu
- R-Doors: 3 degF.sf.h/Btu
- R-window : 1/0.6 degF.sf.h/Btu
- Air change per hour : 1.0

4.3.5 HOUSE WITH ABOVE NORMAL THERMAL INTEGRITY LEVEL

These houses are moderately insulated house and have better HVAC power consumption values than the previous group of houses

The following are the default R-values and air exchange values [19]

- R-Roof : 30 degF.sf.h/Btu
- R-Wall : 19 degF.sf.h/Btu
- R-Floor: 11 degF.sf.h/Btu
- R-Doors: 3 degF.sf.h/Btu
- R-window : 1/0.6 degF.sf.h/Btu
- Air change per hour : 1.0

4.3.6 HOUSE WITH GOOD THERMAL INTEGRITY LEVEL

These houses are considered to be new and have very well insulation levels making them power savers in terms of HVAC power consumption.

The following are the default R-values and air exchange values [19]

- R-Roof : 30 degF.sf.h/Btu
- R-Wall : 19 degF.sf.h/Btu
- R-Floor: 22 degF.sf.h/Btu
- R-Doors: 5 degF.sf.h/Btu
- R-window : 1/0.47 degF.sf.h/Btu
- Air change per hour : 0.5

4.3.7 HOUSE WITH VERY GOOD THERMAL INTEGRITY LEVEL

These houses are newly built and have extremely well insulations on them; they are the highest power savers in terms of HVAC power consumption patterns of all the above house variants.

The following are the default R-values and air exchange values [19]

- R-Roof : 48 degF.sf.h/Btu
- R-Wall : 22 degF.sf.h/Btu
- R-Floor: 30 degF.sf.h/Btu
- R-Door: 11 degF.sf.h/Btu

- R-window : 1/0.31 degF.sf.h/Btu
- Air change per hour : 0.5

4.3.8 HOUSE WITH UNKNOWN THERMAL INTEGRITY LEVEL

When a house is modelled in GridLAB-D it gives the operator to design the house with desired values or an operator can choose from a set of default thermal integrity level houses designed for the very purpose, however if thermal integrity values are not defined or chosen from available options the software assumes that the thermal integrity level is unknown and sets it to default values. If the thermal integrity level is set to unknown and operator defines the R-values and air exchange rates then the user defined values will be used during simulation.

The following are the default R-values and air exchange values [19]

- R-Roof : 30 degF.sf.h/Btu
- R-Wall : 19 degF.sf.h/Btu
- R-Floor: 22 degF.sf.h/Btu
- R-Door: 5 degF.sf.h/Btu
- R-window : 1/0.47 degF.sf.h/Btu
- Air change per hour : 0.5

CHAPTER 5

DEMAND RESPONSE CASE STUDIES

5.1 ENERGY CONSUMPTION BY DIFFERENT POPULATION SIZES

The study of energy consumption by different population of houses is performed to understand the energy consumption patterns by these houses; once these simulations are analyzed further assumptions can be based on these results.

To understand the pattern of power consumption a similar set of houses are simulated. For each of those houses the thermal integrity levels are same, air conditioner sizes are same and are located in the same area with similar climatic conditions; the floor areas are only varying using a random normal distribution between 2500 square feet to 3000 square feet.

Figure 5.1.1 shows the simulation results in the form of graphical representation for 100, 500, 1000, 5000 and 10000 houses. It is clear from figure 5.1.1 that the electrical power consumption patterns are highly correlated for similar houses which have same HVAC system but different floor areas.

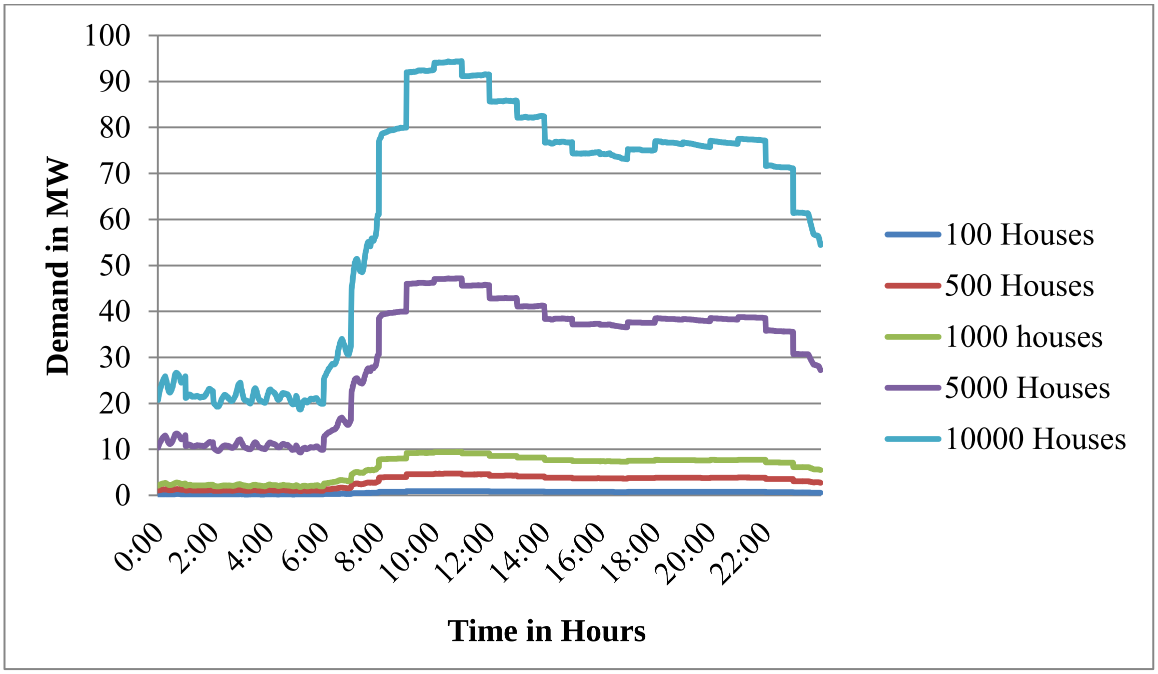


Figure 5.1.1 Energy consumption patterns for different populations of houses

Furthermore, since the simulations were performed for a single day we can co-relate these results to understand that the indoor air temperature is a function of a combination of various factors like outdoor climate, building parameters and installed HVAC system.

5.2 DEMAND RESPONSE PROGRAM FOR HIGH TEMPERATURE DAYS

There are a lot of demand response programs available as stated in chapter 2 of this document. For this research work a simple demand response using direct load control (DLC) is used. This method has best been documented for demand response and occupant comfort in [20]. A ten minute air conditioner cycle off time is used, since longer durations of interruptions may cause issues with occupant comfort and may result in higher non participation.

The results from report [20] shows that the indoor temperature rises no more than 2 degree Fahrenheit when the air conditioner is turned off for ten minutes, even when the outdoor temperatures are more than 100 degree Fahrenheit, and for the same ten minute air-conditioner shut off, the rise in indoor temperature is less than 2 degree when the outdoor temperature is below 100 degree Fahrenheit.

Simulation assumptions for thermal integrity levels

- In the following simulations houses with normal level thermal integrity levels will be considered as a default house. It is assumed houses that fall under the other thermal integrity levels are equal in number and will be compensated by normal level thermal integrity houses.
- Houses with different thermal integrity levels are spread evenly for the population of houses considered.

An Area with 600 houses is simulated with a mixture of different floor areas and air conditioner sizes. Each house is unique and the floor area and air conditioner sizes of these houses are distributed using random normal distribution. A case generator code described in chapter 3 is used to generate these houses. The floor areas are randomly distributed from 2500 Square feet to 3000 Square feet. The air conditioners are sized [21] approximately to maintain 75 degrees Fahrenheit indoor temperature through most of the time during the summer season (June through September), and are distributed randomly within a 1000 Btu/hr. window.

Load control program on these houses were performed on various days through the summer period. Each of these days has had a specific weather condition.

- Simulations were performed for July 19th, August 19th and 20th because they were found to be hottest days in the summer; maximum demand response potential can be realized on these days.

In the load controlled simulation performed on each of those residential houses had their air-conditioners cycled off for one ten minute period during the system peak load period. The ten minute cycle off periods are spread out evenly throughout the peak period. Batches of houses were controlled to turn off their air-conditioners between those periods.

All the simulations for the above said days are performed with and without demand response program, and observed the resulting reductions in energy and thereby reducing the peak demand for that day.

5.2.1 CASE STUDY 1

July 19th

Figure 5.2.1.1 shows the indoor and outdoor temperatures on that day for a single house with normal thermal integrity level having an area of 2500 square feet and air conditioner sized at 36350 Btu/hr.

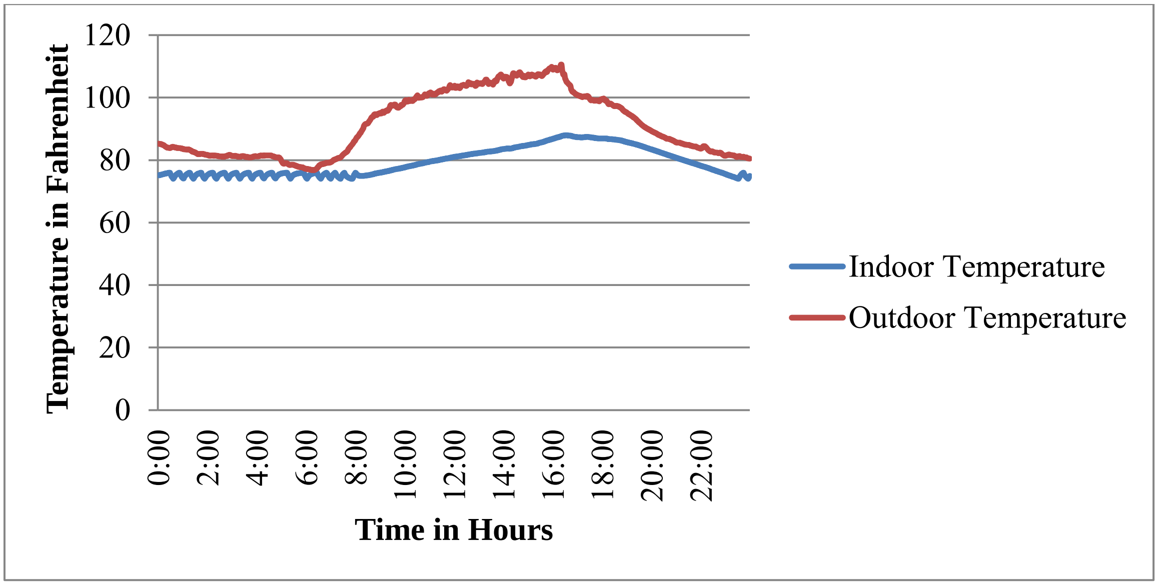


Figure 5.2.1.1 Comparison of Indoor To Outdoor Temperature

Figure 5.2.1.2 shows the indoor and outdoor temperature when the air conditioner was shut off for ten minutes. Here a small spike in the indoor air temperature can be found at 9 AM this is because the air conditioner was shut off and during this ten minute period; this rise in indoor air temperature is found to be less than 2 degree Fahrenheit. This makes the ten minute demand response program maintain the ASHRE standards [22] of allowable cyclic variation in indoor temperature to be less than 2 degree Fahrenheit, within a period of 15 minutes or less than that.

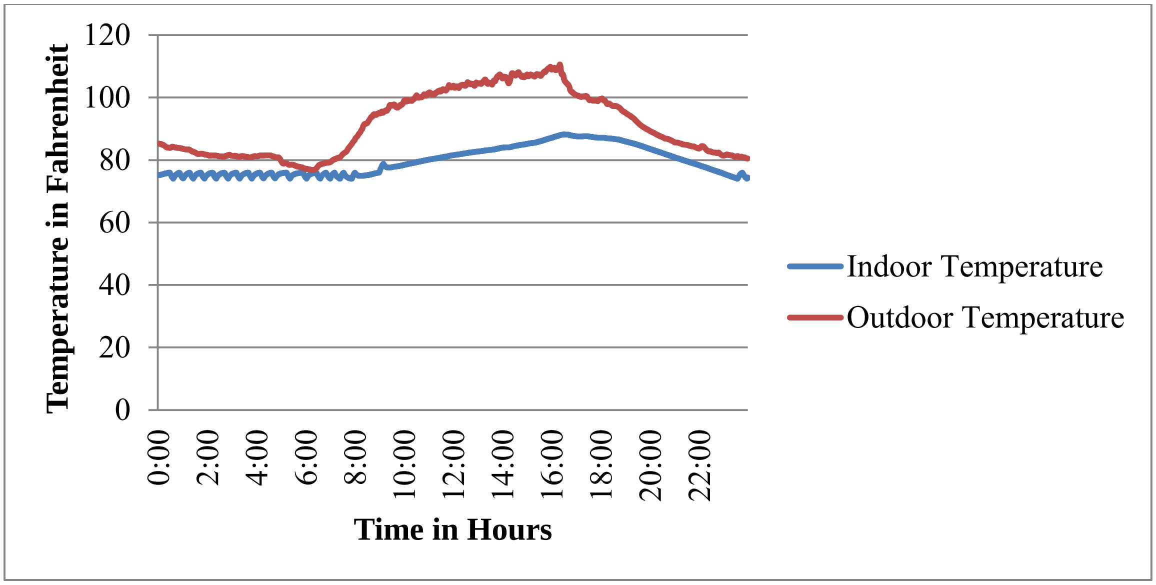


Figure 5.2.1.2 Comparison of Indoor to Outdoor Temperature with Demand response

Figure 5.2.1.3 shows the real time demand for all the 600 houses through the day. The step rise and fall in the graph is due to the behavior of air conditioners and other appliances who also cycle on/off like the refrigerator, plug loads turned on/off by the user, water heater etc. It also shows that the greatest demand was observed from 9 AM through 11 AM.

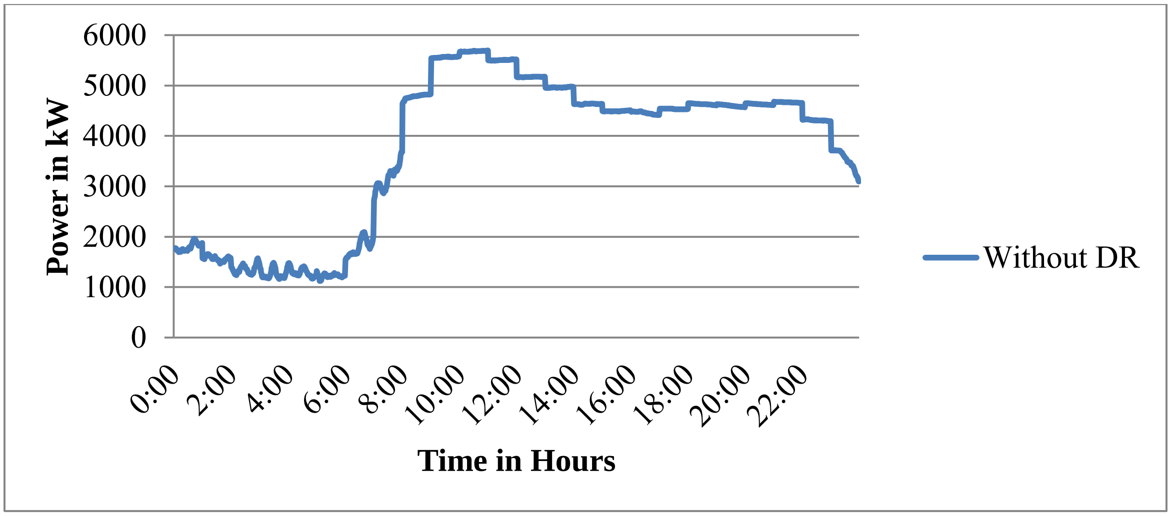


Figure 5.2.1.3: Real Power Demand Without Demand Response

Figure 5.2.1.4 shows the real time demand for all the houses when the demand response was initiated on each of those houses for ten minutes and spread over a time period of 2 hours from 9 AM to 11 AM.

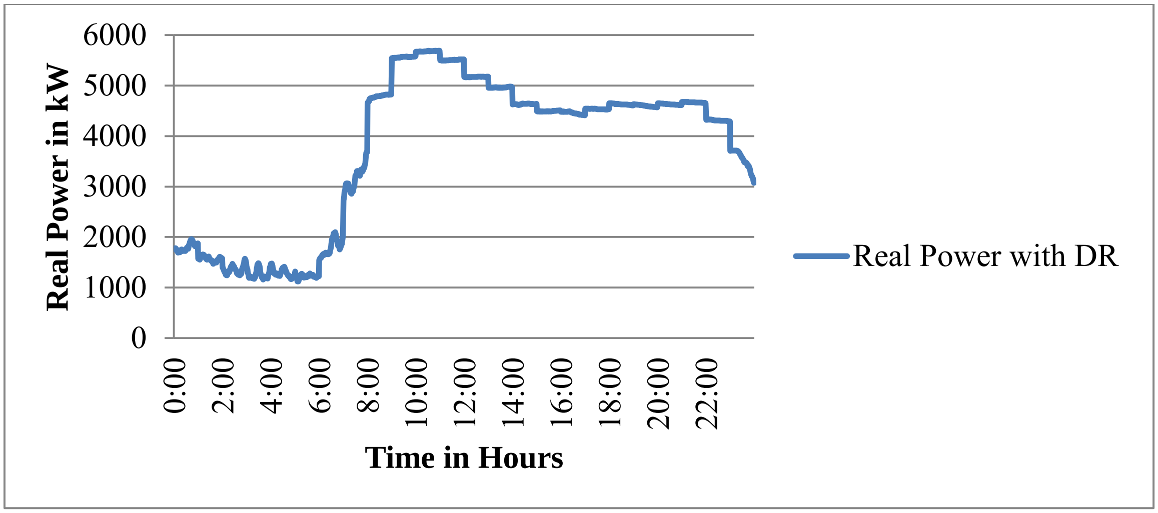


Figure 5.2.1.4 Real Power Demand with Demand Response

Figure 5.2.1.5 shows the real time demand response when both demand response is applied and when it is not applied. When the demand response was initiated on those 600 houses the net resultant reductions observed in terms of electrical demand for the two hour period is 78.43 kW

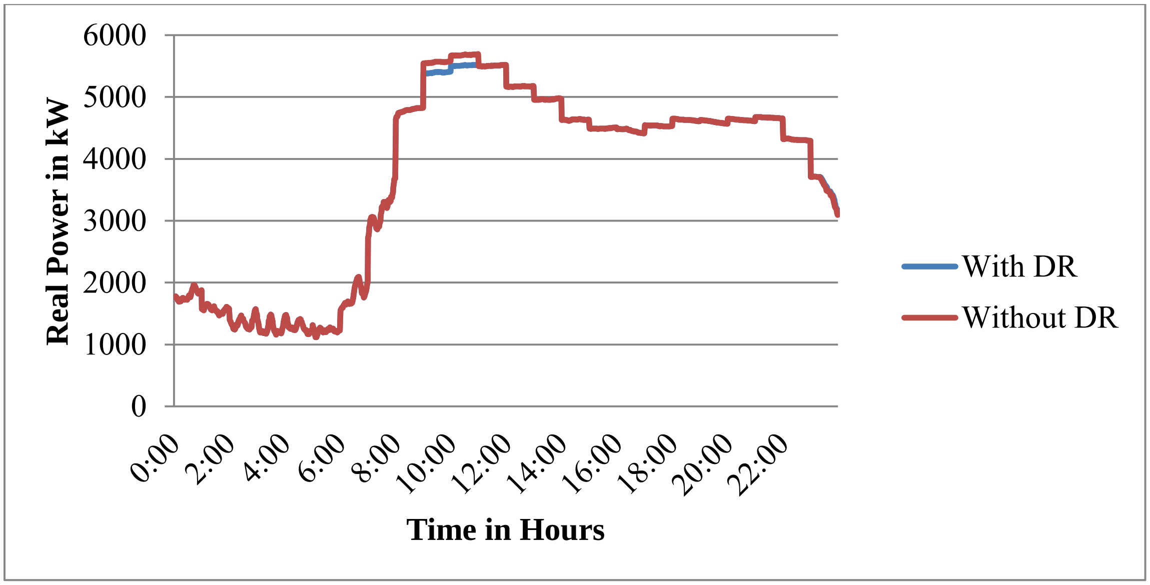


Figure 5.2.1.5 Real Power Demand With and Without Demand response

5.2.2 CASE STUDY 2

August 19th

Figure 5.2.2.1 shows the indoor and outdoor temperatures on that day for a single house with normal thermal integrity level and area of 2500 square feet and air conditioner sized at 36350 Btu/hr.

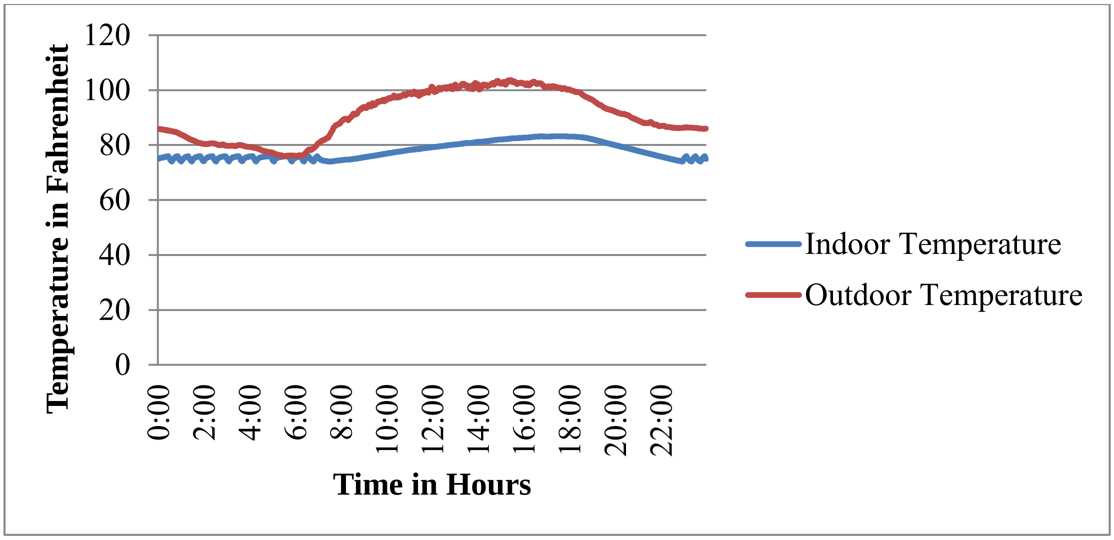


Figure 5.2.2.1 Comparison of Indoor to Outdoor Temperature

Figure 5.2.2.2 shows the indoor and outdoor temperature when the air conditioner was shut off for ten minutes. Here a small spike in the indoor temperature can be found at 9 AM, this rise in indoor air temperature is less than 2 degree Fahrenheit making this demand response program follow the ASHRE standards [22] for allowable cyclic air temperature changes over a fixed period of time.

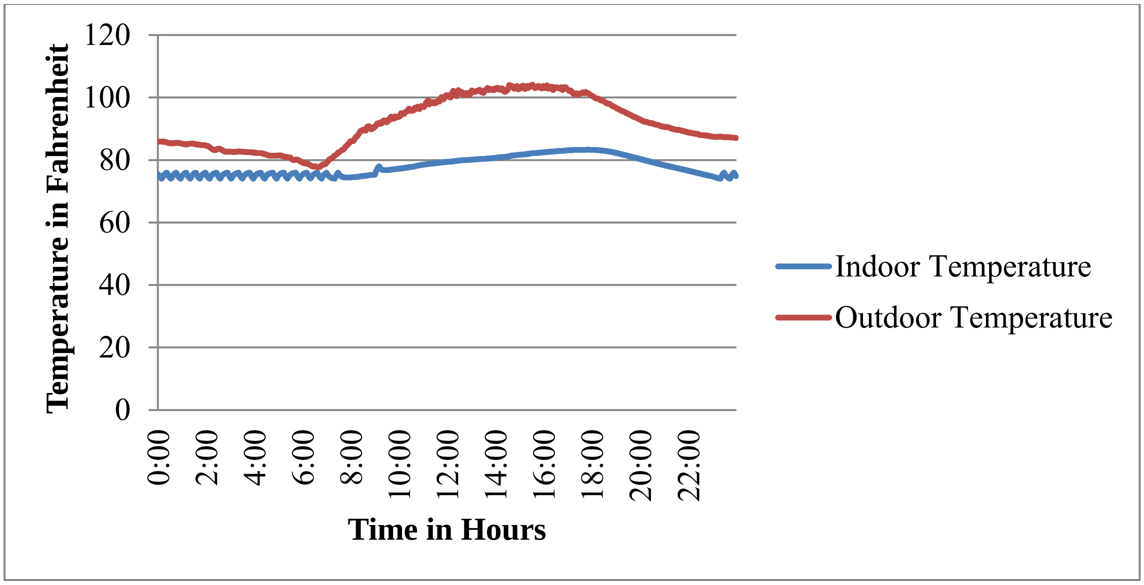


Figure 5.2.2.2 Comparison of Indoor to Outdoor Temperature with Demand response

Figure 5.2.2.3 shows the real time demand for all the 600 houses through the day. It also shows that the greatest demand was observed from 9 AM through 11 AM.

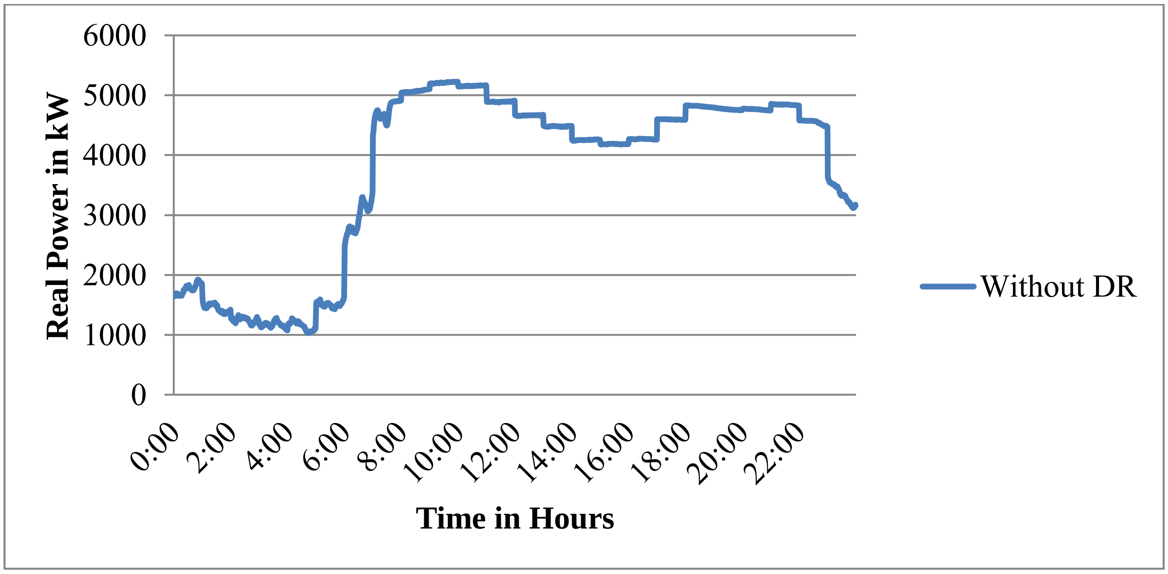


Figure 5.2.2.3 Real Power Demand Without Demand Response

Figure 5.2.2.4 shows the real time demand for all the houses when the demand response was initiated on each of those houses for ten minutes and spread over a time period of two hours 9 AM to 11 AM.

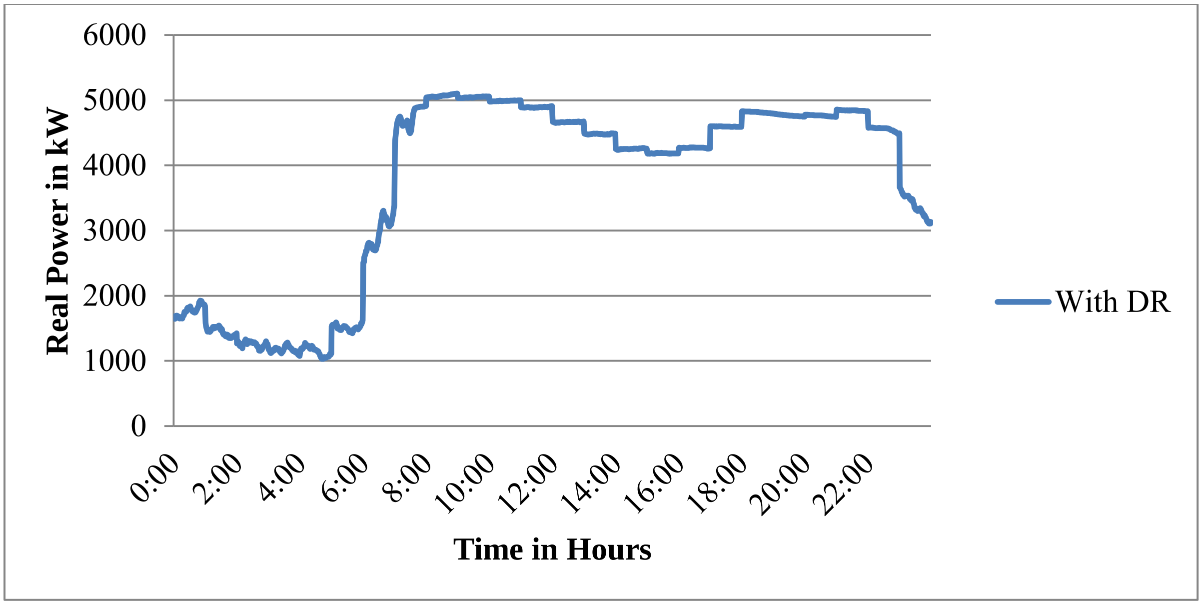


Figure 5.2.2.4 Real Power Demand With Demand Response

Figure 5.2.2.5 shows the real time demand response when both demand response is applied and when it is not applied. When the demand response was initiated on those 600 houses the net resultant reductions observed in terms of electrical demand for the two hour period is 75.47 kW

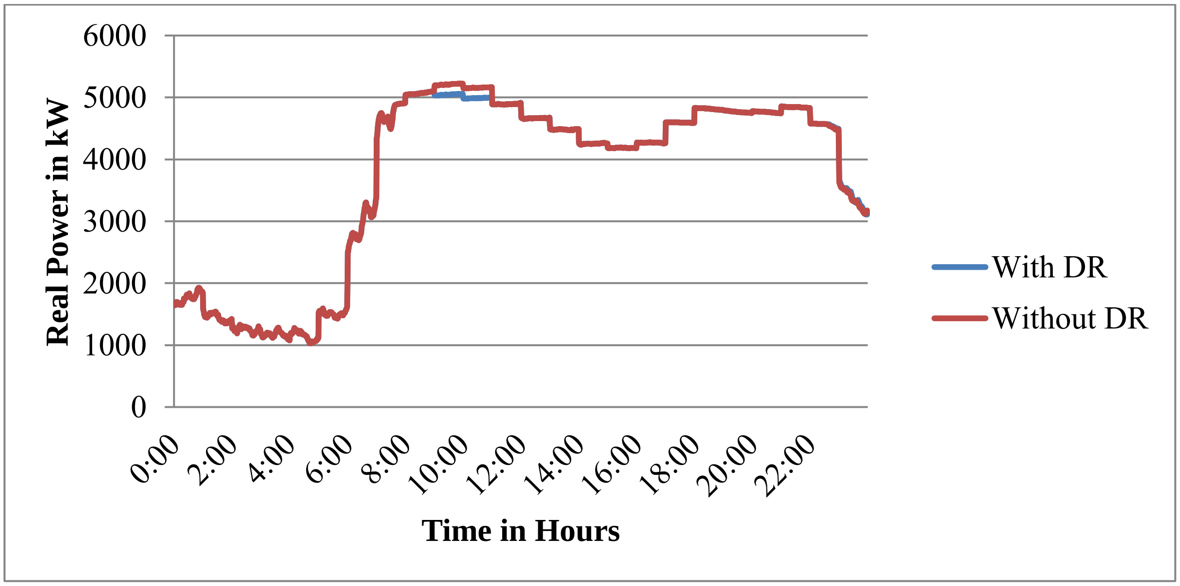


Figure 5.2.2.5 Real Power Demand Without Demand Response

5.2.3 CASE STUDY 3

August 20th

Figure 5.2.3.1 shows the indoor and outdoor temperatures on that day for a single house with normal thermal integrity level and area of 2500 square feet and air conditioner sized at 36350 Btu/hr.

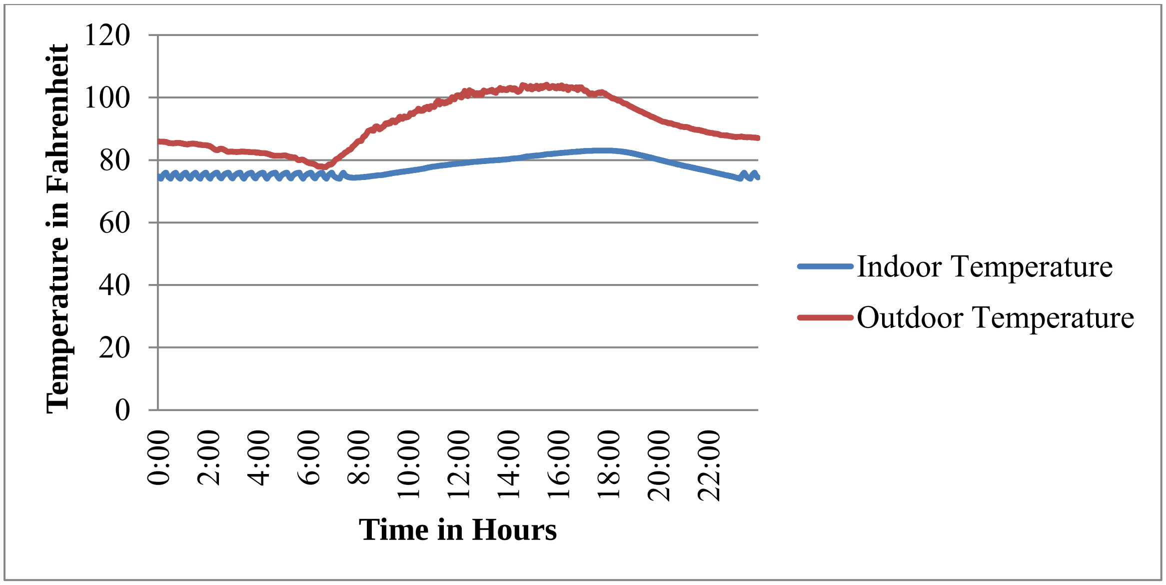


Figure 5.2.3.1 Comparison of Indoor to Outdoor Temperature

Figure 5.2.3.2 shows the indoor and outdoor temperature when the air conditioner was shut off for ten minutes. Here a small spike in the indoor temperature can be found at 9 AM; this rise in indoor air temperature is less than 2 degree Fahrenheit making this demand response program follow the ASHRE standards [22] of allowable cyclic changes in air temperature over a fixed period of time.

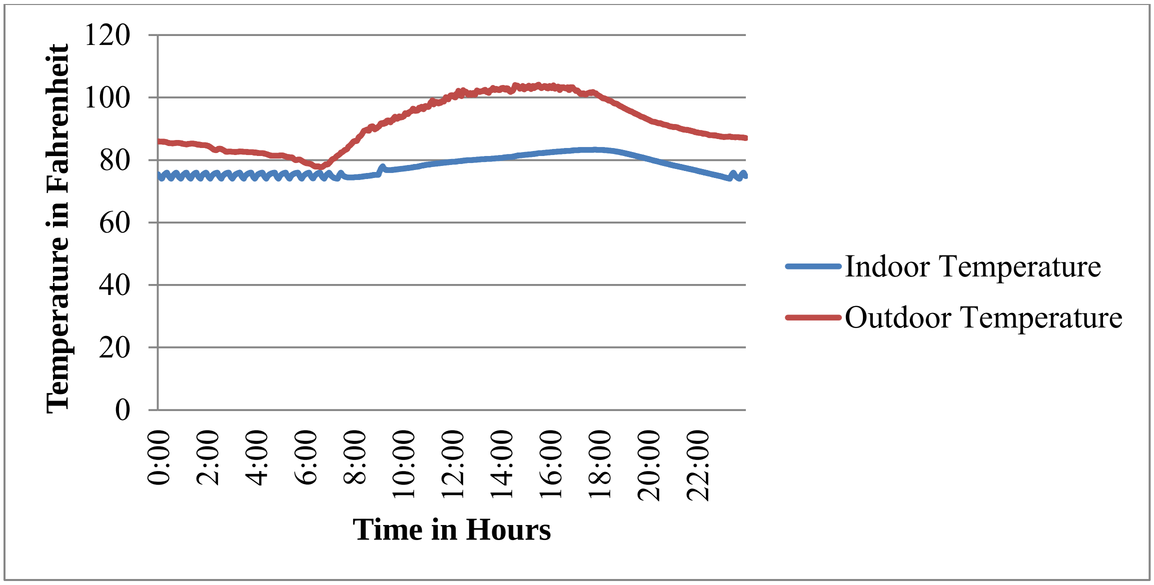


Figure 5.2.3.2 Comparison of Indoor to Outdoor Temperature with Demand response

Figure 5.2.3.3 shows the real time demand for all the 600 houses through the day. The cyclic rise and fall in the graph is due to the behavior of air conditioners and other appliances who also cycle on/off like the refrigerator, plug loads turned on/off by the user, water heater etc. It also shows that the greatest demand was observed from 9 AM through 11 AM.

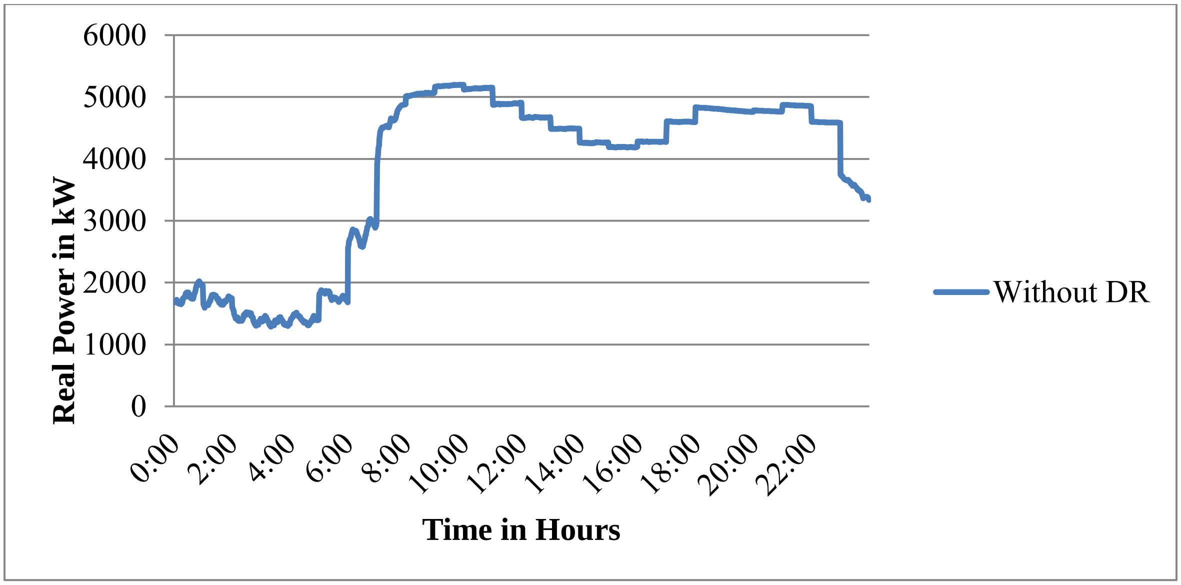


Figure 5.2.3.3 Real Power Demand without Demand Response

Figure 5.2.3.4 shows the real time demand for all the houses when the demand response was initiated on each of those houses for ten minutes and spread over a time period of two hours 9 AM to 11 PM.

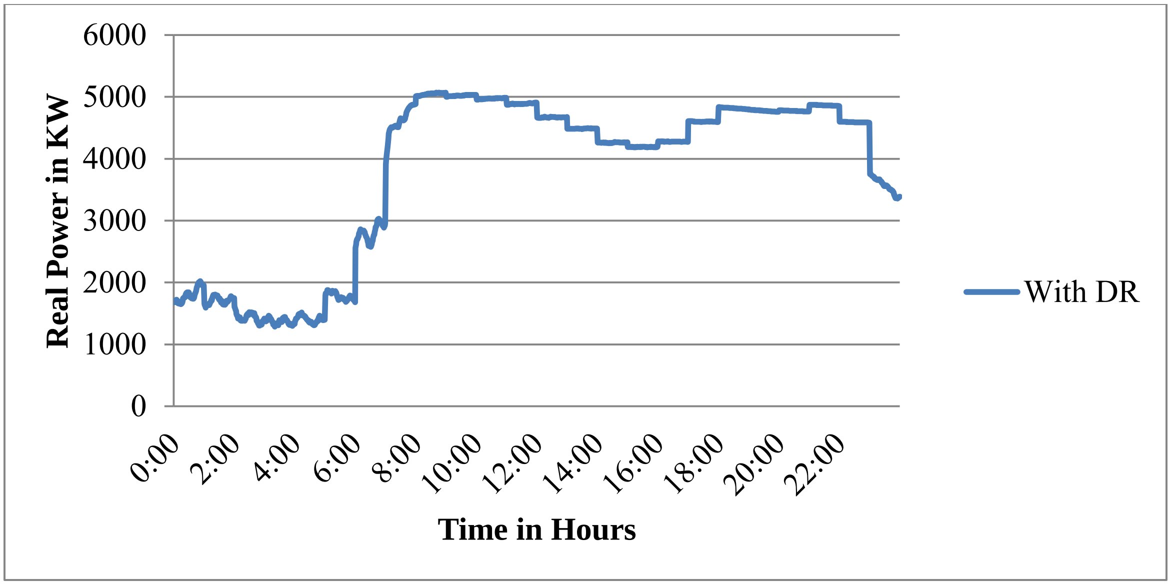


Figure 5.2.3.4 Real Power Demand with Demand Response

Figure 5.2.3.5 shows the real time demand response when both demand response is applied and when it is not applied. When the demand response was initiated on those 600 houses the net resultant reductions observed in terms of electrical demand for the two hour period is 76.875 kW

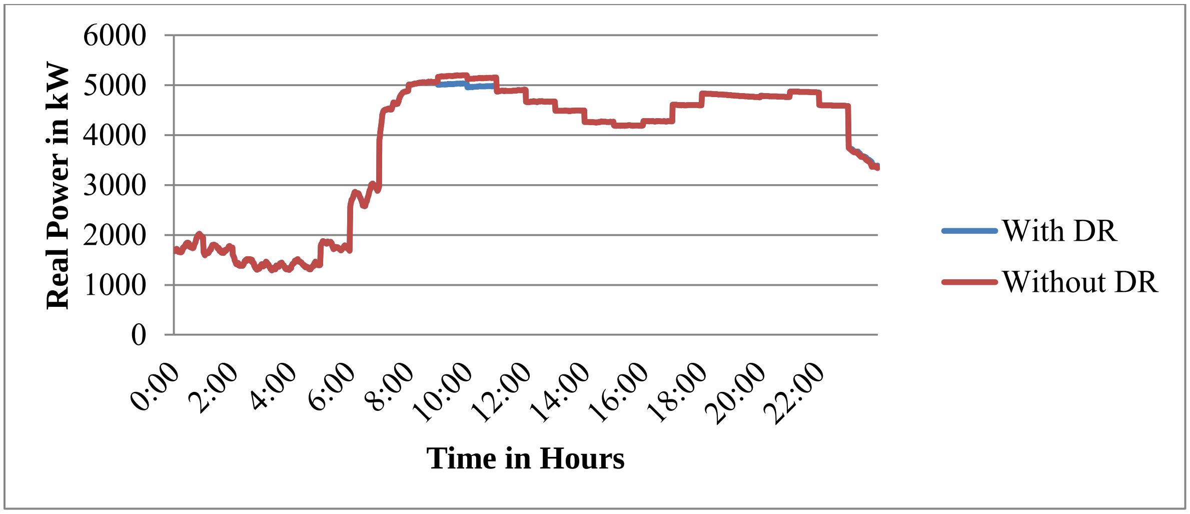


Figure 5.2.3.5 Real Power Demand with and without Demand Response

5.3 CO-ORDINATION OF ENERGY EFFICIENCY AND DEMAND RESPONSE

An Electric Power Research Institute study [7] estimates that “the combination of demand response and energy efficiency programs has the potential to reduce non-coincident summer peak demand by 157 GW”

Three different thermal integrity level houses are simulated separately and each level is simulated with and without demand response. The potential reductions in terms of electrical demand are then analyzed when demand response and residential thermal integrity levels are coordinated.

To analyze the potential of electrical power consumption reductions for a single day on these houses, a simulation is run on the hottest day of the year; July 19th, 2003 and the demand response was run from 9 AM to 11 AM when the highest demand was recorded for the day.

Assumptions:

- The following simulations are performed with only the HVAC systems running on the houses. This assumption makes the recorder function on the software to record only the contributions of the HVAC to the grid.
- The indoor air temperature contributions made by the other appliances are assumed to be negligible.

5.3.1 HOUSE WITH LITTLE THERMAL INTEGRITY LEVEL

A group of 300 houses with little thermal integrity levels are simulated with and without demand response program for duration of two hours during the peak load time from 9 AM to 11 AM. These houses had their air-conditioner shut off for a period of ten minutes. Figure 5.3.1.1 shows the graphical comparison of the real power consumed by these houses when the demand response was applied and when it was not applied. The average load at all times on the grid for these houses when demand response was not in effect is found to be 1013.31 kW. When demand response was applied to these houses the average load at all times on the grid for these houses is found to be 1003.22 kW. Also the reduction in demand due to demand response alone is 65 kW for the two hour period.

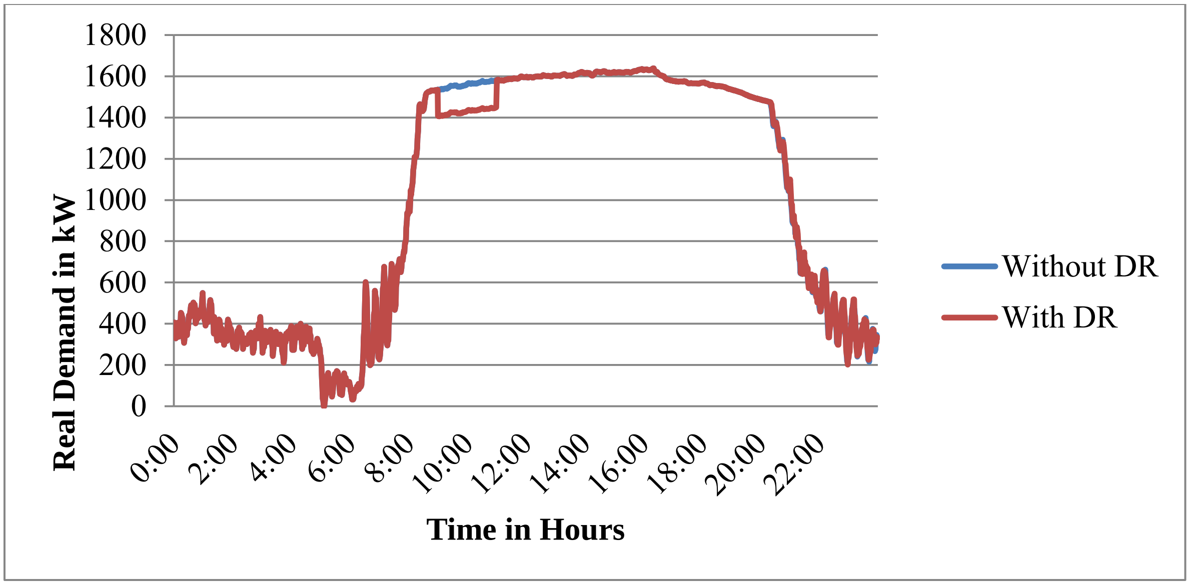


Figure 5.3.1.1 Real Power Demand with and without DR for Houses with Little Thermal Integrity Level

5.3.2 HOUSE WITH NORMAL THERMAL INTEGRITY LEVEL

Figure 5.3.2.1 shows the real power demand curves of the 300 houses simulated with and without demand response and having normal thermal integrity level on each of them. The demand response was initiated for two hours between 9 AM and 11 AM and the air conditioners on each of those houses were turned off for ten minutes. The average load on the grid at all times due to these houses was found to be 631.82 kW. When Demand response was initiated for two hours on these houses the average load at all time on the grid for these houses is found to be 626.27 kW. The demand reduction due to demand response alone is calculated to be 41.88kW for the two hour period.

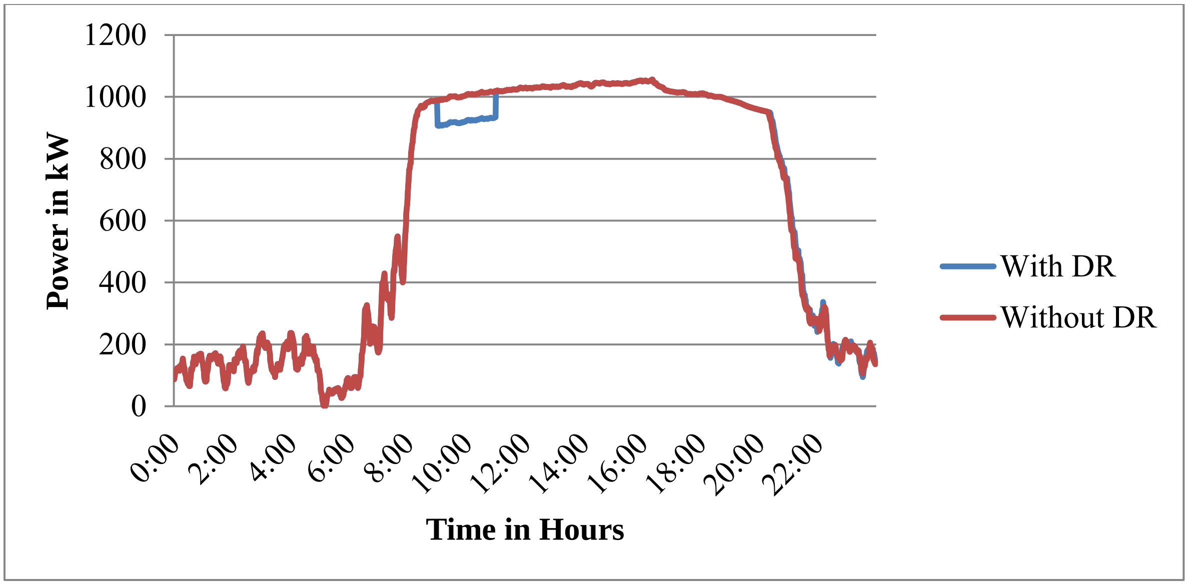


Figure 5.3.2.1 Real Power Demand with and without DR for Houses with Normal Thermal Integrity Level

5.3.3 HOUSE WITH GOOD THERMAL INTEGRITY LEVEL

Figure 5.3.3.1 shows the real power demand curves for the 300 houses simulated with good thermal integrity levels and also with and without demand response. The average load at all times on the grid when demand response was not applied is found to be 492.60 kW, and when demand response was initiated then the average load at all times is found to be 488.89 kW. The demand reduction due to the demand response alone for the two hour period was found to be 33.57 kW.

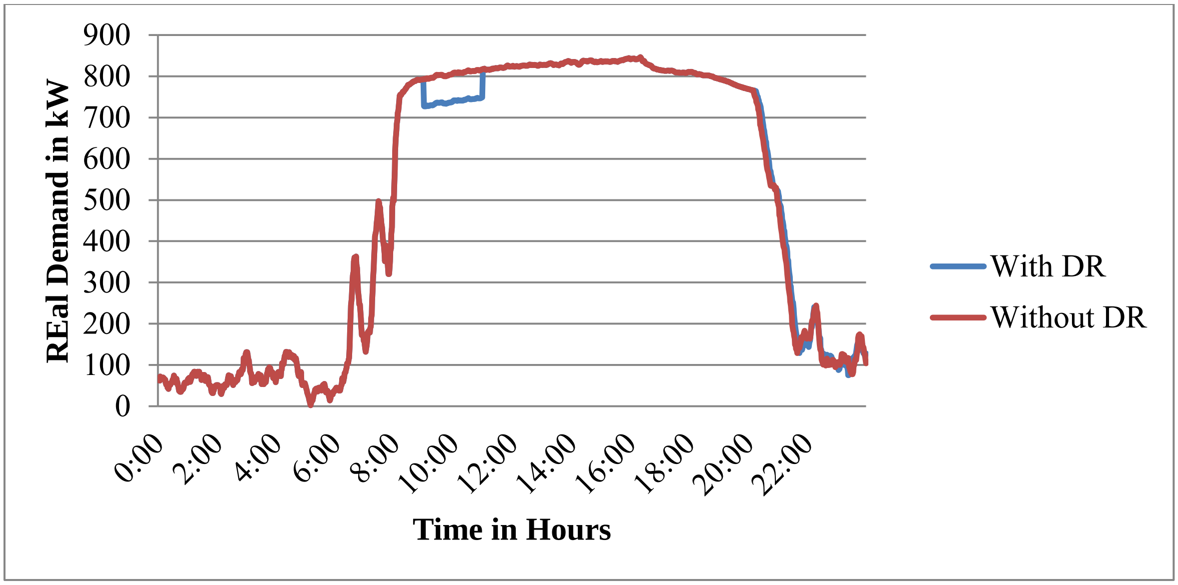
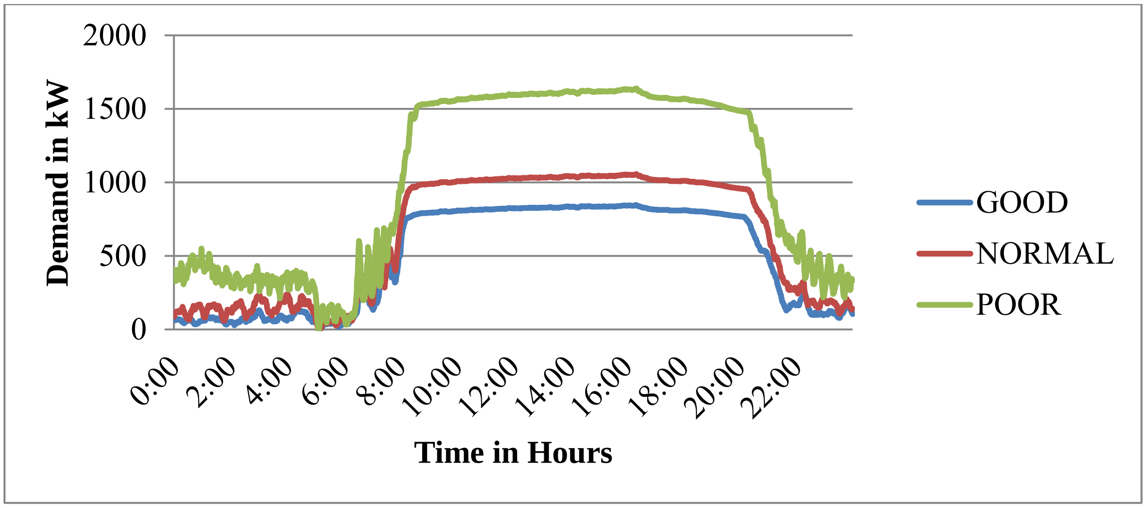


Figure 5.3.3.1 Real Power Demand With and Without DR for Houses With Good Thermal Integrity Level

5.3.4 COMPARISION OF POWER CONSUMPTION BY VARIOUS THERMAL INTEGRITY LEVEL HOUSES

Figure 5.3.4.1 shows the comparison of the real power consumed by HVAC systems on all the 300 houses. Each thermal integrity level houses contributions are observed on this graph. It also shows that the net energy consumed by good thermal integrity level houses is least among the three integrity levels.



5.3.4.1 Comparison of Real Power Demand by Various Thermal Integrity Level Houses.

CHAPTER 6

SUMMARY

In this research work a thorough investigation of demand response program in the residential sector of United States is performed. A direct load control method that is popular in the residential sector of demand response program is used to control only the air-conditioner. GridLAB-D software is used to perform the simulations for demand response. Various thermal integrity levels of houses are considered to find the potential reduction of demand in each case. Case studies are performed on several hot days identified in the year 2003 for Lamont, Oklahoma. The resultant findings are assumed to be the maximum potential of demand reduction because they were performed on the hottest days of the year. ASHRAE standards [22] for consumer comfort levels are met during the entire evaluation. Temperature set point for all the houses are set within the acceptable standard values that are defined by the ASHRAE standards [23].

The following are the research findings from the simulations

- The energy consumption patterns for different populations of houses are highly co-related which have same HVAC systems and same climatic conditions but differ in floor areas, which shows that the indoor air temperature is highly dependent on outdoor air temperature and thermal integrity levels of the buildings.
- Demand response was applied by shutting off the air conditioners for ten minutes on the 600 houses that were simulated, top three hottest days of the year were found for the demand response program. System peak load was found for these days and DR was applied for duration of two hours. The simulation results showed a considerable reduction in demand for these days in 230.76 kW. This aggregated demand reduction can be assumed as a virtual power plant with a capacity of 230.76kW.
- Simulations with just the HVAC loads were performed for a population of 300 houses each with three different levels of thermal integrities, the energy consumptions for these three batches of houses are found to be 1013.31 kW for the houses with little thermal integrity level, 631.82 kW for the houses with normal integrity level and the least was recorded from the houses with good thermal integrity levels at 492.60 kW. On an average 520.71 kW of energy would be reduced on the grid for one day if the residential energy efficiency is increased from little to good integrity levels.
- Demand response was applied on these 300 houses individually who have just HVAC loads and it is found that the effective reduction in demand is less for houses with better thermal integrity levels. The houses with good thermal integrity levels registered a reduction of 33.57 kW of energy, the houses with normal integrity levels

registered a demand reduction of 41.88 kW and the highest demand reduction was possible for the houses with less thermal integration levels at 65 kW.

CHAPTER 7

CONCLUSION

Demand response can be used to reduce the peak load at times when the existing resources are unable to support the load demand. It has a great potential in residential sectors, even though other players also contribute to a significant demand reduction, demand reduction from residential houses outplays the others. There are a number of challenges that needs to be overcome to maximize the potential of residential load reduction during peak load times. Some of the challenges include customer satisfaction, customer comfort, stochastic residential load patterns, lack of proper demand control equipment's etc. Despite of all these challenges residential demand response still stays the highest contributor to the demand reduction in many areas of the United States.

Residential demand response mainly needs to satisfy the customer by providing an attractive incentive and also needs to take care of the customer comfort levels. In this research the demand response is analyzed for population of houses in a particular area, the best way to analyze the demand response is to aggregate a group of houses and then apply demand response to study the resulting demand reductions from these group of houses which can act as virtual power plants for that period of time, also the direct load control program that is used in this research works helps the customers to avoid keeping times to turn off the air conditioners during the demand response hours because the aggregator or the utility controls the devices remotely, thereby avoiding any penalty charges for violating the terms.

In this research only a ten minute cycle off of the air conditioners was done remotely to comply with the ASHRAE standards [22] of not letting the indoor air temperature to rise more than 2 degree Fahrenheit, thereby satisfying the customer regarding comfort related issues. More number of participants can be expected if the duration is less and more participation leads to even more demand reduction.

Best results were found when the residential houses thermal integrity levels are increased. The combination of both residential thermal energy efficiency and demand response could lead to even more reduction of net demand and thereby saving a lot of energy and resources. Though the demand reductions on better thermally integrated houses is less than the one that have poor thermal integrity levels, the overall energy consumption by better thermally integrated houses is far more less than poorly built houses.

The use of new climate data that was built specifically for this research work is more accurate than the TMY 2 climate data that the GridLAB-D uses. The maximum number of houses that were generated using the case generator code specifically built for this research were ten thousand, the number could be larger but the simulation run time may go unexpectedly high in some cases it may also run for several days before we can actually analyze the results .This research work could be used as a stepping stone for those researchers, academicians and utility planners who plan to implement demand response for a group of houses, or community areas where aggregation of similar sets of houses is possible. An estimate of demand reduction can be easily found by simulating those houses under various conditions and also by using the study case generator a number of houses can be generated.

The electric utility companies can also use these simulation results as a reference to estimate the demand reduction possible when the thermal integrity levels of the houses in the existing demand response areas are upgraded. The methods and simulations used in this research work are expected to contribute to the future demand response planning, power system planning and operation and demand response scheduling projects.

CHAPTER 8

FUTURE WORK

Demand response can be implemented in more than one ways to reduce the peak load; there are many models that can be more efficient for reductions in demand when compared to direct load control model used in this research work. This research work could also be extended to commercial establishments where air conditioner control can be realized. While applying this to commercial establishments instead of turning off the air conditioner, setting it to a higher temperature by one or two degrees more than its usual value and then looking at its behavior on the grid would be an interesting area to look at.

Apart from air-conditioner control, other high energy consuming devices like water heater, electric vehicle chargers, clothes dryer could be included in the end user control system and then analyze the potential of reduction of these houses.

Integrating peak pricing with the existing model and scheduling demand response per the peak pricing would also be an area of interest to work in the future.

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