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Demand Side Load Control in Residential Buildings with HVAC Controller for Demand Response

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Demand Side Load Control in Residential Buildings with HVAC Controller for Demand Response

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Dedicated to my parents,

Young Gun Yoon and Jae Ok Song

and to my brother,

Ji Hwan Yoon

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Demand Side Load Control in Residential Buildings with HVAC Controller for Demand Response

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Demand Response (DR) is a key factor to increase the efficiency of the power grid and has the potential to facilitate supply-demand balance. Demand side load control can contribute to reduce electricity consumption through DR programs. Especially, Heating, Ventilating and Air Conditioning (HVAC) load is one of the major contributors to peak loads. In the United States, HVAC systems are the largest consumers of electrical energy and a major contributor to peak demand. In this research, the Dynamic Demand Response Controller (DDRC) is proposed to reduce peak load as well as saves electricity cost while maintaining reasonable thermal comfort by controlling HVAC system. To reduce both peak load and energy cost, DDRC controls the set-point temperature in a thermostat depending on real-time price of electricity. Residential buildings are modeled with various internal loads using building energy modeling tools. The weather data in different climate zones are used to demonstrate

that DDRC decreases peak loads and brings economic benefit in various locations. In addition, two different types of electricity wholesale markets are used to generate DR signals. To assess the performance of DDRC, the control algorithms are improved to consider the characteristics of building envelopes and HVAC equipment. Also, DDRC is designed to be deployed in various areas with different electricity wholesale markets. The indoor thermal comfort on temperature and humidity are considered based on ASHRAE standard 55. Finally, DDRC is developed to a hardware using embedded system. The hardware of DDRC is based on Advanced RISC Microcontroller (ARM) processor and senses both indoor and outdoor environment with Internet connection capability for DR. In addition, user friendly Graphic User Interface (GUI) is generated to control DDRC.

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Chapter 1

Introduction

This chapter briefly describes background about the electricity demand and building energy consumption. In addition, the motivation of the research is provided. This chapter presents the scope, contribution, and the organization of the dissertation.

1.1 Background

Residential and commercial buildings are the major contributors to electrical energy consumption in the United States. The commercial sector including office buildings, retail, and hotels, consumes 35.4 percent of total electricity use in 2010. Residential buildings such as single family homes and apartments use nearly 3 percent more electricity than the commercial sectors. The remaining quarter of total electrical energy is consumed by industrial and transportation sectors. About 74 percent of electrical energy is used by residential and commercial buildings for operations and occupations. Figure 1.1 presents the portion of electricity use by end-use sector in 2010.

The residential buildings are the largest electricity user in power grid in the United State compared to other sectors. In addition, electricity con-

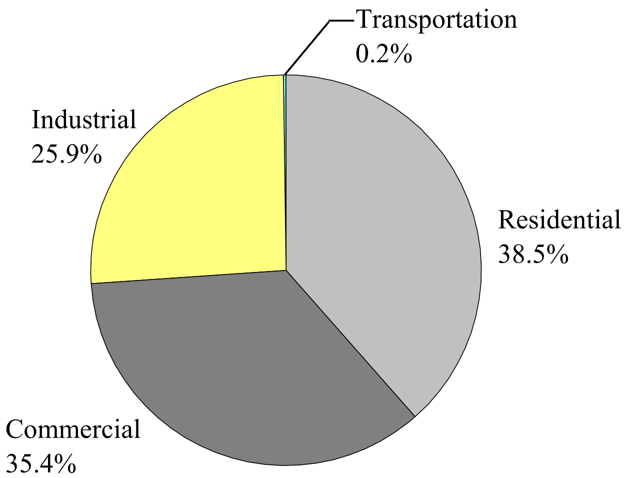


Figure 1.1: Retail Sales of Electricity to Ultimate Customers, Total by End-Use Sector(2010) – [Source] U.S. Energy Information Administration, *Electric Power Monthly*, Table 5.1, September 2012

sumption at residential buildings has on average increased during the last two decades, even if electrical energy use in the last few years has decreased. The size of houses in the 2000's is bigger than in 1980's. So, air conditioning and heating loads to operate Heating, Ventilating, and Air Conditioning (HVAC) system are raised. Also, the increase in numbers of electronics in households also contributes to increase electricity use, although many appliances such as televisions, and refrigerators have become more efficient. Figure 1.2 shows the electrical energy use in residential sector for last twenty years.

Figure 1.3 illustrates electricity consumption in household by equip-

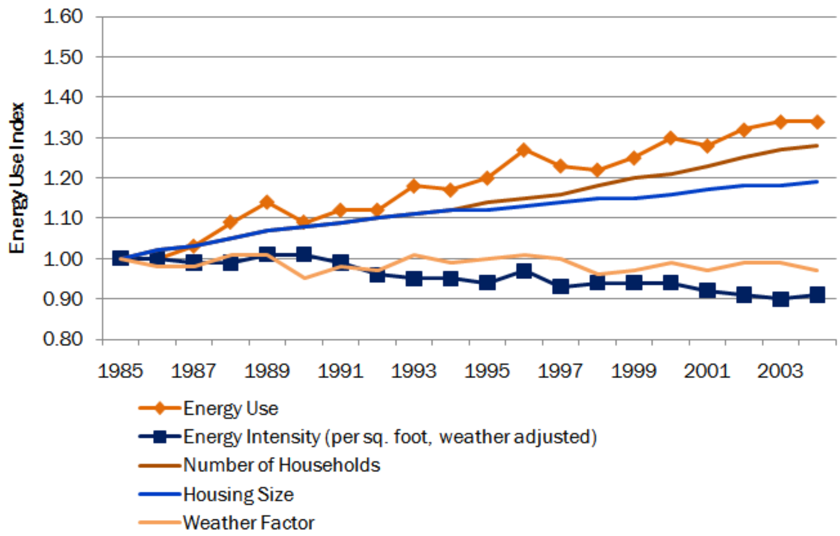


Figure 1.2: Residential Energy Use, Energy Use Intensity, and Energy Use Factors – [Source] DOE, Energy Efficiency and Renewable Energy, *Trend Data: Residential Buildings Sector*

ment type. The major loads in homes are caused by Heating, Ventilating, and Air Conditioning (HVAC) system. The air conditioner consumes 22 percent of electricity use and 9 percent is for space heating. Lighting is the second largest load and accounts for 14 percent of energy use. Electrical water heater and refrigerator consume 9 percent of electricity each. In addition, electronics including television, microwaves, and computers account for 14 percent. In summary, electricity consumption by HVAC system is the biggest load in residential electrical energy use.

Heating, Ventilating, and Air Conditioning (HVAC) equipment in residential is typically a simple centralized system controlled by thermostats. Coils for space cooling and heating are located in the air handler unit. Ther-

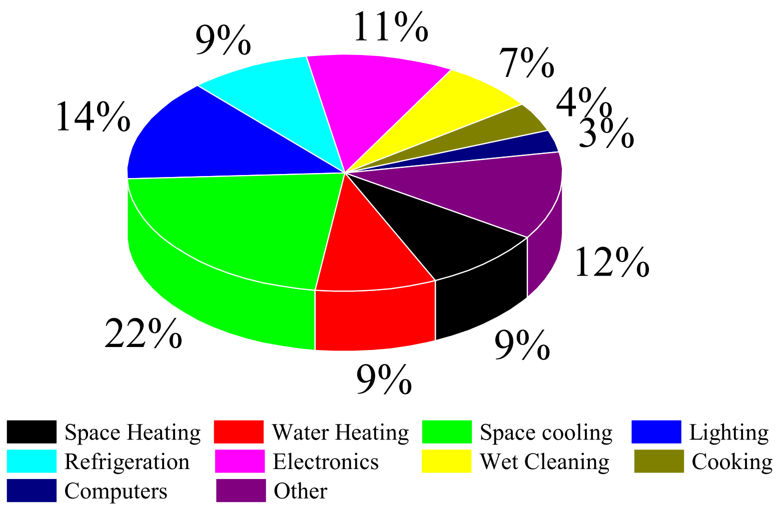


Figure 1.3: Residential electricity consumption by end use (2010) - [Source] DOE, *Buildings Energy Data Book*, Table 2.1.4, March 2012

mal energy exchange between the air and coils to warm the air up or cool it down occurs inside the air handler unit. A fan supplies cool or warm air into a house depending on operation modes: cooling and heating. The thermostat controls the air conditioner and heater by comparing the indoor temperature with the desired temperature. The layout of typical Heating, Ventilating, and Air Conditioning for residential buildings is shown in Figure 1.4.

The heat pump system is widely used for cooling and heating in residential buildings. It works as an air conditioner or heater by changing the operation cycle. A heat pump can absorb heat from a cold space and release it

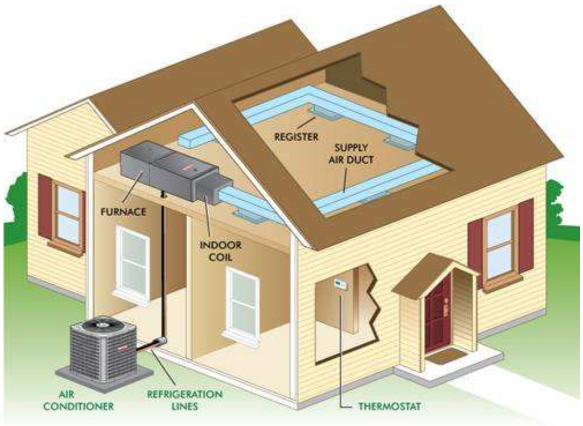


Figure 1.4: Layout of a typical residential HVAC system

to a warmer one. For the air conditioning cycle, a heat pump absorbs thermal energy in a home and emits it outside. The heating cycle is totally opposite to the cooling cycle. The outdoor thermal energy is absorbed, then discharged inside the house for warming up the indoors. Figure 1.5 shows how a heat pump works as air conditioner and heater in one piece of equipment.

In addition, controlling a heat pump is easy when a thermostat is used. The thermostat controls a heat pump depending on the temperature differences between the set-point temperature (target temperature) and indoor temperature. For cooling mode, a heat pump is triggered to work with cooling cycle when the temperature inside of a home is higher than the set-point temperature.

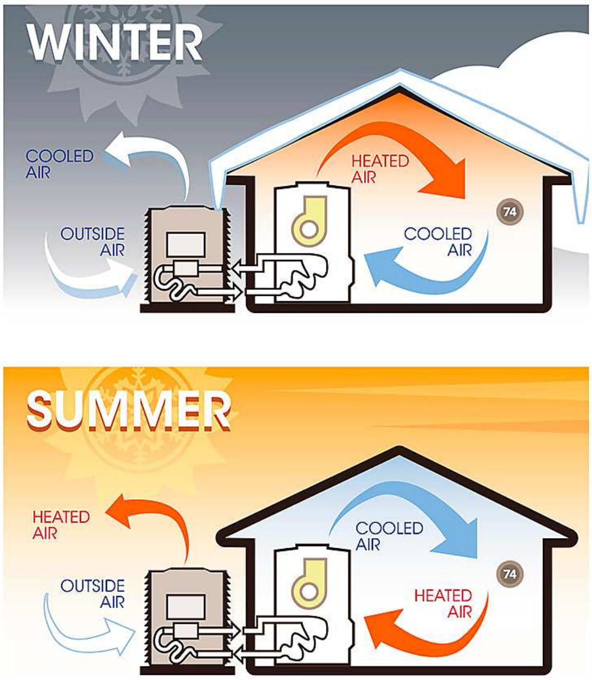


Figure 1.5: The operation of heat pump as an air conditioner or heater

1.2 Motivation and Value of the Research

In conventional power grids, electricity providers such as utilities or power generation companies supply electric power to meet demands. Peak loads occur for relatively short periods and reduce overall power grid efficiency. In Electric Reliability Council of Texas (ERCOT) power grid, loads from residential buildings are the contributor to cause peak loads during summer season. In 2011, it was the hottest summer in Texas. Heavy air conditioner uses in residential buildings caused peak loads. Figure 1.7 presents loads changes from Spring to Summer season. In Spring, on March 31, the residential load was 6,139MW and 20 percent of total ERCOT load. However, the electricity load from residential buildings was increased to 35,308MW on August 3, and accounted for 52 percent [2]. The reduction of air conditioner loads by controlling Heating, Ventilating, and Air Conditioning (HVAC) system can contribute to decrease peak loads as well as to improve the efficiency of power grids.

Our research focuses on control of electricity loads by Heating, Ventilating, and Air Conditioning (HVAC) equipment to reduce peak loads during peak period using the smart grid technology and Demand Response (DR). The smart grid technology contributes to increasing the efficiency of the power grid by controlling loads. Demand Response (DR) is one smart grid technology to control peak loads. In DR, suppliers such as retail electricity providers communicate with consumer to request reduction in peak loads or to shift them to other times through smart meters or their own gateways. Then, consumers

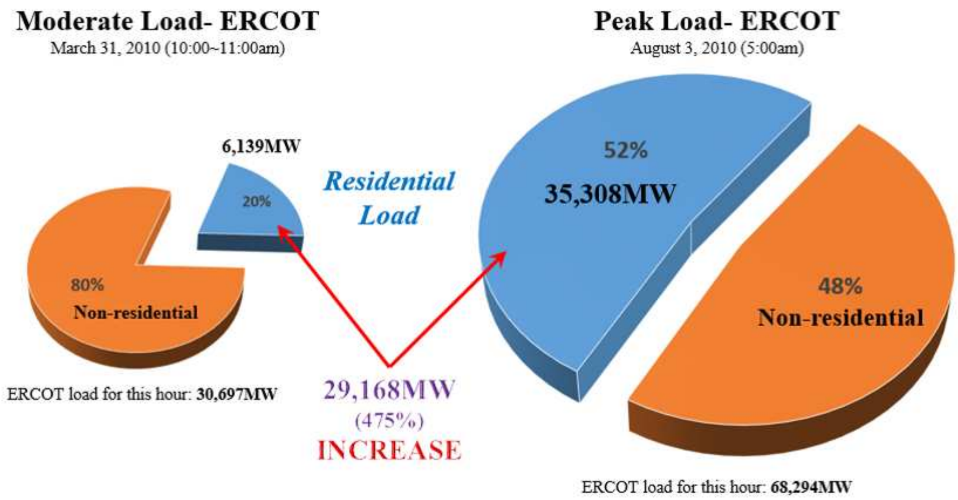


Figure 1.6: Residential load changes in ERCOT grid by HVAC use (2010)

respond to the request to reduce electricity use from power suppliers.

The dynamic price of electricity is a key factor for DR. Wholesale prices change every hour or more often depending on the relation between demand and supply of electricity in the wholesale market. The price of electricity reflects the status of power grids. So, electricity price tends to increase with increasing demand for electricity. When the demand for electricity is high, the electricity price is high. Our research uses price signal based Demand Response (DR) because the energy cost in monetary unit is more familiar to consumers than electricity usage in kWh. So, participants are able to easily understand how DR works to save energy and cost. In addition, their preferences can be reflected on DR program by using a threshold price.

Electric power consumption of Heating, Ventilating, and Air Conditioning (HVAC) system is easy to manage using a thermostat. When a thermostat is used as the controller, complicated control topologies such as variable frequency drive (VFD), and refrigeration cycle control are not required to control HVAC system. The change of set-point temperature (or target temperature) is able to reduce electrical power consumption during peak periods having high price of electricity possibly shifting demand to other times. Furthermore, control of HVAC loads is an effective way to reduce peak loads because HVAC loads account for 31 percent in total electricity use at home by end use.

In contrast, the HVAC controller described in [29] controls directly a compressor motor in HVAC system using Variable Frequency Drive technology (VFD). This technology is complicated so that the cost to deploy or retrofit a controller into homes will be increased. Furthermore, VFD technology does not guarantee the compatibility with other HVAC systems by different manufacturers. Thus, the proposed controller in [88] may not be feasible to install in many buildings. Different from other controller, DDRC maintains the current thermostat system by adding functions with sophisticated DR algorithm.

Thermal comfort is an important factor for the indoor environment. A major reason to use Heating, Ventilating, and Air Conditioning (HVAC) system is to keep inside of buildings in thermal comfort. Changing the set-point temperature may cause residents to feel thermal discomfort. Our research considers thermal comfort when changing the set-point temperature.

1.3 Objectives and Scope of the Research

The objective of this research is the development of a thermostat for residential HVAC system with Demand Response (DR) capability while considering thermal comfort of the indoor environment. In this research, we propose a newly developed thermostat, Dynamic Demand Response Controller (DDRC), to control electricity loads of HVAC equipment during peak periods.

The proposed dynamic thermostat controls the HVAC system in residential buildings by changing the set-point temperatures in thermostats depending on the price of electricity and the preference of occupants. The set-point temperature will be increased or decreased for the cooling and heating mode, respectively, when the threshold price is below the current price of electricity. The threshold price (preset price by consumers) is the baseline price when customers want to participate in the energy saving programs. Also, the America Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) thermal comfort is considered.

To evaluate the performance of the proposed Dynamic Demand Response Thermostat and impact to the building, different detailed residential buildings will be modeled using EnergyPlus, which is building energy simulation software. The internal loads and detailed occupation schedules will be set to represent various houses and building users. The dynamic thermostat will be demonstrated for single family homes in various locations. Two different climate zones will be chosen: Austin, TX (Climate Zone 2, hot and moist) and Chicago, IL (Climate Zone 4, cold and moist). In addition, the real-time prices of electricity are used from ERCOT (Austin, TX) and PJM (Chicago, IL). The years of the dynamic price to evaluate the performance of the thermostat are 2011 for Austin (the hottest year) and 2013 for Chicago (the coldest year).

In an effort to evaluate the DDRC by considering different residential building, occupants and location, the energy consumption to operate HVAC system, the annual operation cost, and the impact on the thermal comfort will be analyzed for cases with and without the proposed thermostat. Also different settings of DDRC will be studied such as internal load change, location and type of dynamic price.

The research will be divided into three phases:

A. Design control algorithm to control a thermostat

(a) Prediction of HVAC power consumption

(b) Using a threshold price to change the target temperature

(c) Set temperature change rate based on the price difference

(d) Limit temperature change rate for thermal comfort

(e) Develop residential models using EnergyPlus

B. Evaluation of performance of Dynamic Demand Response Controller

(a) Peak loads reduction during peak time

(b) Decrease of annual electricity consumption

(c) Savings of annual energy cost to run HVAC system

(d) Maintain indoor environment in thermal comfort

C. Development of hardware of Dynamic Demand Response Controller

(a) Design of graphic user interface

(b) Sensing temperature and humidity

(c) Ethernet connection for DR signal

(d) Relay control board to enable heat pump

1.4 Contributions

The Dynamic Demand Response Controller (DDRC) developed in this work reduce peak loads in order to increase the efficiency of the electric power grid while considering the indoor environment at residential buildings. Our main contributions are summarized as follows.

- We estimated the electricity loads to use Heating, Ventilating, and Air Conditioning (HVAC) equipment using linear regression of calculated values in order to understand the building energy. Using a building energy modeling tool, required thermal energy for cooling and heating is predicted and converted to the electricity load of the heat pump. This prediction provides the analysis of how much electricity loads are changed when Demand Response signal is enabled.

- We proposed the Dynamic Demand Response Controller with newly developed control algorithm. The DDRC responds to price-based DR signals to reduce peak loads when the electric power grid is stressed. It provides Demand Response and gives benefits to both retail electricity providers for peak load reduction and end users for energy cost savings.

- We showed the performance of the proposed Dynamic Demand Response Controller to maintain thermal comfort while it responds to the Demand Response signal. It is important for the Heating, Ventilating, and Air Conditioning (HVAC) system to meet criteria such as ASHRAE standard 55. Analysis of thermal discomfort contributes to ensuring that consumers will continue to response to the Demand Response signal to reduce peak loads.

- We developed the hardware of Dynamic Demand Response Controller for end users. The control algorithm to respond to the Demand Response signal is implemented into the hardware. It demonstrated that the proposed Dynamic Demand Response Controller contributes to reduce peak loads during peak period as well as provide energy cost savings to end users.

1.5 Organization of the Dissertation

The rest of this dissertation is organized as follows. Chapter 2 presents the modeling of single family homes using building energy modeling tools:

EnergyPlus/OpenStudio. Based on historical wholesale price, dynamic retail prices of electricity are generated. Chapter 3 introduces the control algorithms of the Dynamic Demand Response Controller (DDRC). The basic control policy implements price based Demand Response (DR). Improved control policy of DDRC that considers attributes of building envelop is presented. In addition, different locations and wholesale market changes are considered. Chapter 4 evaluates the performance of DDRC using two proposed control algorithms for different climate zones, internal load sizes, floor plans, and price types. Chapter 5 illustrates the development of DDRC hardware. Conclusions are drawn in Chapter 6. Appendix A presents the indoor thermal comfort region on pychrometric charts to show the DDRC minimizes thermal discomfort.

Chapter 2

Modeling of residential buildings and real-time price of electricity

This chapter presents the modeling of single family homes using EnergyPlus which is a building energy modeling tool. Based on architectural features, two different sizes of house are designed. In addition, the dynamic retail prices of electricity are built by analyzing the historical wholesale electricity prices at Electric Reliability of Texas (ERCOT) and Pennsylvania, New Jersey, and Maryland (PJM) Interconnection wholesale market.

2.1 Introduction

Home electricity consumption in the United States has increased by 10% over the last two decades [1]. In addition, Electrical energy consumption in residential buildings in the United States has generally been increasing from 2001 to 2011 except for a few years during the economic crisis. Moreover, the average retail price of electricity has gradually increased in nominal terms over the same period [30]. Of the total electricity consumption in homes, families spend on average 27% of total electricity consumption for heating and air conditioning [2]. The energy and peak load growth necessitates new power plants and transmission lines. In hot climate zones, air conditioning (AC) loads are a major contributor to cause peak load on the power grid. For example as shown in Figure 1.6, in Texas where the Electric Reliability of Texas (ERCOT) manages the power grid, the residential load was 6.1 GW and 20% of grid electricity load on March 31, 2010. However, the residential load in ERCOT was tremendously increased to 35.3 GW, 52% of total load, on August 3, 2010 [3] because of the hot weather. This heavy AC load during summer on the power grids in hot climates is the major contributor to peak load. Recently, there have been capital expansions that will tend to increase the retail price in real terms. Furthermore, due to heavy AC load, the cost for power generation is not only increased but also overall grid efficiency is reduced. This research discusses a proposed Dynamic Demand Response Controller (DDRC) and shows how it can be used for control of the AC system depending on the retail price of electricity. The objective of this study is to model the dynamic demand response controller that changes set-point temperature based on the dynamic price of electricity and occupant preferences. For dynamic price of electricity, two types of real-time tariffs are used by some utilities in the United States: Day Ahead Market Settlement Point Price (DAMSPP) and Real Time Market Settlement Point Price (RTMSPP). For houses with different sizes and floor plans, this study quantifies capacity to reduce peak loads as well as cost while maintaining the thermal comfort inside houses within an acceptable range.

The increase of home energy usage due to Heating, Ventilating, and Air Conditioning (HVAC) requires more generation and transmission line capacity to meet the high peak demand and also reduces the overall power grid efficiency. Therefore, home energy demand increases costs for production of electricity and for capacity. For example, the cost to increase transmission capacity is $400/MW-mile to $3,000/MW-mile for new construction [4]. Reduction of Heating, Ventilation and Air Conditioning (HVAC) load during the peak time period is important to peak load reduction, resulting in significant savings for both utilities and customers.

Austin Energy, the municipal utility in Austin, Texas, distributed 3,000 remotely controllable thermostats for free to their customers in 2003 to reduce HVAC loads at peak. By 2009, more than such 86,000 thermostats were installed in many customers' residential and commercial buildings in the Austin Energy service area. Temporarily switching off compressors brought 90MW load reduction out of approximately 2,000MW peak load during on-peak periods [5]. Control of the thermostat is an effective way to reduce the HVAC loads for Demand Response (DR). However, thermostats that Austin Energy provided are not able to respond to real-time retail electricity prices due to lack of communication and functionality. Dynamic controlled thermostats in [6] and [7] manage HVAC operation by turning on and off based on indoor air temperature tolerance or dead band. These thermostats are not able to consider retail price in their HVAC control. So, HVAC load may not be cut off during the peak price period.

In previous research related to the demand power control, large electricity loads such as commercial buildings, industries, retail and museums are analyzed to reduce high demand at peak time [31]. However, residential buildings are also a major contributor to peak loads. To address problems related to peak load caused by residential heating, ventilating and air conditioning (HVAC) systems, the DDRC is modeled in this research in various residential buildings [34]. Different from other dynamic response controllers analyzed in previous studies in [6, 8-10, 18, 26, 27, 32, 44,45], detailed house models are developed to analyze HVAC electricity consumption under consideration of various building geometries and physical properties that affect energy efficiency using EnergyPlus/OpenStudio energy simulation software [20,21,29]. The model developed for this study overcomes some shortcomings of previous DDRC related research. For example, some of the previous studies related to DDRC [8, 6, 18, 27, 32] did not have a HVAC model to control temperature, and therefore, could not analyze how much electricity is saved for cooling or heating during peak load period. Other studies related to demand response controllers [9, 10, 26] added simple HVAC models but the oversimplified Equivalent Thermal Parameter (ETP) model in their controller could not consider the impact of specific building features on the change of the setpoint temperature. Building structures such as insulation levels [11]-[13], attic [14], and windows [15, 16, 33] considerably influence the electricity consumption by HVAC. Also, geographical location and seasonal outdoor environments [17] change HVAC loads. The performance of DDRC applied in two different size house models with different internal loads and locations also focuses on thermal comfort in different parts of the house.

Furthermore, the energy consumption by HVAC system is significantly influenced by locations and the size of internal loads. Energy efficiency codes are differ by climate zone [41]. So, the building behaviors to consume electricity are different even if the buildings have the same floor plan. Previous control of HVAC system in [34, 76] used residential models in one place with hot weather condition only. Another factor to change energy consumption of building is the internal load such as indoor activities and occupation schedule. Our previous work [34, 76] used fixed internal loads. In addition, the method to estimate internal loads in [77] connected HVAC loads to internal load changes and another work [78] considered indoor activities. However, both researches did not reflect the locations and characteristics of building envelope in the demand response. So, this research uses two locations: Austin, TX for hot weather and Chicago, IL for cold weather with two different internal load settings. In this research, DDRC demonstrated its performance in different locations and building environments.

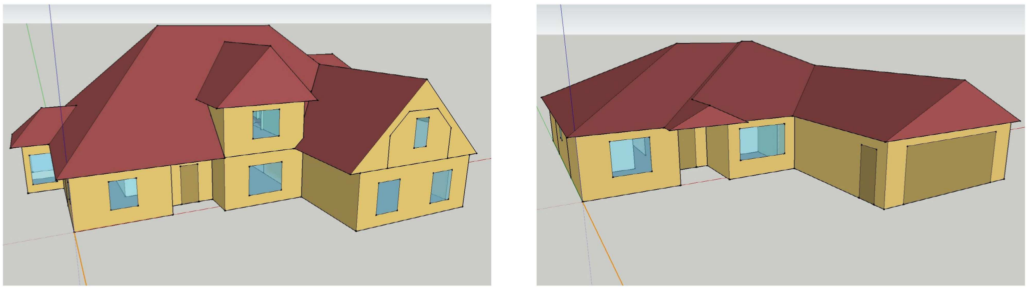
Another previous study in [8] changes HVAC loads when the retail price varies. The set-point temperature for cooling is changed when the rolling average of price in the last 24 hours is sufficiently different from the current price. If the retail price is sufficiently smaller than a rolling average price then the desired cooling set-point temperature is reduced. Customers can change desired set-point temperatures. However, the price tolerance cannot be chosen. Another advancement of our newly developed DDRC is in innovative use of the retail price model. Previous work related to the retail price based control [28] used Critical Peak Price (CPP). However, this is partial real-time price since the price of electricity only changes during selected peaks and stays flat rate at other times. Similarly, the price data in [18] used the zonal market price of ERCOT for 2006. In 2010, ERCOT market changed from a zonal market to a nodal market where Real-Time Locational Marginal Prices are calculated every 5 minutes. In our study, the historical wholesale price of electricity in ERCOT's nodal market are used together with corresponding weather file for buildings' cooling and heating load calculation to synthesize a real-time tariff. Comparing to our controller that includes this real-time tariff in the decision about the set-point temperature change, the similar controller analyzed in the previous study [28] changes the electricity consumption by changing the set-point temperature without using the electricity price signal as an input.

A customer specified threshold retail price is compared to the real-time retail price of electricity. When the retail price is above the threshold price, DDRC changes the set-point temperature of the thermostat according to the price difference between the retail price and the threshold. For the cooling case, DDRC increases cooling set-point temperature by one Celsius degree step. Similarly, for heating, it decreases heating set-point temperature from original set-point temperature. The change of thermostat set-point temperature is done automatically after customers set their preferences for the threshold price. One of the contributions of the analysis in this research is that it considers both day-ahead and real-time prices for customers because many utilities in the United States provide DR program to their customers with day ahead or real-time wholesale price based tariffs [36-38]. In the ERCOT wholesale market, the day-ahead price is calculated every hour one day before the electricity is delivered to the customers. In contrast to the day-ahead prices, real-time prices are calculated depending on current demand every 5 minutes. So, the customers receive a different price of electricity in the same period depending on whether the day-ahead or real-time prices are used.

Therefore, in the present study, two types of retail prices are used to analyze the advantages of price type. To evaluate the performance of DDRC, two different residential models with various internal load sizes are modeled and two hot and cold locations are chosen to show how much energy and cost can be saved. The price signals are input to two residential buildings' thermostat controllers in real-time using Building Controls Virtual Test Bed (BCVTB) [24]. DDRC, moreover, considers the thermal comfort based on the latest ASHRAE Standard 55 [18, 39] to maintain customer comfort while the set-point temperature changes due to the price signal. The thermostat controller in [72] controlled a set-point temperature moved to high temperature for AC and to low temperature for heating when DR was enabled. This big temperature difference causes thermal discomfort. Other works [79, 80] also did not consider thermal comfort during peak load curtailment. This research shows that DDRC minimizes the thermal discomfort while customers participate in DR programs.

2.2 Design of Single Family Houses

We selected medium and large size of houses, common for U.S. residence in Figure 2.1. House models are developed for using the building simulation tools and the historical price data are collected to generate the dynamic price of electricity as an input in the DR controller. The electricity consumption of homes is varied depending on size, floor plan, and occupation schedule. The house models used in this study are based on the building code for Austin, TX, and Table 2.1 provides specific details about the two houses. Also, detailed occupancy schedules based on typical houses in Austin are considered to model both large and medium houses. Both house models are developed as 3D models using EnergyPlus v7.1 and OpenStudio v0.11.0 [20, 21, 29].



(a) A large size house

(b) A medium size house

Figure 2.1: 3D model of single family houses used in the study: large house (L) and medium size house (R)

Figure 2.2 presents the floor plan of the medium and large single family houses. The medium house has 156 m^2 (1,683 ft^2) of floor area with single story building. There are three bedrooms and one attached garage. It has

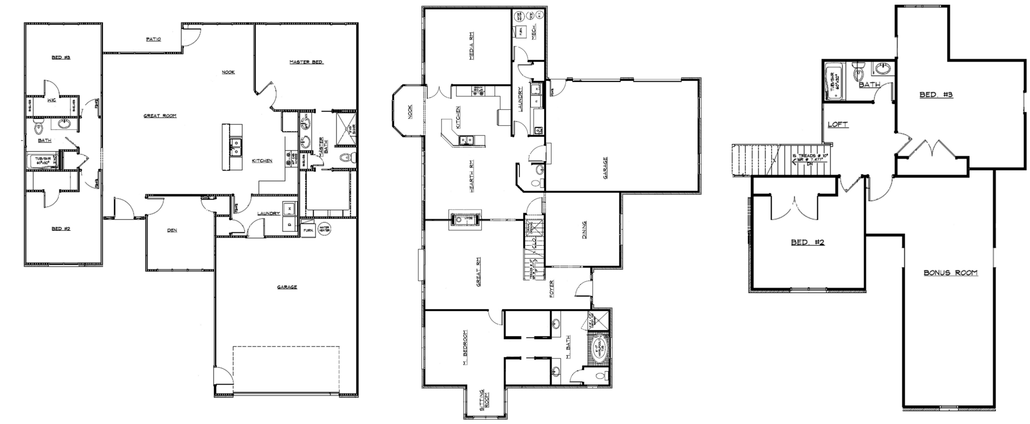
Table 2.1: Building geometry features of the large and medium houses

Component	**Medium house**	**Large house**
Floor Area	156 m^2(1679 ft^2)	305 m^2(3283 ft^2)
Floor	Single storey	Two stories
Floor Plan	3 bedrooms, 1 garage	5 bedrooms, 1 garage
Orientation	South	South
Window to wall ratio	8 %	18.1 %
Internal loads		
Occupant	4 Residents	4 Residents
Lighting	Normal - 2.6 W/m^2	Normal - 2.6 W/m^2
	Heavy - 3.5 W/m^2	Heavy - 3.5 W/m^2
equipment	Electronics, computer, water heater, kitchen appliance, washer, dryer	
Thermal Zone	3 zones	4 zones
Infiltration	0.25 ACH	0.25 ACH
	Austin, TX	
Windows	U=3.69 W/m^2-K, SHGC=0.3	
Wall	R=2.29 m^2/K-W	
Ceiling	R=5.28 m^2/K-W	
	Chicago, IL	
Windows	U=1.99 W/m^2-K, SHGC=0.3	
Wall	R=3.52 m^2/K-W	
Ceiling	R=6.69 m^2/K-W	

three thermal zones: living zone, garage and attic. Cooling and heating are only applied to the main zone with one thermostat. Other zones (attic and garage) have natural ventilation by infiltration and temperature is free floating. We did not use detailed infiltration modeling. Since the focus of the research is to evaluate thermostat controller we did not put effort to characterizing the model houses for infiltration at 50Pa. So, the infiltration is constant to 0.5 Air Change per Hour (ACH) for two residential models in our research. The window to wall ratio is 8.0%. The large house is twice the size of the medium house; 305 m^2 (3,280 ft^2). Its floor plan has five bedrooms and one attached garage with two levels. The thermal zones in a large single family house are 1st floor, 2nd floor, garage and attic. Both 1st and 2nd floor are applied HVAC with two independent thermostats [39]. So, the temperature changes in the 1st and 2nd floor are changed independently. Similar to a medium house, the other two zones do not have HVAC system and have natural ventilation. A large house has higher window to wall ratio, 18.1%, than a medium house so that the influence of the sunlight and shade impacts on the large house more than the medium house. For this reason, the capacity of cooling and heating in a medium house is less than the large house's. Both houses are oriented to South. They have the same type of HVAC system, a packaged terminal heat pump.

The internal loads are differently set to heavy and normal loads. A heavy internal load is generated with 140% of lighting loads and 150% of internal equipment such as electronics, and appliances from a normal load. This research aims to demonstrate that the proposed HVAC controller is effective for the demand response in any house size and different internal loads. So, each house model, a large and medium houses, has two different internal loads setting to analyze how much changes of internal load impact on energy consumption at homes.

Packaged terminal heat pump systems are used for both large and medium houses. The capacity of HVAC is fixed even if the internal loads



(a) Main floor of a medium house (b) 1st floor of a large house (c) 2nd floor of a large house

Figure 2.2: The floor plans of two single family houses: a medium house and large house

are changed. For a large house, it is assumed that multi-zone heat pump system is equipped. The cooling and heating capacities are the same but the second floor has about half capacity of the first floor due to half size of floor area. So, the total cooling and heating capacity of a large house are 58,000 BTU/hr each. A medium house has 156 m^2 of floor area which is half of a large house's floor area. So, the capacity of heat pump is half of a large house: 29,000 BTU/hr. Table 4.2 presents the capacity of heat pump in BTU/hr and COP for cooling and heating.

2.3 Dynamic Retail Price of Electricity

The dynamic price of electricity that changes every hour or more often is the key factor for demand response. In the United States, the wholesale

Table 2.2: The capacities of heat pumps and COPs

Type	BTU/hr			COP
	Large house		Medium house	
	1st floor	2nd floor	Main floor	
Cooling	40,000	18,000	29,000	3.0
Heating	40,000	18,000	29,000	4.0

markets for electricity are established to trade or bid the amount of electricity depending on supply and demand. The Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) manage these wholesale markets under the regulations. These wholesale electricity markets are open to wide participation. As a result, many private utilities and companies for power generations are able to participate in markets. Depending on the status of power system grid, ISO/RTOs adapt different types of wholesale electricity market.

Many DR programs are serviced in ISO/RTOs including PJM, CAISO, NYISO, and MISO [18]. For example, PJM market provides DR programs based on both day-ahead and real-time price of electricity. On the other hand, New York ISO (NYISO) and New England ISO (NEISO) choose day-ahead price only. Furthermore, DR programs that many utilities or ISO/RTO provide use day-ahead electricity price [81, 82]. Therefore, this research uses the hourly day-ahead price (DAP) rather than the real-time price (RTP) for the proposed HVAC controller. The weather condition of year 2011 was the hottest year in Austin, TX. So, air conditioning (AC) loads were not only very high, but also the price of electricity was expensive. In contrast, Chicago suffered the coldest weather during winter from 2013 to 2014. To maximize the effect of DR, the year 2011 of the historical price data for Austin, TX is selected at Austin Energy Network (AEN) [36]. For Chicago, IL, the year of 2013 at Commonwealth Edison (ComEd) is used for the price data [54]. The unit of electricity price at the wholesale market is \$/MWh. However, retail customers pay their electricity bill in \$/kWh. Thus, the prices of electricity are converted to \$/kWh.

Many utilities in the United States provide DR programs [36-38]. Their real-time tariffs in DR programs are based on day ahead or real-time wholesale price. For instance, Niagara Mohawk, New York, NY provided real-time pricing based on day ahead wholesale price in the NY ISO market. Commonwealth Edison in Chicago, IL also has real-time tariff for residential based on wholesale price in the PJM market [36]. Different from these utilities, Georgia and Alabama power companies offer both day ahead pricing based on day ahead wholesale price and hour ahead price based on real-time wholesale price [37].

Two types of retail prices are used because many utilities choose one or use both types of prices to build their tariffs. One of the retail prices is Day Ahead Price (DAP) and another price is Real-Time Price (RTP). For the ERCOT simulations, these prices are based on historical wholesale electricity price in the ERCOT wholesale market. DAP is generated using Day Ahead Market Settlement Point Prices (DAMSPP) [42] and RTP is based on Real-

Time Market Settlement Point Prices (RTMSPP) in ERCOT [43]. DAMSPP is hourly based price but RTMSPP is updated in every 15 minutes. So, RTMSPP is converted to hourly based price by averaging prices of RTMSPP in an hour interval to match time scale to DAMSPP in this research. In addition, choosing the highest prices of RTMSPP for an hour interval and the original price of RTMSPP that has prices changing every 15 minutes are also simulated. However, our preliminary analysis shows that for both the large and the medium houses using these two types of RTMSPP (the highest and 15 minutes based prices) have little difference compared with the results using the average price of RTMSPP. Thus, the average of RTMSPP in an hour is chosen to convert to the hourly based hypothetical retail price.

In addition, we also model a house are located in Chicago, IL to evaluate the performance that DDRC can work in any locations with different markets . Thus, two different wholesale markets are chosen; ERCOT and PJM. ERCOT (Electric Reliability Council of Texas) manages power grid in the most part of Texas including Austin area. Its wholesale market has the energy market (both day-ahead and real-time wholesale market), and ancillary service. PJM Interconnection services the wholesale market in Northeast of U.S. including Chicago area. The wholesale market in PJM has a capacity market in addition to day-ahead, real-time, and ancillary services market. All other services in PJM market are similar to ERCOT. The capacity market is designed to ensure sufficient power generation can satisfy the peak demand reliably [53].

Figure 2.3 presents the histograms of the annual historical price data at AEN (2011) as the representative price in ERCOT and ComEd (2013) as the representative price in PJM for a year. The price data at AEN has higher frequency of prices than \$0.11/kWh compared to the price at ComEd. The minimum (MIN), average (AVG), and maximum (MAX) prices of electricity on each month for a year are shown in Figure 2.4. The maximum price of electricity at AEN is much higher than at ComEd even though both locations experienced severe weather condition. As a result, the electricity price at ComEd is almost always under \$0.05/kWh but AEN price is higher than ComEd and also fluctuates depending on demand. The reason why the electricity price at AEN is higher than at ComEd is that ERCOT does not have a capacity market [85]. In the real-time market, the cost of power generations is expensive to maintain the system balance between supply and demand when the power demand is high compared to supply. In contrast, PJM's capacity market is designed to reduce the incidence of such conditions. In addition, ERCOT increased the maximum wholesale price of electricity from \$3,000 to \$5,000/MWh in 2014 [38]. This is about 67% increase from the previous price limitation, \$3,000/MWh. Due to the different type of wholesale market, ComEd energy price with the capacity market is lower than the energy price at AEN.

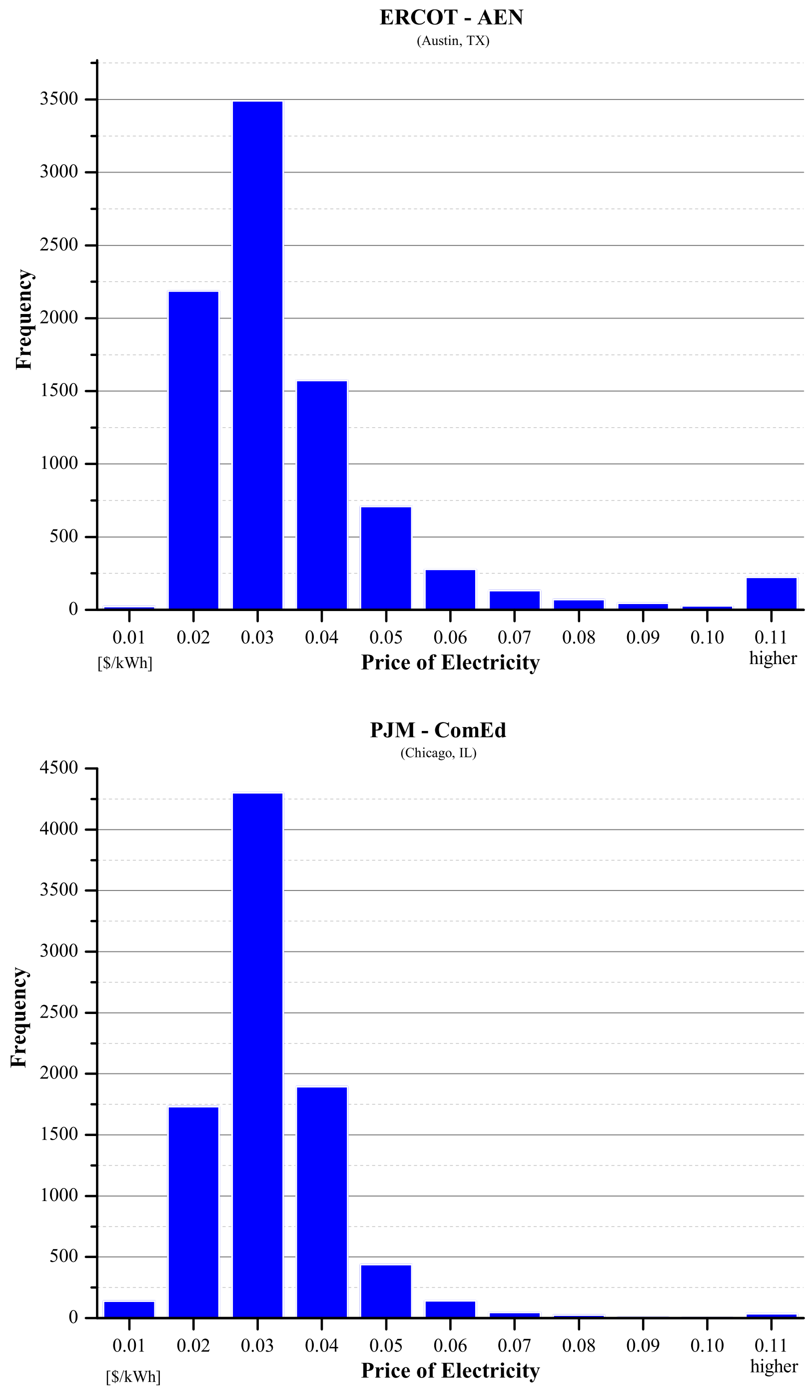


Figure 2.3: The histogram of electricity price in Austin, TX and Chicago, IL

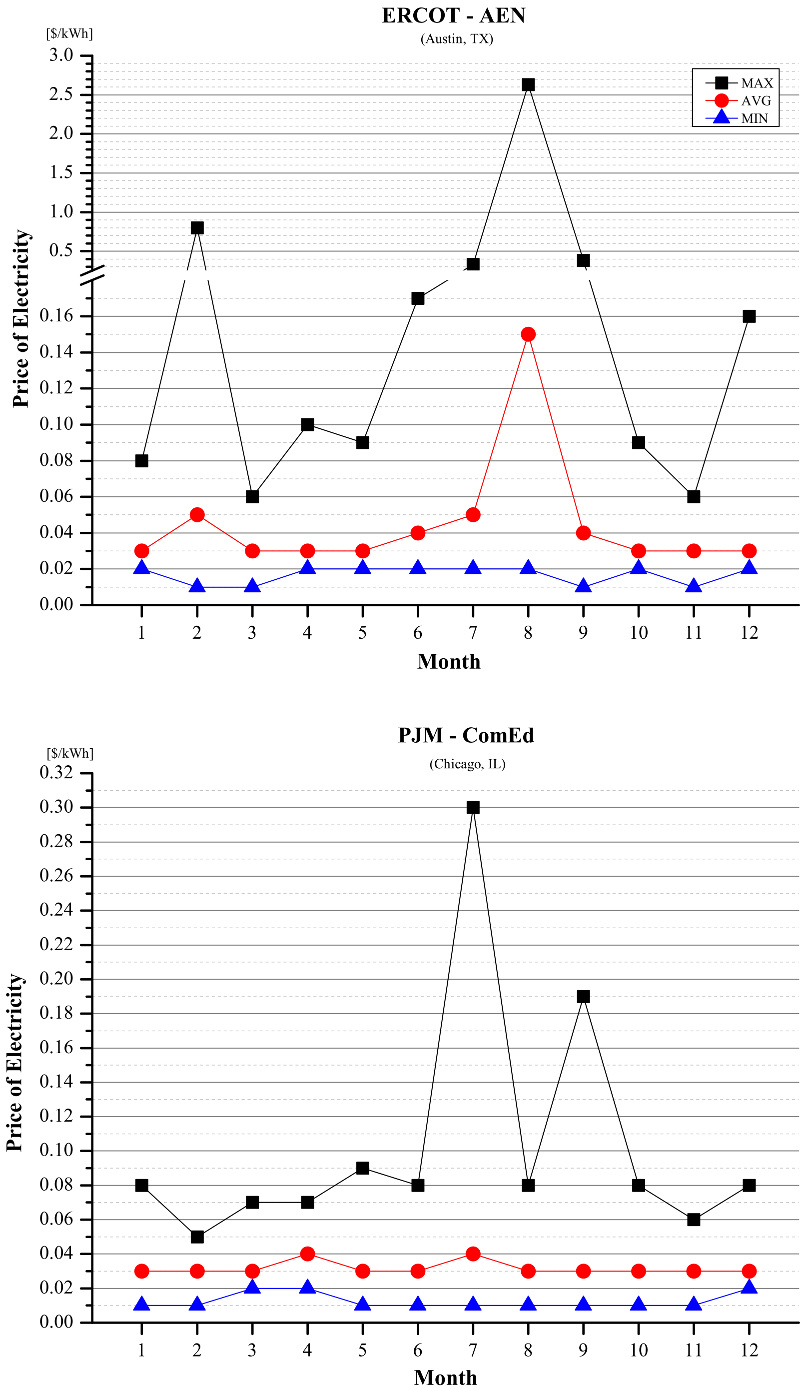


Figure 2.4: The monthly Max, Average, and Min of electricity price in two cities

The retail prices of electricity are based on the historical wholesale electricity price at Electric Reliability Council of Texas (ERCOT) and Pennsylvania-New Jersey-Maryland (PJM) Interconnection. The electricity retail price is set equal to 100% of wholesale price in \$/kWh. In addition, we assume that transmission and distribution costs are changed separately. The load zone and year of historical wholesale electricity price used in our research are shown as follows:

The historical data of wholesale electricity price

(a) Day Ahead Price (DAP) − YR 2011

: Austin Energy Network (AEN) − ERCOT

(b) Real Time Price (RTP) − YR 2011

: Austin Energy Network (AEN) − ERCOT

(c) Day Ahead Price (DAP) − YR 2013

: Commonwealth Edison − PJM

The aggregation through DR may impact on the electricity price in wholesale market [86, 87]. However, this research focuses on four residential models in different locations. This small amount of aggregation by DR from house models does not significantly change the wholesale price. Thus, we assume that the theoretical price data is not changed after DR.

2.4 Simulation Cases

In this research, two house models are simulated with different conditions. The simulation conditions to estimate the performance of DDRC with dynamic pricing have three stages:

A. DDRC with dynamic price of electricity

(a) Fixed set-point temperature setting (Normal case)

(b) Changing set-point temperature by DDRC (DDRC case)

B. DDRC with various price types and floor plans

(a) Normal and DDRC cases

(b) Two different floor plans: large and medium houses

(c) Two types of dynamic price: DAP and RTP

C. DDRC with different internal loads and climate zones

(a) Normal and DDRC cases

(b) Two different floor plans: large and medium houses

(c) Various internal loads: heavy and normal loads

(d) Different climate zones: zone 2 (Austin, TX), zone 5 (Chicago, IL)

Chapter 3

Control Algorithm of Dynamic Demand Response Controller

This chapter introduces two different control algorithms for the proposed controller. Linear regression estimation is used to calculate Heating, Ventilating, and Air Conditioning (HVAC) loads when the set-point temperature in a thermostat changes. Then, the price trigger as a Demand Response (DR) signal is added to decide new set-point temperature to reduce peak load when DR is requested. Improved DDRC control policy is also suggested to enable DDRC to be used in various places with different circumstances. Next, the implementation of the simulations using EnergyPlus and MATLAB/SIMULINK is illustrated in this chapter.

3.1 Base Control Policy with Dynamic Price of Electricity

The proposed Dynamic Demand Response Controller (DDRC) changes the set-point temperature of the thermostat in 1°C increments for both cooling and heating when the current retail price (P) is higher than the threshold price (P_{th}) that customers want to implement for energy savings. On the other hand, if the threshold price (P_{th}) is above the current retail price (P), the thermostat with DDRC maintains the initial cooling and heating set-point temperature. In short, DDRC thermostat only changes the set-point temperature when the electricity retail price is higher than the customer's preference. Figure 3.1 shows the framework for simulation of the DDRC.

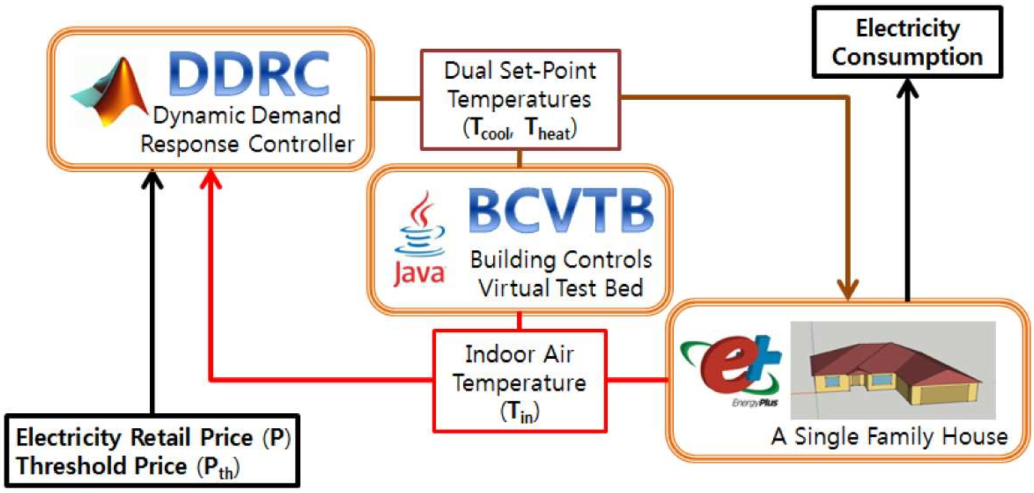


Figure 3.1: Framework of dynamic demand response controller

In this research, the HVAC controller for a residential house model is first simulated to calculate the electricity consumption when the indoor temperature is maintained equal to the set-point temperature.

3.1.1 Estimation of Slope of Electricity Consumption by HVAC

The electricity consumed by HVAC depends on the size of the house, HVAC type, architectural and geographical feature. The HVAC model should consider many factors including indoor and outdoor circumstances in order to estimate the electricity consumption precisely. However, thermostat controllers in [6], [18], [27],and [28] do not have an HVAC model. Thus, these controllers cannot calculate how much electricity was consumed by HVAC nor evaluate whether loads were shifted or curtailed during peak period compared to normal operation.

Other thermostats in [9], [10], [26] have HVAC models to calculate HVAC electricity consumption. Previous work reported in [10] and [26] used the ETP model. Only outdoor air temperature impacts on the indoor air temperature in the ETP model. An HVAC model in [9] added thermal energy obtained from the sun. However, these models cannot reflect the outdoor circumstance changes such as wind, precipitation, shading as well as the indoor environments including activities, ventilation, and equipment uses.

In contrast to [9], [10], and [26], an important contribution of this work is in using a precise HVAC model based on EnergyPlus to calculate the electricity consumption. The indoor air temperature is not only influenced by outdoor temperature but also by ground temperature, indoor activities, internal load, and building size. So, these factors that impact on indoor air temperature change should be considered to control HVAC load during peak period. EnergyPlus considers these variables during simulation processing [29].

In our study, EnergyPlus is used to develop HVAC load functions for the DDRC algorithm. These functions show the HVAC electricity savings as a function of the thermostat set point temperature change. The single family house is initially simulated with set-point temperatures fixed at 23°C for cooling and 22°C for heating; these are the initial condition of set-point

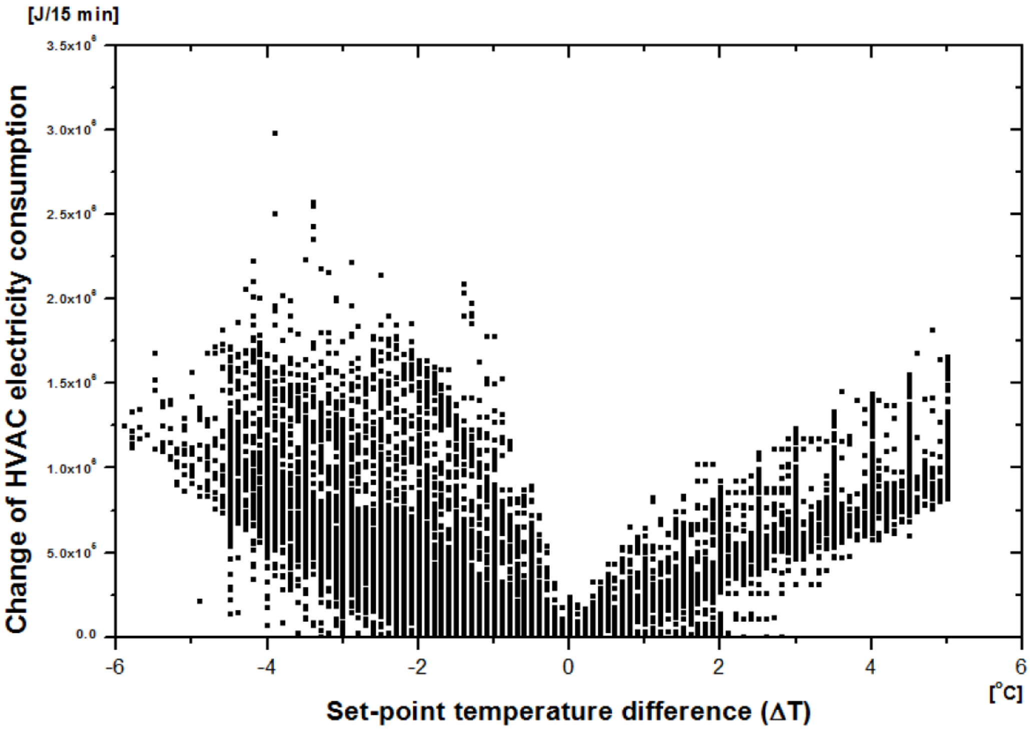


Figure 3.2: Scatter plot of HVAC electricity consumption changes versus set point temperature difference

temperatures (T_{sp}) setting. The simulation results are calculated for each time step (ts) of 15 minutes. The change in HVAC electricity consumption is then evaluated for increases and decreases by 0.5°C steps compared to T_{sp}. The HVAC electricity consumption changes are calculated by subtracting the electricity consumption at the modified set-point from the consumption at the initial set-point for each step. The temperature change that subtracts the indoor temperature from the set-point temperature is denoted by ΔT. Figure 3.2 shows how much electric energy in Joule by HVAC is changed versus ΔT.

The following equations represent regression the cooling and heating data

$$\Delta T = T_{in} - T_{sp} \ [C^o] \tag{3.1}$$

$$E_{cool} = -199163.34\Delta T + 46530.67 \ [J] \tag{3.2}$$

$$E_{heat} = 196204.81\Delta T + 13010.29 \ [J] \tag{3.3}$$

Electricity consumption by HVAC is calculated in Joule per 15 minute time step. So, unit conversion should be needed to change Joule into kW by dividing by 3.6×10^6 to provide HVAC electricity consumption equations in kW. When the price of electricity is below P_{th}, the set-point temperature is maintained at the initial value $T_{sp,ts}$. In this research, only temperature is adjusted to control room zone. The initial set-point temperature ($T_{sp,ts}$) for cooling is set to 23^{o}C and for heating is set to 22^{o}C, so that HVAC electricity consumption is finally derived as a function of ΔT in (3.4) and (3.5):

$$kW_{cool}^{HVAC} = -0.055\Delta T + 0.013 \ [kW] \tag{3.4}$$

$$kW_{heat}^{HVAC} = 0.055\Delta T + 0.004 \ [kW] \tag{3.5}$$

3.1.2 Price Trigger and Coefficient of Price over Temperature

Previous works in [8], [27], and [28] used the average price of electricity for the last 24 hours to trigger set-point temperature change by comparing with the current price. However, using average price as a trigger is not suitable for high fluctuation of retail price in real-time market. In addition, AC may be turned on at time when AC load should be curtailed. The difference between the lowest and highest price signal in [8] is about \$0.021 per kWh. On the other hand, the price difference in the ERCOT market on August 3, 2011 was about \$2.97 per kWh. The average price of electricity has a high value on this day. Therefore, thermostat controllers in [8], [27], and [28] do not change a set-point temperature even if the price of electricity is high since tremendous high electricity price impacts on the average price of electricity for last 24 hours.

In contrast, the proposed DDRC uses the price difference between the current price and a threshold price set by customers. Reference [28] considers the chosen comfort setting in its controller but the coefficient for comfort is unit-less. So, it is difficult for residents to choose the coefficient based on their preference. Our DDRC reflects the preferences of occupants using a threshold price (P_{th}). The threshold price (P_{th}) is the base price to change set-point temperature on a thermostat. Customers choose the threshold price depending on their preference. In this simulation, threshold price is set to \$0.04 per kWh. DDRC compares electricity retail price (P) with threshold price (P_{th}) when new retail price is updated every 15 minutes. The price difference (ΔP) is the subtraction of electricity retail price from threshold price. When retail price is higher than threshold price, ΔP is a positive number and DDRC starts to work. Otherwise, ΔP is less than equal to zero so that DDRC stops working immediately and maintains or returns to the initial set-point temperature. High price difference is effective to increase set-point temperature for cooling or to decrease it for heating at high peak load period.

$$\begin{aligned} \Delta P \ [\$/kWh] \quad &= P - P_{th} \\ &= P - 0.04 \end{aligned} \tag{3.6}$$

The linear regression coefficient of temperature as a function of retail price converts electricity price to temperature that the thermostat accepts. It is the result of correlation between outdoor air temperature (T_{out}) at Mueller AP, Austin Texas, 2011 and retail price (P) converted from wholesale price from ERCOT's RTSPP, 2011. Outdoor air temperature considerably impacts prices in the wholesale market. Wholesale price generally increases when outdoor air temperature is hot due to increment of AC load demand. On the other hand, if outdoor environment is getting cold, retail price is also raised due to heating demand increase. The heating and cooling loads are linearly increased from the temperature where both cooling and heating loads are at a minimum. Based on ERCOT data for 2011, the linear regression coefficients of temperature with respect to to retail price for both cooling and heating are shown in (3.7) and (3.8).

$$a \ [C^o \cdot hr/\$] = \begin{cases} 2.254, & \text{for cooling} \quad (3.7) \\ -3.683, & \text{for heating} \quad (3.8) \end{cases}$$

3.1.3 Control of The Thermostat

DDRC is based on based on the electricity cost to change the set-point temperature. So, the coefficient of temperature is used to convert the electricity cost to the temperature for the thermostat. In this research, based on experimental data, twice the price difference (ΔP) was chosen to decrease HVAC load at on-peak. Temperature change for DDRC is calculated in (3.9) and (3.10) below. When retail price (P) is much higher than threshold and desired temperatures for cooling and heating are far from current temperature (T_{in}), temperature change rate is sharply increased. The maximum temperature change rate is therefore limited to 3°C in both cooling and heating mode because sudden huge temperature change impacts on human health through thermal shock and also gives large mechanical burden to heat pump. In addition, customers feel discomfort in high temperature difference from initial set-point when retail price is high for an extended period. Finally, the temperature change rate is discretized with 1C°steps.

$$\Delta T_{cool}^{rate} = a \cdot HVAC_{cool} \cdot 2\Delta P \quad [C^o] \tag{3.9}$$

$$\Delta T_{heat}^{rate} = a \cdot HVAC_{heat} \cdot 2\Delta P \quad [C^o] \tag{3.10}$$

New set-point temperatures at higher retail price (P) than threshold price (P_{th}) are determined by (3.11) and (3.13). DDRC thermostat remains at initial set-point temperature when retail price is lower than threshold price. As retail price increases beyond threshold price, DDRC starts increasing the set-point temperature for cooling or delays heat pump operation time depending on the price difference (ΔP). Conversely, set-point temperature is decreased for heating mode, with 23°C and 22°C the initial set-point temperature for cooling and heating, respectively:

$$T^{new}_{sp,cool}\ [C^o] = \begin{cases} 23 + \Delta T^{rate}_{cool}, & \text{for } P > P_{th} \qquad (3.11) \\ 23 & \text{for } P \leq P_{th} \qquad (3.12) \end{cases}$$

$$T^{new}_{sp,heatl}\ [C^o] = \begin{cases} 22 - \Delta T^{rate}_{heat}, & \text{for } P > P_{th} \qquad (3.13) \\ 22 & \text{for } P \leq P_{th} \qquad (3.14) \end{cases}$$

3.2 Improved Control Algorithm of DDRC for various circumstances

The DDRC described in the last section was used for several case studies. It has several drawbacks including that it is not easily adaptable to different climate zones and markets. In this section, an improved control algorithm is developed that is more easily adaptable.

The improved control algorithm for DDRC again takes the price signal of electricity to participate in the utility's DR program. Then, the set-point temperature in a thermostat is automatically increased or decreased depending on cooling and heating mode while considering the thermal comfort. Different from the control policy in section 3.1, the improved algorithm is designed as a universal controller that works with various type of HVAC system and in many places with different wholesale electricity markets.

3.2.1 Estimation of HVAC Electricity Consumption

The equations to estimate HVAC power consumption when the current indoor temperature goes to the target set-point temperature are obtained using a statistical method. The Richardson model in [69] also estimates electricity loads in residential houses. However, this model does not consider house size, equipment type, and load changes. Different capacity or Coefficient of Performance (COP) for HVAC consumes different amount of electricity. In addition, the different set-point temperature settings also cause changes of electricity power consumption. So, similar to section 3.1 [34, 76], this research simulates two house models in various conditions such as different set-point temperature, internal load changes, and weather conditions. Finally, the power consumption coefficients for HVAC (k) in two locations are derived using the linear regression method. The value of the constant term from the linear regression results is so small that it can be ignored. So, only gradient of linear equation is used to estimate HVAC power consumptions. This power consumption in kW is the average power consumption for an hour because the simulation step in this research is an hour. In addition, almost of all utilities in U.S. charge the electricity bill to their customers in $/kWh. Table 3.1 shows that cooling and heating coefficient (k) of power consumption are calculated for both large and medium houses in two locations.

Table 3.1: Temperature-electricity constant for cooling (k_c) and heating (k_h)

	Austin, TX		Chicago, IL	
[kW/C°]	Large house	Medium house	Large house	Medium house
k_c	0.09	0.044	0.092	0.057
k_h	0.049	0.036	0.068	0.041

The temperature difference (ΔT) is defined in equation (3.15). The estimated power consumptions of HVAC for each mode are derivate as follow in equation (3.16) and (3.17).

$$\Delta T = |T_{in} - T_{sp}| \tag{3.15}$$

$$E_c = k_c \times \Delta T \tag{3.16}$$

$$E_h = k_h \times \Delta T \tag{3.17}$$

Our previous work in section 3.1 did not consider the characteristics of HVAC equipment in DR algorithm. Other work [68] shows that the size of heat pump capacity significantly impacts on energy consumption in residential buildings. So, the characteristics of HVAC equipment are considered in HVAC control algorithm. Equation (3.18) and (3.19) express that the thermal capacity of HVAC equipment is converted to electrical energy by considering the efficiency of HVAC.

$$kW_{rating}^{cool} = \frac{BTU/hr}{3412.142 \times COP_c} \tag{3.18}$$

$$kW_{rating}^{heat} = \frac{BTU/hr}{3412.142 \times COP_h} \tag{3.19}$$

The coefficient, which is the correlation between historical electricity price data and local weather data, is required to convert HVAC electricity estimate to temperature unit in [34, 76]. To find this correlation coefficient, local historical price data must be utilized. For example, when local historical price data are updated every year, the coefficient should be calculated again. Also, moving from one market to another (ex ERCOT to PJM) causes to recalculate the coefficient. This is a big limitation to deploy the controller in other places. Our current work aims at a universal controller that can work with various type of heat pump in different location. So, the estimated electricity consumptions of heat pump for cooling and heating with ΔT are normalized by the rating power of HVAC (kW_{rating}) as follows blow.

$$HVAC_c = \frac{E_c}{kW_{rating}^{cool}} \tag{3.20}$$

$$HVAC_h = \frac{E_h}{kW_{rating}^{heat}} \tag{3.21}$$

3.2.2 Normalized Electricity Price Signal

The Dynamic Demand Response Controller (DDRC) takes the signal of dynamic electricity price to change the set-point temperature for DR program. Depending on economic situations, incomes in each household are different. Therefore, the electricity bills that household can afford to pay are dissimilar. The proposed DDRC considers the economic ability in household by again utilizing threshold price (P_{th}) when customers participate into utility program. Depending on demand loads, the electricity price changes. For instance, 2011 was the hottest year in Austin, TX. Air conditioning loads were significant loads in the power grid. As a result, day-ahead price of electricity in ERCOT wholesale market occasionally approached the maximum price, \$3,000/MWh. The fluctuation of electricity price was also very high in a same day between on-peak and off-peak time. The previous control algorithm in section 3.1 does not reflect the price fluctuation that causes sudden change of the set-point temperature. To consider it, the standard deviation of electricity price for a day (σ_{day}) is calculated based on day-ahead price which is announced a day before. The parameter σ_{day} normalizes the price difference ($P_c - P_{th}$) between the current price of electricity (P_c) and threshold price (P_{th}). The normalized price (P_N) is presented in equation (3.22) and (3.23). DTC changes the set-point temperature when P_c is higher than P_{th}. Otherwise, the set-point temperature maintains the preset temperature (T_{sp})that customers set. From Figure 2.3, the threshold price (P_{th}) is set to \$0.04/kWh because the dynamic prices of electricity in both Austin and Chicago maintain under \$0.03/kWh for most hours. Thus, DTC starts to operate itself when P_c is higher than \$0.04/kWh.

$$P_N = \begin{cases} \dfrac{P_c - P_{th}}{\sigma_{day}} & \text{for } P_c > P_{th} \qquad (3.22) \\ 0 & \text{for } P_c \leq P_{th} \qquad (3.23) \end{cases}$$

3.2.3 The Change Rate of The Set-point Temperature

The proposed Dynamic Demand Response Controller changes the set-point temperature in a thermostat depending on the price difference while considering thermal comfort. The thermostat control in [22] sharply changes the set-point temperature when the price is low or high. This causes the thermal discomfort due to sudden temperature change. DDRC increases 1°C (2°F) step from the preset set-point temperature (T_{sp}) during cooling mode. Opposite to AC mode, heating set-point temperature is decreased by 1°C (2°F). To maintain indoor thermal comfort, the maximum temperature change by DDRC is limited to ±3°C. Equation (3.24) and (3.25) express the change rate of the set-point temperature (ΔT_{sp}) for cooling and heating modes

$$\Delta T_{sp}^{cool} = HVAC_c \times P_N \times \Delta T \qquad (3.24)$$

$$\Delta T_{sp}^{heat} = HVAC_h \times P_N \times \Delta T \qquad (3.25)$$

Finally, new adjusted set-point temperature (T_{sp}^{new}) is determined in equation (3.26) and (3.27). When P_{th} is higher than P_c, ΔT_{sp} goes to zero. So, DDRC maintains the preset environment for thermal comfort. Otherwise, DDRC controls the set-point temperature depending on the difference price between P_c and P_{th}. In this research, T_{sp} for cooling is 25°C (77°F) and heating T_{sp} is 21°C (70°F).

$$T_{sp}^{new} = \begin{cases} T_{sp} + \Delta T_{sp}^{cool} & \text{for cooling mode} \quad (3.26) \\ T_{sp} - \Delta T_{sp}^{heat} & \text{for heating mode} \quad (3.27) \end{cases}$$

3.3 Controller Implementation

DDRC is implemented using MATLAB/SIMULINK. It receives two inputs from EnergyPlus and Building Controls Virtual Test Bed (BCVTB) and generates new set-point temperature for each cooling and heating mode. EnergyPlus is developed and distributed by US Department of Energy. It not only calculates annual energy from the outdoor environment and internal load but also the annual energy consumption. A whole year of retail price based on ERCOT's SPP of Austin Energy Network is embedded into SIMULINK function code. Figure 3.3 presents SIMULINK model of DDRC.

Simulation step time of EnergyPlus can be chosen from 1 minute to 1 hour. A 15 minute simulation step is used for both SIMULINK and EnergyPlus to match electricity retail price change interval with 15 minute interval real-time price of electricity. When hourly day ahead price is chosen, an hour time step is used to evaluate the performance of DDRC. However,

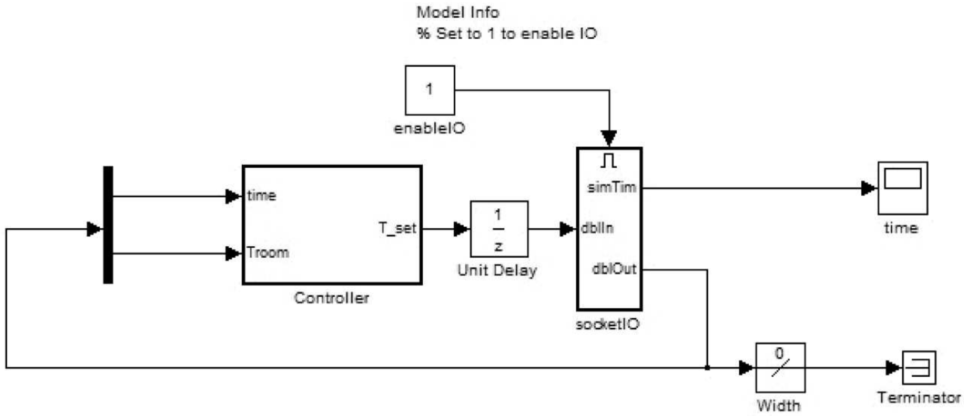


Figure 3.3: Dynamic demand response controller in MATLAB/SIMULINK

both simulation tools cannot exchange their data with each other. Furthermore, EnergyPlus does not provide a function to control a building model during simulation. BVCTB solves this connection problem on both simulation tools. The Lawrence Berkeley National Laboratory (LBNL) developed BCVTB to improve EnergyPlus function. The codes to connect with BCVTB and to hold its signal are inserted in the EnergyPlus input file. In order to match simulation step time for both EnergyPlus and SIMULINK, BCVTB sets a simulation clock which is based on 1 second and sends it to both simulation programs. Total simulation time is 3.1536×10^6 seconds, a year. BCVTB is based on JAVA language and connect to other simulation tools such as SIMULINK+EnergyPlus and Dymola+EnergyPlus. Virtual Internet Protocol (IP) port is opened to both EnergyPlus and SIMULINK by BCVTB [23]-[25].

EnergyPlus sends indoor air temperature (T_{in}) to BCVTB and receives

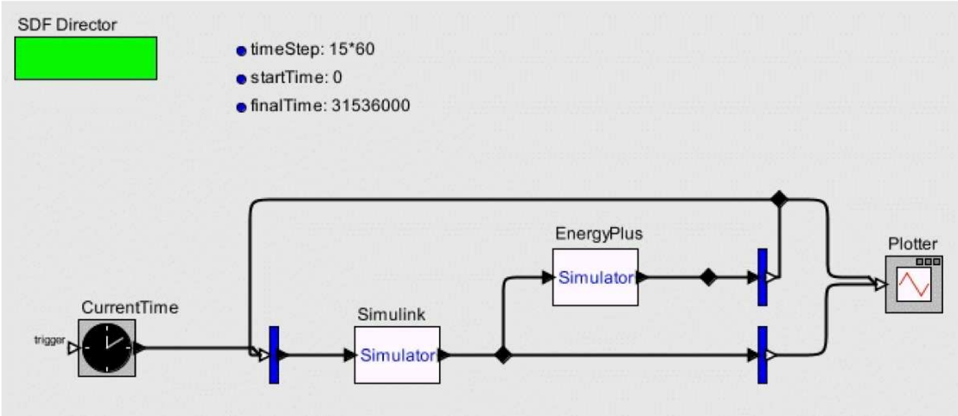


Figure 3.4: Diagram of connection EnergyPlus with SIMULINK using BCVTB

new set-point temperature for cooling ($T^{new}_{sp,cool}$) and heating ($T^{new}_{sp,heat}$) from it. SIMULINK accepts T_{in} from BCVTB and sends both $T^{new}_{sp,cool}$ and $T^{new}_{sp,heat}$ to BCVTB. But both EnergyPlus and SIMULINK do not run at the same time. BCVTB pauses one program until another program finishes simulation and returns the result for a simulation step. BCVTB plays a role of exchange server to connect different two programs and modeling of BCVTB is presented in Figure 3.4.

Chapter 4

The Results of The Performance of DDRC

This chapter shows the performance of the proposed Dynamic Demand Response Controller (DDRC) under various circumstances. The target home models have different floor plan, size, and internal loads. In addition, different types of retail electricity prices from two wholesale markets. Furthermore, weather data from different climate zones are used to evaluate the performance of DDRC.

4.1 DDRC with dynamic price of electricity

In this section, the medium size of the house model and 15 minute based real-time price (RTP) from ERCOT are used for the evaluation of DDRC performance. The results are presented for energy and cost savings in cooling (August) and heating (January) modes. Also, the thermal comfort is discussed to show that DDRC minimizes thermal discomfort while the set-point temperature is changed.

4.1.1 Simulation Condition

The thermostat is set to 23°C for cooling and 22 °C for heating. Cooling and heating are applied for all season to evaluate the performance of DDRC with the base policy at tight HVAC operation. The medium size house with the internal load is chosen. The dynamic price of electricity is used 15 minute based Real-Time Price (RTP) at ERCOT wholesale market at 2011.

4.1.2 Air Conditioning Loads: August

Air conditioning load in August is the highest of the whole year due to high outdoor air temperature. Wholesale electricity price also increases along with high temperatures. During 2011, ERCOT limited the maximum wholesale price to $3,000 per MWh. From the retail price policy, the maximum electricity retail price is $3/kWh. During August, retail price reaches the maximum price for more than 6 days during peak time. DDRC changes set-point temperature to curtail HVAC electricity as electricity retail price is higher than the threshold price. Figure 4.1 shows indoor air temperature of a single family house model in August for both fixed set-point temperature and the DDRC case.

During August, indoor air temperature without DDRC thermostat maintains initial cooling and heating temperature which are in between 22°C and 23°C. The DDRC changes the set-point temperature so that indoor air temperature ranges from 21°C to 26°C. When the thermostat is fixed at initial cooling and heating set-point temperature, HVAC consumes 733.48 kWh dur-

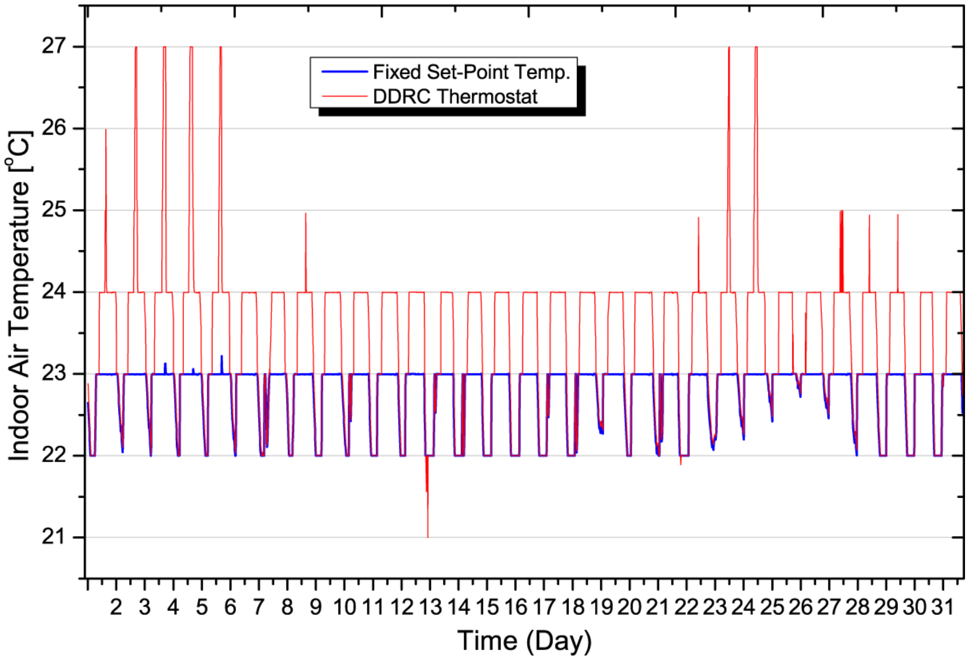


Figure 4.1: Indoor air temperature changes in August

ing August. On the other hand, DDRC thermostat reduces total electricity consumption to 628.49 kWh in total during August. For this DDRC thermostat setup, the electricity consumption by HVAC is curtailed by 14.32% of the total electricity consumption during August when DDRC is applied to HVAC control. In addition, DDRC is effective to reduce electricity load in peak time. For example, on August 3, the electricity price reached the maximum price of $3 for more than two hours during on-peak time. Figure 4.2 presents the electricity consumption changes for August and Figure 4.3 demonstrates how DDRC can reduce HVAC loads compared with fixed set-point temperature case. On August 3, retail price reaches the maximum price, $3/kWh at 15:30

and persists until 17:30. DDRC rapidly increases cooling set-point temperature to 25^{o}C. Therefore, HVAC electricity loads at the maximum retail price are reduced by 21.04% and 30.59% curtailment of electricity cost during on-peak from 15:30 to 17:30.

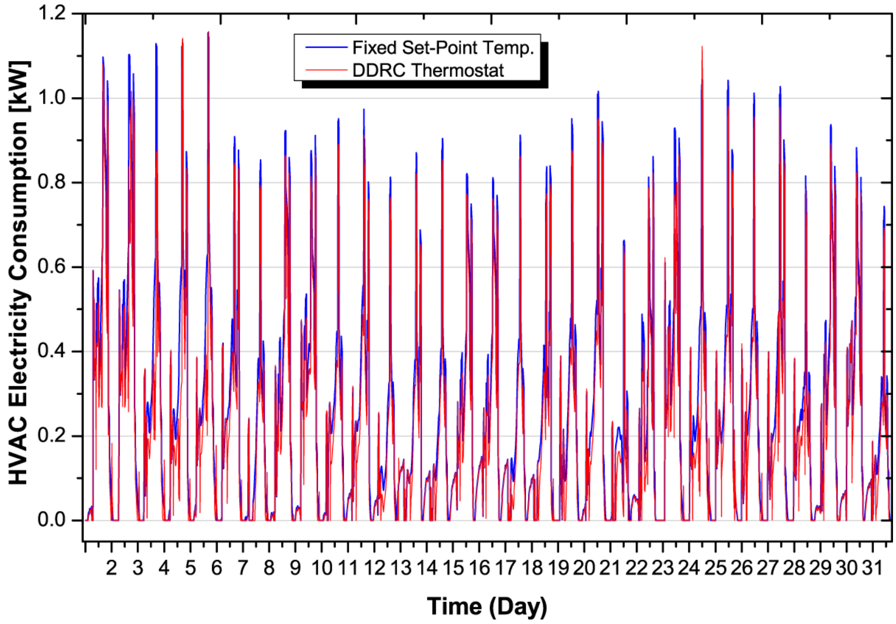


Figure 4.2: HVAC electricity consumption during August

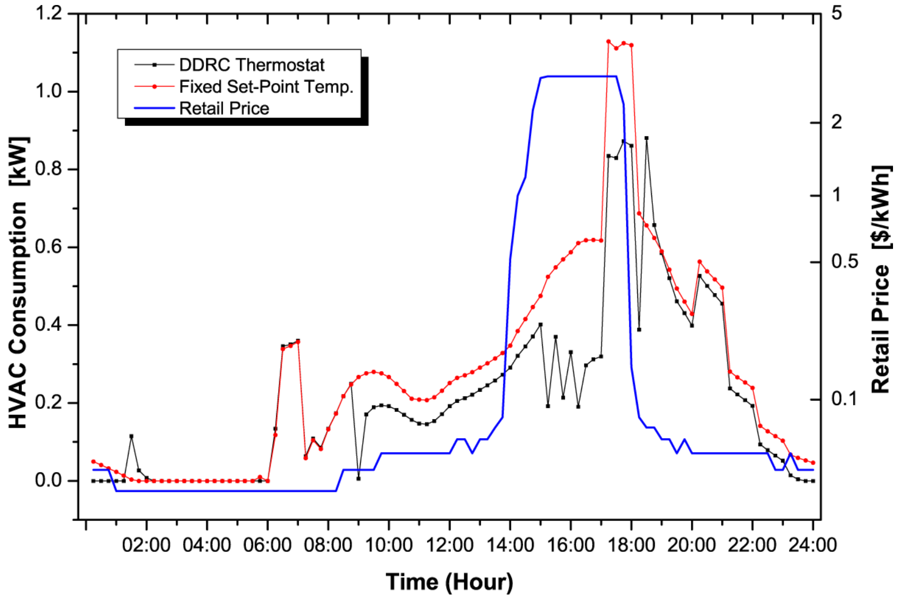


Figure 4.3: Significant electricity peak load reduction by DDRC on August 3

4.1.3 Heating Loads: January

Heating loads in January are not as high as air conditioning loads during summer season because the temperature in Austin, Texas maintains above zero degrees Celsius during most of the winter season. Indoor air temperature on January ranges from 20^{o}C to 24^{o}C with the DDRC and is shown in figure 4.4. There is a $4C^{o}$ temperature difference but this range is smaller than the range during the summer season, especially August. Total HVAC electricity consumption on January is cut by 10.65% with DDRC. Electricity cost for HVAC operation is also decreased by 14.13% over fixed set-point temperature case. HVAC electricity consumption variation is illustrated in Figure 4.5.

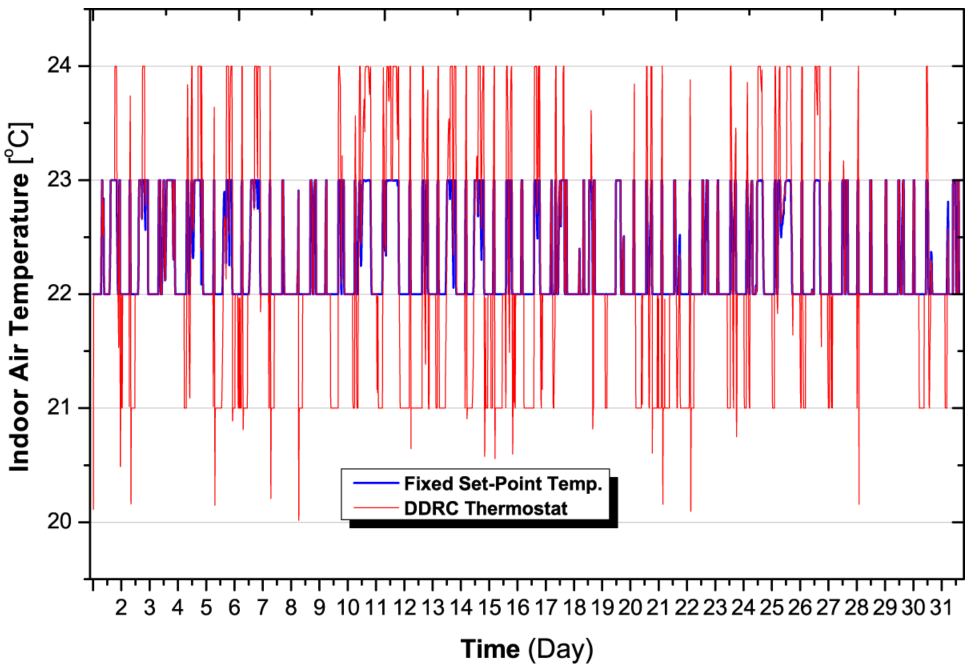


Figure 4.4: Winter season indoor air temperature comparison, January

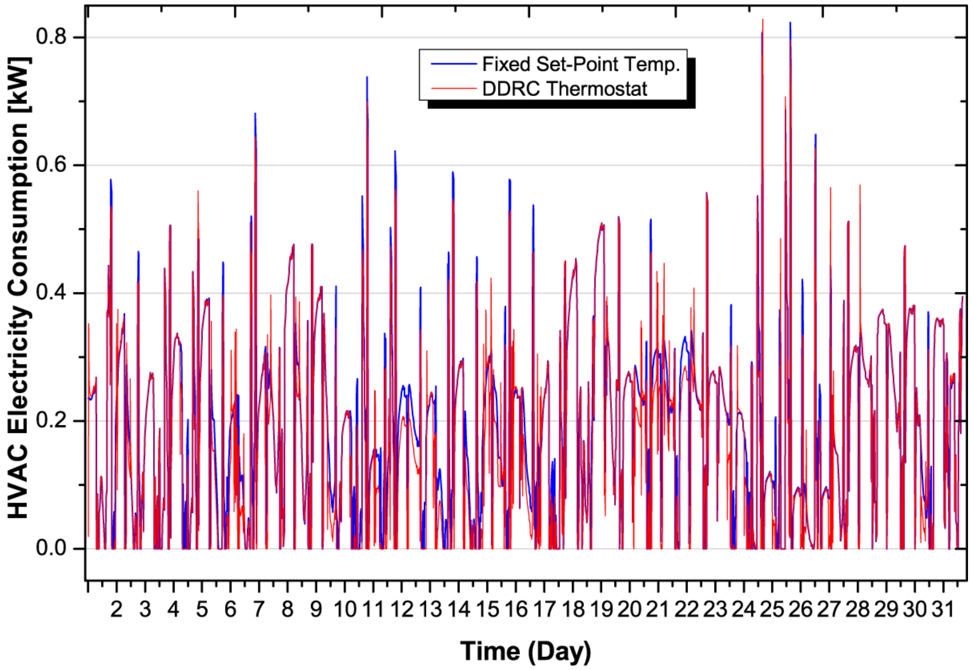


Figure 4.5: January HAVC electricity consumption comparison

As in the summer season, during the winter, the DDRC effectively curtails peak loads of HVAC. On January 20, two peak periods occurred in the morning and at night since the outside temperature is low. The high retail price due to increase of electricity demand is inputted to DDRC and then DDRC sharply decreases heating set-point temperature by up to $2C^o$ in the morning and late night. After the first peak at 9:00 am, DDRC temporarily increases heating set-point temperature for a while to reduce discomfort while there is a low retail price of electricity. However, the second peak at 20:00 appears at night and set-point temperature for heating is decreased again. Due to this immediate action by DDRC, HVAC electricity consumptions on peak time are considerably dropped by 11.96 %. Moreover, DDRC also saves electricity cost to run HVAC system by 20.3% during peak period. HVAC load changes according to retail price change on January 20 are presented in Figure 4.6.

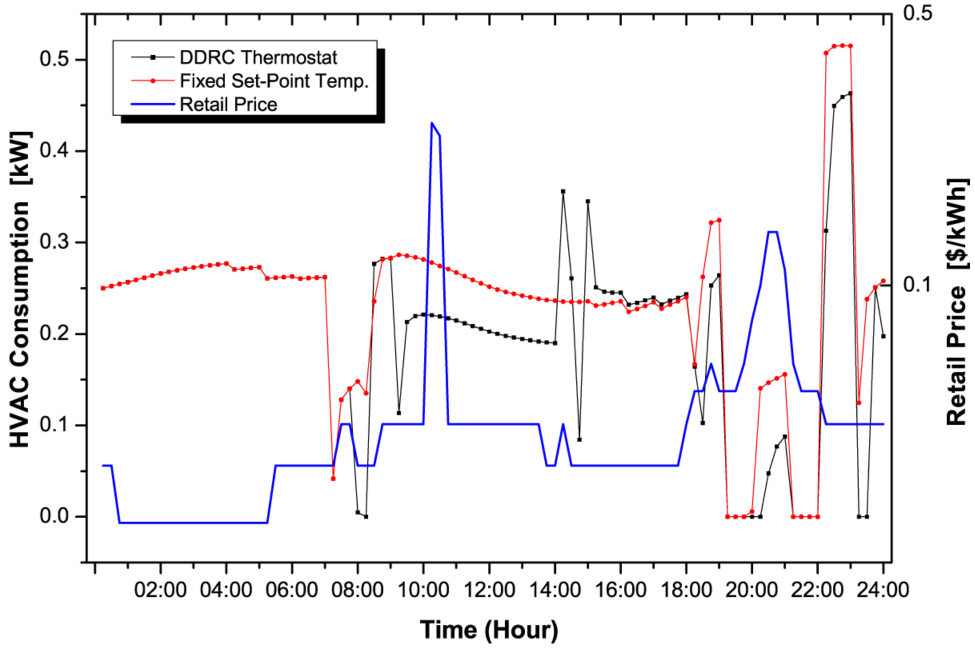


Figure 4.6: HVAC load changes on January 20, winter season

4.1.4 Total Energy Savings

For given set point thermostat (start cooling if T > 23^{o}C and heating if T < 22^{o}C) the modeled house consumes 6886.28 kWh for heating and cooling. However, HVAC system consumes 6257.65 kWh for the whole year when DDRC is applied to the thermostat. Figure 4.7 illustrates the comparison of electricity consumption by HVAC in non-DDRC and DDRC thermostat case. There is a 9.12% of electricity savings from HVAC when DDRC automatically changes set-point temperature depending on electricity retail price change. If customers let their HVAC system operate at fixed set-point temperature regardless of electricity retail price change, then their payment would be 14.14% higher than when the DDRC is used.

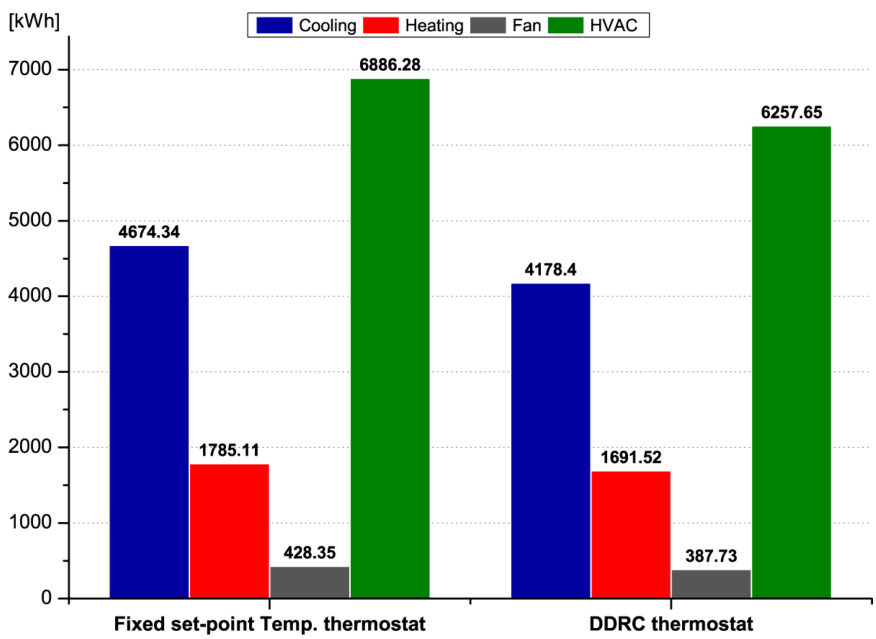


Figure 4.7: Comparison of annual HVAC electricity consumption

We also considered the effect of a wider-dead band in the base case simulation. The simulation results show that a wider thermostat dead-band decreases the potential for energy saving with DDRC. For example, increasing the dead-band from1 C°(start cooling if $T > 23$°C and heating if $T < 22$°C) to 5 C°(start cooling if $T > 26$°C and heating if $T < 21$°C) decreases the total energy saving with DDRC from 9.11% to 2.74%. Also, different house sizes and/or thermal properties (such as insulation, glass area. etc.) may impact the saving due to using the DDRC. An elaborate study with sensitivity analysis that includes multiple type of houses and thermostat set-point are needed to fully assess the economic potential of DDRC.

4.1.5 Indoor Thermal Comfort

The DDRC can save energy and money but also potentially introduces thermal discomfort due to the change of the thermostat set-point (too hot or too cold feeling). Figure 4.8 shows the indoor environment of the house on January and August for both normal operation and DDRC thermostat. In the case of the fixed set-point temperature, Figure 4.8 (b), the thermostat of the house for comfort is set to 22°C for heating and 23°C for cooling and all the air temperatures are in this range. Most of the indoor air temperatures with the DDRC thermostat in Figure 4.8 (a) are in the range of 21-24°C where there is a ±1 C°of dead-band. Table 4.1 provides the percentage of time when the indoor air temperatures are out of the base-case dead-band (22-23°C) for the whole year. The percentage of time when the temperature is out of thermostat dead-band is 29.1%; however, the temperature is more than 2 C°difference deviation from dead-band temperature range only 0.3% of the time.

Table 4.1: Percentage of indoor air temperature for a year

Type (%)	Indoor Air Temperature (C°), $[T_1, T_2]$ $[T_1 \leq T_{in} < T_2]$					
	[19,21]	[21,22]	[22,23]	[23,24]	[24,25]	[25,27]
Fixed	-	-	50.4	49.6	-	-
DDRC	0.1	4.7	44.5	26.3	24.2	0.2

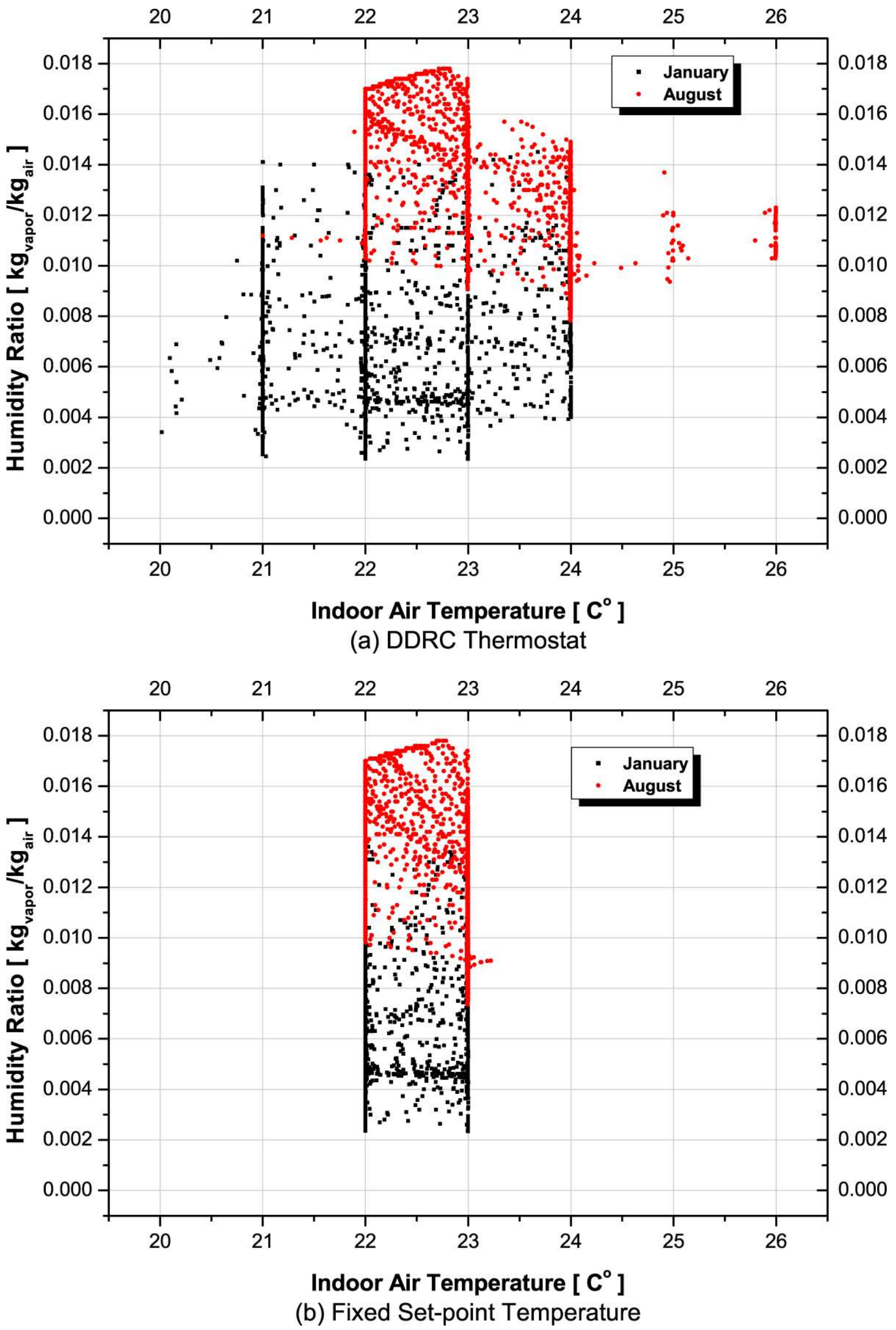


Figure 4.8: Indoor thermal comfort comparison in January and August

4.2 DDRC with various price types and floor plans

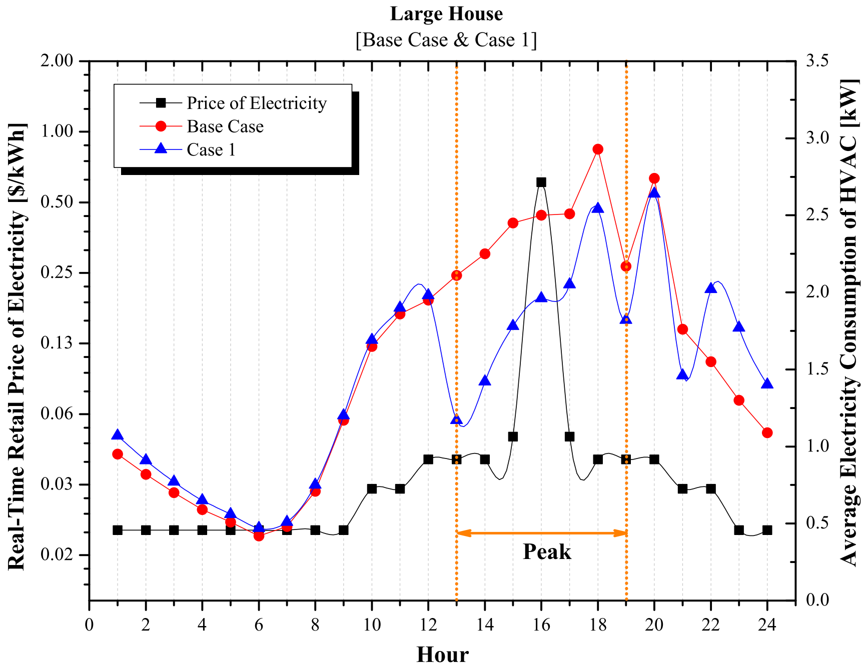
The performance of the proposed Dynamic Demand Response Controller (DDRC) is evaluated in terms of saving energy cost and reducing peak loads during peak time. Two different types of retail price are used; hourly based day ahead price (DAP) and 15 minute based real-time price (RTP). In addition, total annual electricity consumption is reduced for both the large and medium houses when the proposed DDRC thermostats are installed. The indoor environments in houses maintain thermal comfort during most times compared with the base case, which has fixed set-point temperature. EnergyPlus documentation recommends simulating the building with 15 minute time-step [49-51]. However, an hour time-step is chosen in this research since the price signal of electricity changes every hour. So, an hour simulation step is chosen to demonstrate the performance of the proposed thermostat controller to match the interval of the price signal. In additional studies, it was verified that the results with 15 minute time-step is less than 0.5% different from an hour based simulation results for both HVAC and total electricity consumptions. So, the time-step does not impact on the simulation results.

4.2.1 Simulation Condition

In this case, The thermostat is set to 26°C for cooling and 22 °C for heating. Cooling days is from April 1st to October 31st. During this period, space heating is not applied. During the rest of days for a year, only space heating is applied. So, the indoor temperature for some hours were out of the thermal comfort when the indoor temperature is lower than 22 °C during the cooling days since space heating it not applied in both with and without DDRC cases. For heating days, the indoor environment is the same as cooling season due to lack of air conditioning. Both the medium and large houses with the internal load are chosen. The dynamic prices of electricity for this case are selected 15 minute based Real-Time Price (RTP) and hourly Day Ahead Price (DAP) at ERCOT wholesale market at 2011. DDRC adjusted the set-point temperature with the based policy.

4.2.2 The Large House

For the large house with fixed set-point temperature, the base case consumed 15.8 MWh of total electricity for a year. AC is turned on from April 1st to October 31st. A heater starts to supply heat into a house when AC mode is deactivated. HVAC electricity consumption was 7.8 MWh which is 49% of total electricity consumption. It has a large floor plan and window area so that high HVAC loads are demanded for cooling and heating into a house. When the DR controller is applied, the total electricity consumptions by HVAC are decreased to 7.5 MWh with Real Time Price (RTP) and to 7.4 MWh with Day Ahead Price (DAP). That is, 3.7% in average of energy is saved using DR controller. Especially, on July 30, 2012, RTP reached the maximum price of electricity, $0.61 per kWh at 16:00 to due to heavy AC use. The peak occurred from 13:00 to 19:00 on Austin Energy Network (AEN). The average electricity consumption of HVAC is 17 kWh during peak periods if the cooling set-point temperature is not changed. However, when RTP based DDRC is set to HVAC system, average electricity consumption for cooling was sharply dropped to 12.7 kWh, so that 24.7% of AC load was curtailed.



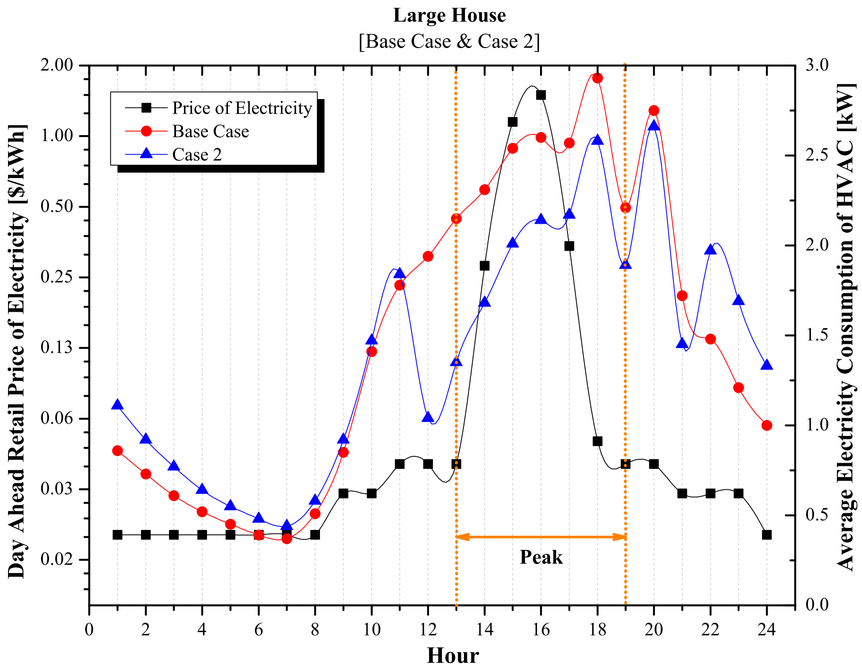


Figure 4.9: The peak load reduction by the DDRC thermostat with RTP and DAP at a large house

For DAP, the highest price of electricity, $1.15 kWh, occurred on August 2, 2012. In the base case, on average 14.2 kWh of electricity is consumed for cooling during peak period from 13:00 to 19:00. Contrary to the base case, the DDRC saves 20.2% of electricity at peak. Figure 4.9 shows how much electricity is curtailed at peak when DR controllers based on RTP and DAP are installed in HVAC. In monthly electricity use, the consumptions of electricity by HVAC are high on January and December because of heating. From June to August, heavy AC use causes high electricity consumption because of hot weather conditions in Texas. Figure 4.10 presents how much electricity HVAC system consumes for each month. DAP based DR controller is slightly more effective to decrease monthly HVAC electricity consumption than RTP based.

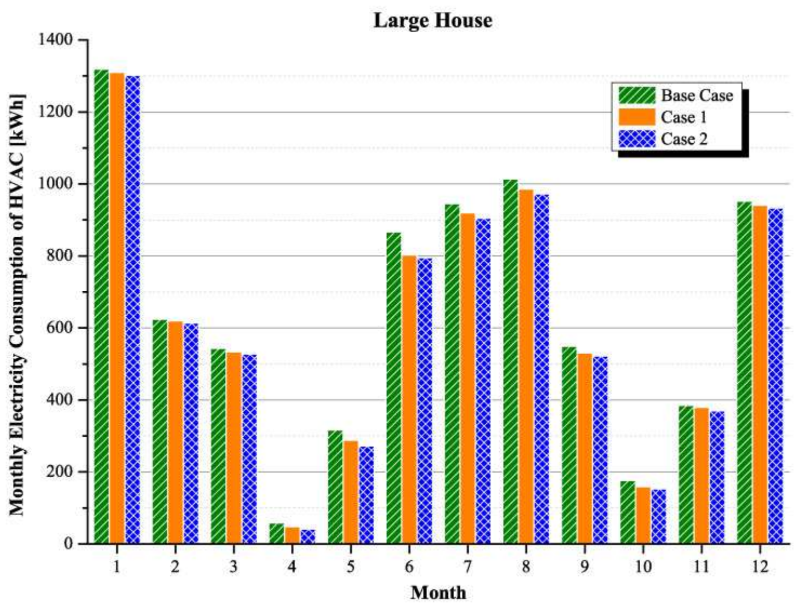


Figure 4.10: Monthly HVAC electricity consumption of a large house

4.2.3 The Medium House

Total electricity consumption in a medium house is 10.9 MWh with the base case. HVAC operation schedule is the same as a large house. HVAC electricity consists of 3.2 MWh in total electricity consumption and amounts to 29% of total use. The proposed Dynamic Demand Response Controller (DDRC) based on both Real Time Price (RTP) and Day Ahead Price (DAP) reduce total electricity use to 10.1 MWh and to 10.8 MWh respectively. When RTP based DDRC is activated, HVAC electricity use is 3.1 MWh. For DAP case, 3.04 MWh for HVAC is consumed. There is 3.8% of average energy savings with DR controller. In contrast to the slight total electrical energy savings, Figure 4.11 illustrates HVAC loads are significantly reduced during peak periods on July 30 with RTP and August 2, 2012 with DAP. Without the DDRC, 9.9 kWh of electricity is consumed during peak period from 13:00 to 19:00 with the base case on July 30. Our DR controller with RTP reduces average AC load to 7.8 kWh, so that 21.4% of AC loads is reduced.

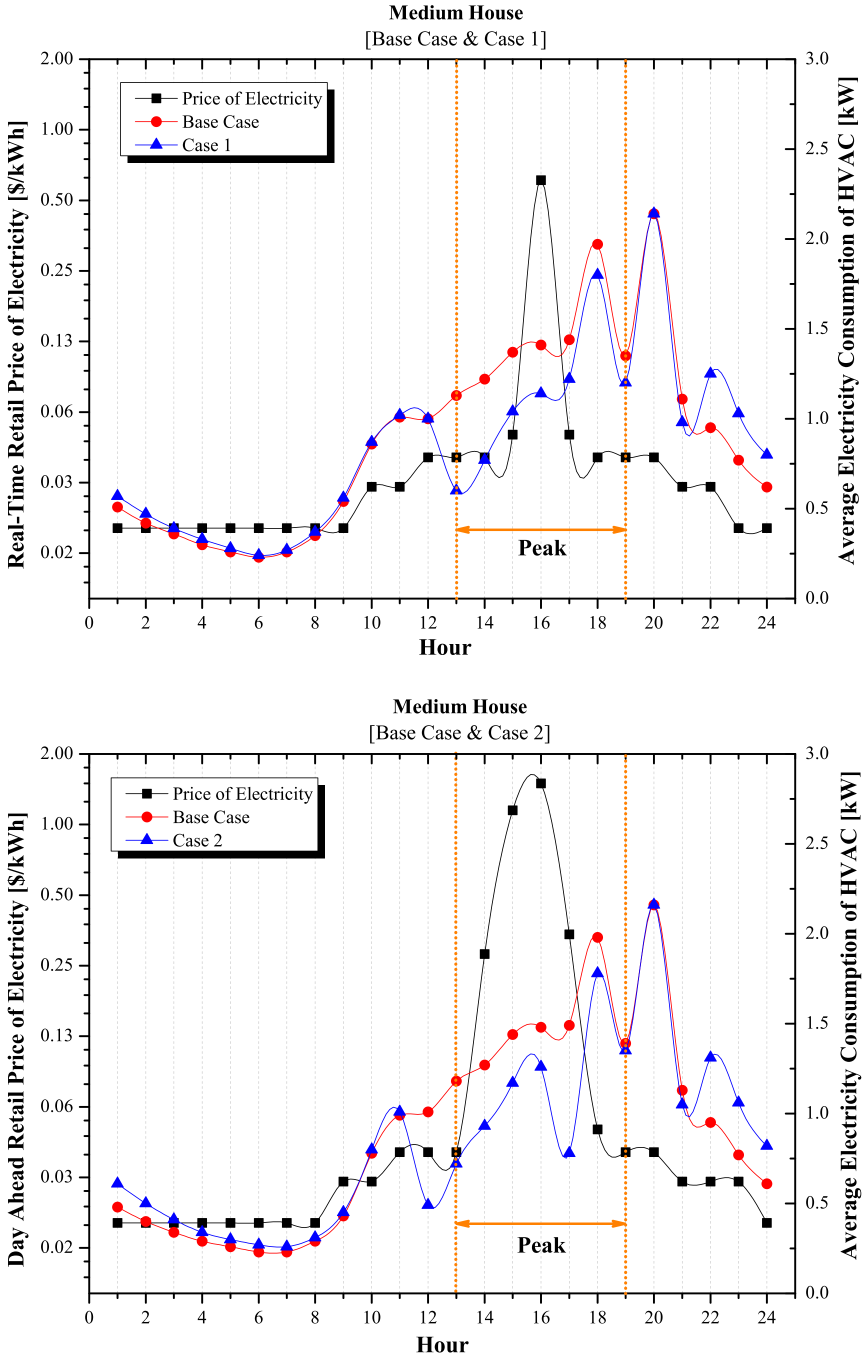


Figure 4.11: The contribution of DDRC thermostat with RTP and DAP to decrease peak loads at a medium house

For DAP case, AC consumes an average of 9.3 kWh on the fixed set-point temperature setting and 12.8% of peak load reduction occurs when the proposed thermostat is applied. There are significant electricity load reductions with the proposed DR controller. Since a medium house has small floor area and fewer windows, the solar irradiation coming into the house is lower than for the large house. So, less electricity is needed for cooling. The monthly HVAC electricity consumption of the medium house in Figure 4.12 is similar to the large house on AC use during summer. AC loads from June to August are high. However, the heating load is much smaller than for the large house.

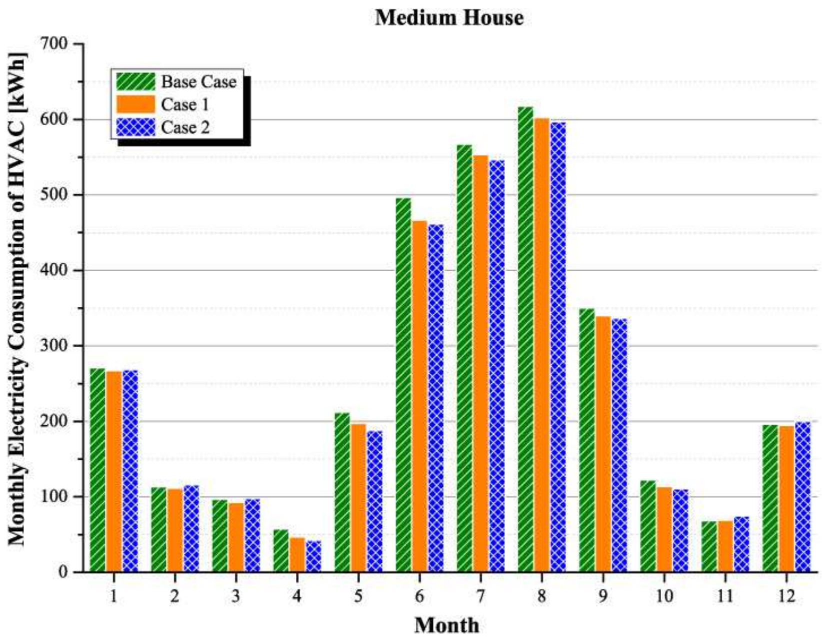


Figure 4.12: A medium house's Monthly HVAC electricity consumption

4.2.4 Annual Energy Cost Savings

The proposed Dynamic Demand Response Controllers (DDRCs) provide electricity savings. For the large house, 7.7 MWh of electricity is consumed for HVAC annually when the thermostat temperature is fixed. Annual HVAC electricity consumption with controller based on DAP is reduced to 7.4 MWh. For RTP case, 7.5 MWh is consumed. These are 4.3% and 3.0% savings under Day Ahead Price (DAP) and Real Time Price (RTP). For the medium house, total annual HVAC consumption of electricity is less than half of that in the large house. When the set-point temperature is fixed, 3.2 MWh is consumed for HVAC use for a year. Our DR controllers with DAP and RTP decrease electricity consumption of HVAC to 3.0 MWh and 3.1 MWh each. That is 4.0% of energy is saved when DR controller accepts DAP. Similarly, RTP based DDRC reduces 3.5% of electricity when customers use HVAC for a year. The comparison of total annual HVAC electricity consumptions of the large and medium houses are shown in Figure 4.13.

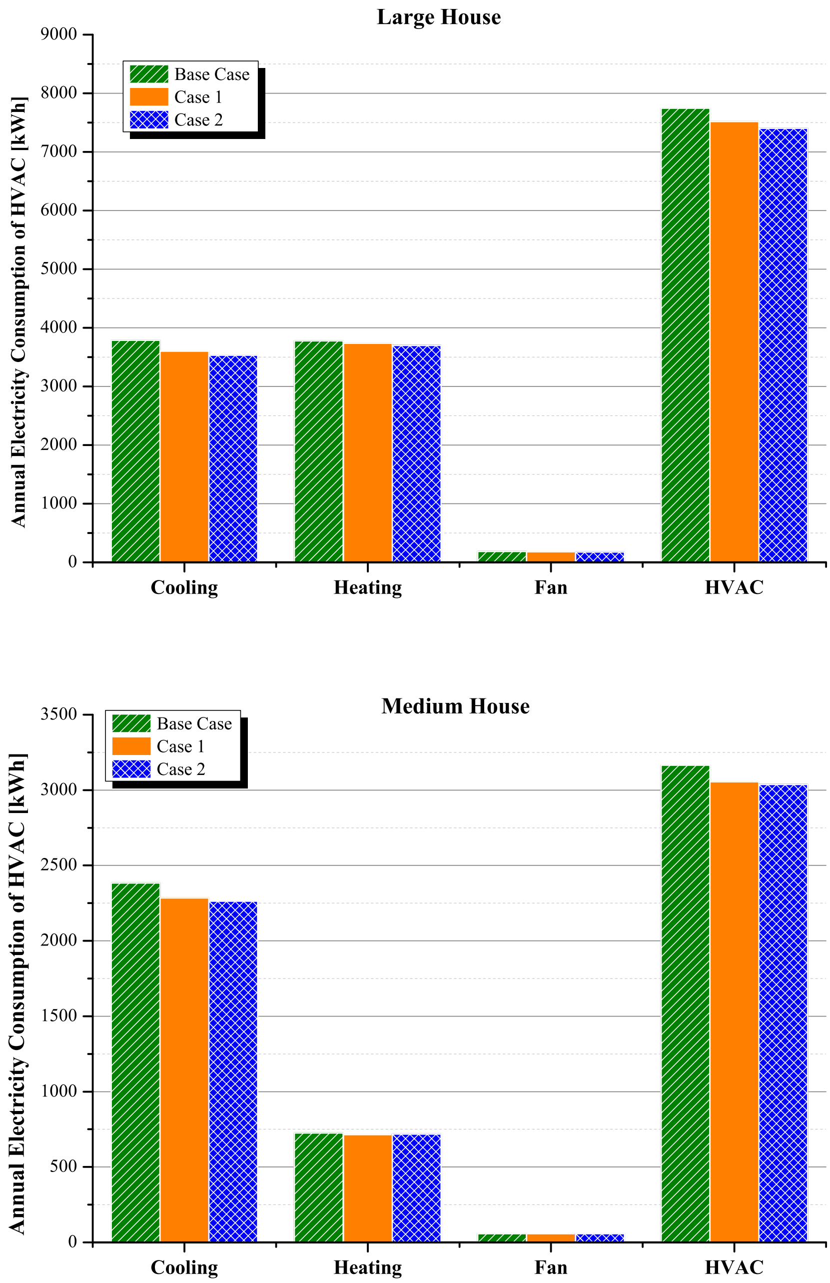


Figure 4.13: The annual electricity savings for a large and medium house

4.2.5 Annual energy cost savings

The results for the DDRC demonstrate the energy costs are saved at peak. The large house's monthly bill to use HVAC is three times higher than the medium house due to its size. On August, especially, heavy AC loads occurred. So, the retail price of electricity is higher than other months. When DR controller is applied, monthly charges are dropped to \$32.9 with RTP tariff and \$46.32 with DAP. Customers who choose DAP for DR program pay a 30% higher electricity bill than when RTP is chosen. Monetary savings are 7.7% and 13.2%, respectively, for RTP and DAP each compared the fixed thermostat temperature setting. For the medium house, \$20.36 and \$28.16 are spent to use AC when RTP and DAP tariffs are applied in DR controller. Compared with non-DR controller cases, DR controllers save 6.3% with RTP and 11.7% with DAP of electricity bill on August. The annual electricity costs for cooling and heating are presented in Figure 4.14. The large house spends twice as much money to use HVAC system as the medium house. The DR controllers in a large house drop costs to \$220.07 with RTP and to \$251.59 with DAP per year. There are 7.7% and 10.8% of saving from the fixed set-point temperature settings. In the case of the medium house, RTP tariff occurs \$96.57 for HVAC use and \$114.8 is charged by DAP based retail price. When DR controllers are applied, there are 8.1% and 10.47% of cost savings for each tariff from non-DR mode. The current tariff for residential customers of Austin Energy is an energy based tier tariff. When residential customers use more electricity in a month beyond a tier level, they will be charged high electricity prices for the additional consumption. From the historical data from Austin Energy [48], residential customers of Austin Energy annually consumed, on average, 11.2 MWh of electricity costing about $1,100 in average, in 2012. This electricity consumption is very similar to the medium house results. When the portion of HVAC use in total electricity consumption is applied to this historical data, we could assume that about 3370 kWh of electricity were used and customers spent about $325 for HVAC use. However, the energy cost to use HVAC system is about $112 if the penalty and extra charge are removed from the current capacity based tier tariff by Austin Energy.

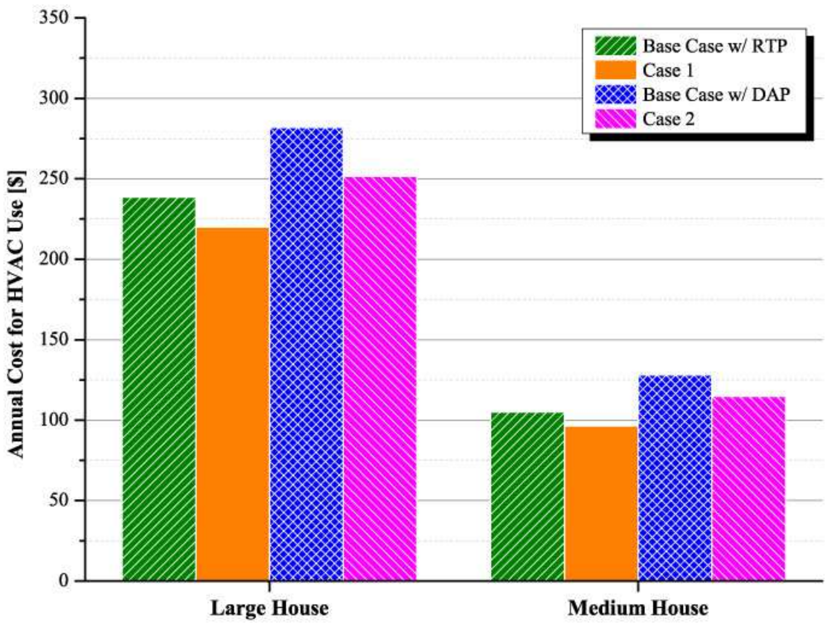


Figure 4.14: The comparison of energy cost for a large and medium house

4.2.6 Thermal Comfort

Thermal comfort is important for the HVAC system. If indoor environment is out of the comfort zone for a long time due to DR program, customers may feel discomfort and stop using the DR controller even if retail price of electricity is high. Our proposed DR controller preserves thermal comfort based on ASHRAE comfort zone [39]. The indoor environments in the large and medium houses for each case are shown in Appendix 1. The purple color plot presents the first floor of the large house and the main floor of the medium house. The second floor of the large house is illustrated in the light blue color plot. The outdoor environment is plotted with a gray color. The blue box is thermal comfort zone for summer. Winter comfort zone is a red box. These two boxes are drawn on the psychrometric chart. The indoor environments almost always stay in the comfort zone. Thus, the thermal comfort is not unduly disturbed through the use of the controllers. The heater mode turns on until March 30. After that day, HVAC changes to AC mode until October 31. The heater starts on November 1. Table 4.2 presents the percentage of total hours in a year when indoor air temperatures are in particular ranges. For the base case, the indoor temperature of a medium house is in the dead-band (22-25°C) for 48.9% of hours in a year. The hours when the indoor temperature is ±1 C°out of the dead-band is 42.8%. When controllers are installed, the indoor air temperatures of a medium house are in dead-band for 47.1% with DAP and 46.7% with RTP. Temperature excursions of ±1 C°from dead-band occur 33.4% and 35.3% for each pricing and ±2 C°excursions occurs around 20% of the year.

Table 4.2: Indoor air temperature in percentage of hours for a year

Type	Indoor Air Temperature (^{o}C), $[T_1, T_2]$, where $[T_1 \leq T_{in} < T_2]$					
	[20,21]	[21,22]	[22,25]	[25,26]	[26,27]	[27,28]
			Medium house - main floor			
Base	4.9	1.7	48.9	41.1	1.7	1.7
Case 1	5.0	2.9	46.7	32.4	11.2	1.8
Case 2	5.1	3.0	47.1	30.4	13.0	1.4
			Large house - 1st floor			
Base	5.7	2.1	47.3	40.3	2.1	2.5
Case 1	6.1	2.9	45.6	31.3	11.6	2.5
Case 2	6.3	3.2	45.0	29.3	13.7	2.5
			Large house - 2nd floor			
Base	7.3	1.9	52.3	38.5	-	-
Case 1	7.6	3.2	50.1	31.8	7.3	-
Case 2	7.8	3.7	49.3	30.3	8.9	-

Without the DDRC, the large house is in dead-band during 47.3% and 52.3% of the time for 1st and 2nd floor respectively. The hours when the indoor temperatures are ±1°C out of the dead-band are 42.3% and 40.4% for 1st and 2nd floors. The first floor maintains within dead-band for 45.6% and 45.0% of hours for case 1 and 2 when the DDRCs are applied. The hours when temperature excursions of ±1°C occur are 32.5% with DAP and 34.2% with RTP in the first floor. For second floor, temperatures are in dead-band for 50.1% and 49.3% for case 1 and 2. Temperature excursion of ±1°C from the initial setting occur 34.0% of hours in a year with DAP and 35.0% with RTP but over 2°C difference are about 15% for each floor.

Considering HVAC mode changes, the indoor environment with the proposed controller is close to the base case but reduce consumption at critical times. About 10% of total hours in average are different from the fixed set-point temperature setting. This small difference shows the proposed DR controller generally maintains the thermal comfort that the customer prefers. Comparing both tariffs based on the dynamic price, the RTP tariff is more effective to maintain the comfort level than DAP.

4.3 DDRC with different internal loads and climate zones

This chapter shows the proposed controller, Dynamic Demand Response Controller (DDRC), reduces the electricity usage to operate HVAC system at homes even though weather conditions and prices of electricity are different with improved control algorithm. This energy savings provide to decrease electricity bill for HVAC operations. In addition, the indoor thermal discomfort is minimized while DDRC changes the set-point temperature in a thermostat to participate DR programs.

4.3.1 Simulation Condition

The thermostat setting is the same as the second simulation case; 26°C for cooling and 22 °C for heating. HVAC operation schedule setting is also same as previous second case. Both the medium and large houses are chosen but the internal loads are set to normal and heavy (150% of normal load) loads. To compare the performance of DDRC in two difference locations, the dynamic prices of electricity are used hourly Day Ahead Price (DAP) at ERCOT wholesale market at 2011 and PJM at 2013. Improved DDRC algorithm is implanted to adjusted the set-point temperature based on DR signal.

4.3.2 Savings of Electricity Consumption

The summer hot weather condition in Austin, TX increases air conditioning loads in residential buildings. A large house with heavy internal loads which are 150% as high as the normal loads consumes 6,570 kWh for cooling and 2,796 kWh for heating of electricity annually without DDRC. Air conditioning loads are about 2.3 times larger than heating loads. When DDRC is installed, the electricity consumptions by cooling and heating are decreased to 6,147 kWh and 2,657 kWh each. DDRC saves 6% of HVAC electricity use. The normal load case of a large house in Austin, TX shows that air conditioner consumes 6,162 kWh when DDRC is not applied. The amount of electricity consumption by heater is 3,131 kWh with the fixed set-point temperature. However, both electric power consumptions at cooling and heating modes are dropped to 5,738 kWh for AC and 2,999 kWh for heating when DDRC enables DR function. There is 6% of electricity savings in a normal load case. The increase of internal loads raises the indoor temperature because of human activities. This creates heavy peak loads during summer season. On the contrary, the heating load increase contributes to decreasing heater usage. The proposed DDRC also brings energy savings out in a medium house. For heavy internal load case, DDRC reduces 5.2% of electricity use compared to the fixed temperature case. HVAC system with DDRC spends 2,775 kWh for cooling and 266 kWh for heating. On the other hand, 2,940 kWh and 278 kWh of electricity are consumed when DDRC thermostat is not retrofitted. The case with normal internal loads is that a medium house uses 2,617 kWh for air conditioning and 354 kWh for heating. DDRC contributes to curtail the electricity consumption to use an air conditioner by 2,460 kWh and a heater by 345 kWh annually. This is 6.2% of energy use savings when customers run the HVAC system for a year. The same as the cases with a large house. The internal load changes impact on HVAC electricity consumption since the indoor temperature is increased or decreased by indoor activities. The electricity consumption of houses in Austin, TX for a year is presented in Figure 4.15.

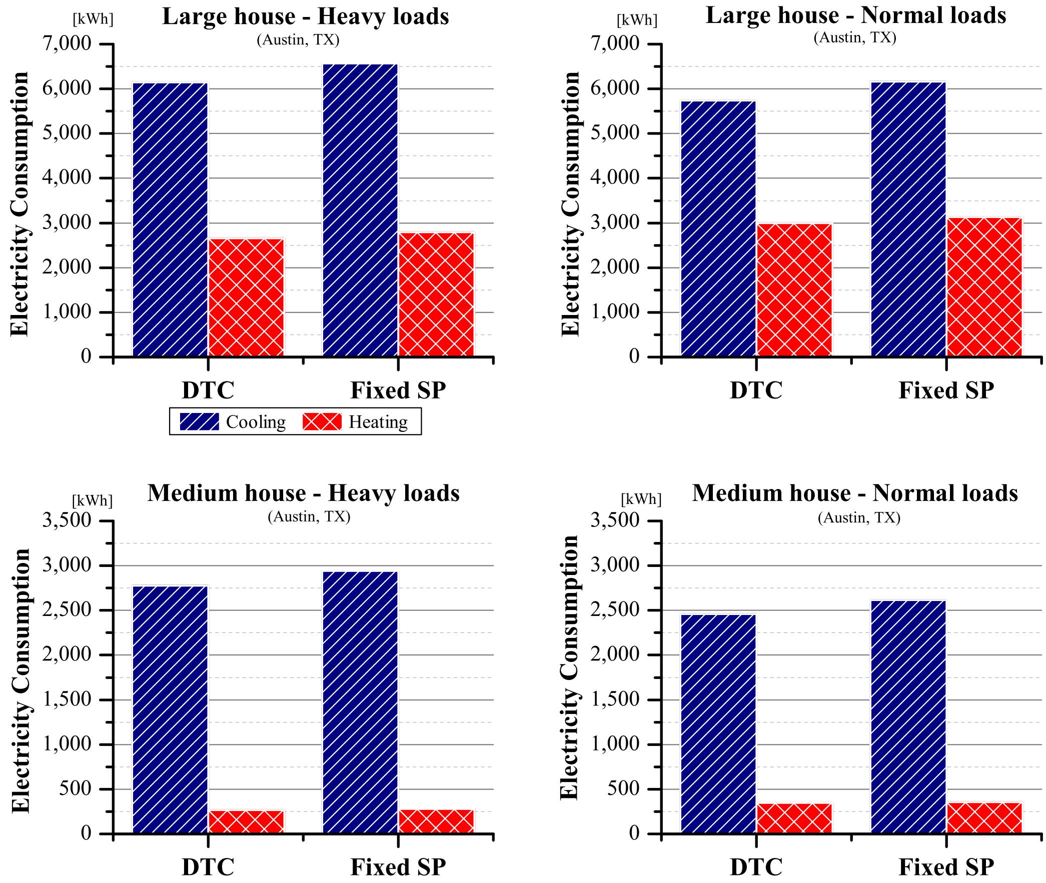


Figure 4.15: The electricity consumption of houses in Austin, TX for whole year

In Chicago, IL, the heating loads are the major contributor to cause peak loads due to severe cold weather during winter. But high internal loads that increase the indoor temperature contribute to drop the electricity consumption when customers use the heater. Figure 4.16 shows the comparison of annual electricity consumption by houses in Chicago, IL. A large house with heavy load consumes 15,255 kWh for heating but the cooling load, 4,609 kWh, is about one third of heating load when the conventional thermostat with fixed temperature setting is installed. Comparing to DDRC, the electricity usage for heating is dropped to 14,830 kWh as well as power consumption of AC is decreased by 4,360 kWh. There is 3.4% of energy savings. The normal load case of a large house spends 15,983 kWh to use heater. Air conditioner consumes 4,630 kWh of electricity. Whereas, HVAC system with DDRC uses 15,540 kWh for heating and 4,341 kWh. The electricity is saved by 3.6% with Dynamic Demand Response Controller (DDRC). For the medium house, the electricity consumption to use heater with heavy internal load is lower than with normal internal load case due to increase of indoor temperature from the heavy internal load. For a medium house with heavy load, power consumption for heating is 3,017 kWh. The annual electricity use by air conditioner is 1,475 kWh when DR function with DDRC is not enabled. DDRC curtails the consumption of electricity to operate HVAC system by 4.8%: cooling – 1,475 kWh, heating – 2,879 kWh. When the internal load is to normal size, the fixed set-point temperature case for a medium house consumes 3,522 kWh to use a heater and 1,387 kWh to run AC. But DDRC provides the reduction of electrical energy usage by 3,406 kWh for heating and 1,304 kWh for cooling. The energy savings is 4.1% compared to a case without DDRC.

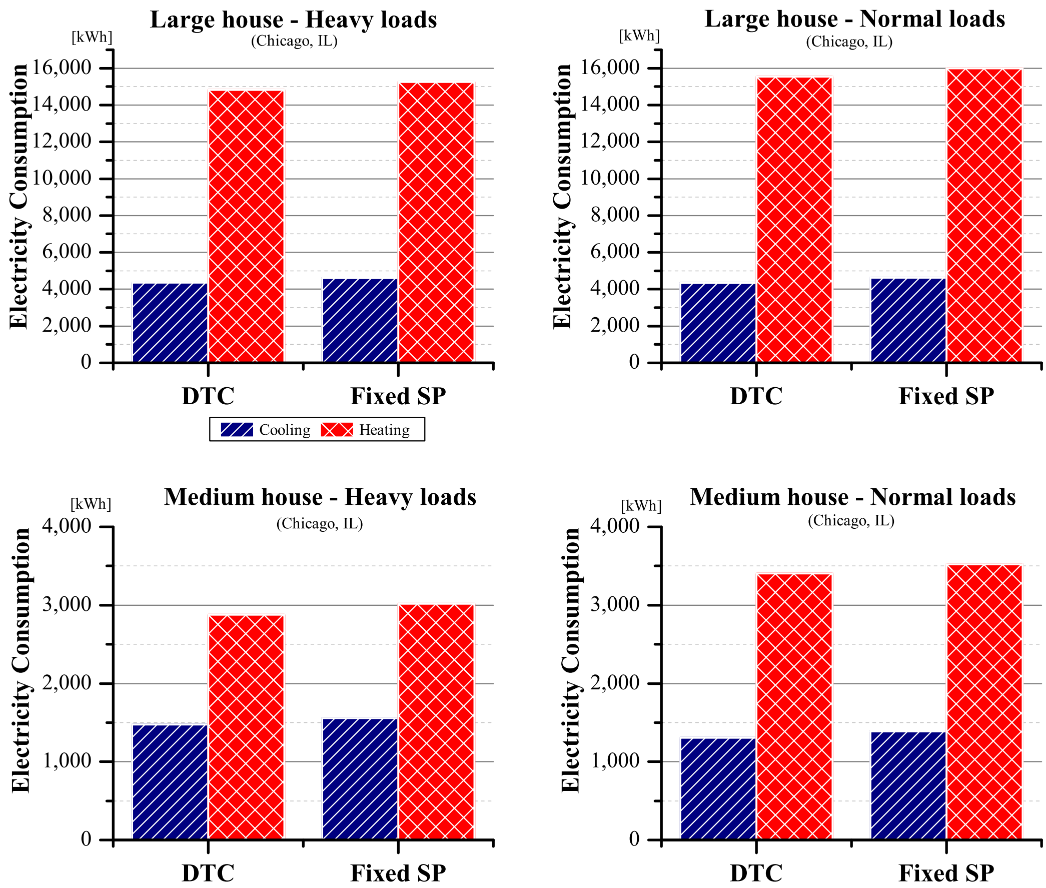


Figure 4.16: The comparison of annual electricity consumption by houses in Chicago, IL

The overall energy savings with the proposed Dynamic Demand Response Controller (DDRC) are different in two locations. The absence of capacity market in the Electric Reliability Council of Texas (ERCOT) means that the real-time price of electricity in Austin, TX rises to higher levels than in Chicago, IL. As we explained in Section 2.3, Austin has higher frequency of time when the electricity price is bigger than \$0.04/kWh compared with Chicago. As a result, DDRC which is installed at homes in Austin, TX more often change the set-point temperature than in Chicago so that the energy saving in Austin is higher than in Chicago.

4.3.3 Energy Cost Savings

The energy costs to run HVAC system changes depending on the price of electricity. The energy component of the electricity price in Austin is higher than in Chicago. So, households in Austin are charged higher electricity bills than in Chicago. A large house with heavy internal loads pays \$726.59 to use cooling and heating annually. However, DDRC gives 11.1% of cost savings to customers. The annual energy cost is \$630.73 with heavy load. When indoor activities are set to normal, customers pay \$717.05 with the fixed set-point temperature setting, and 12% of energy cost is saved by DDRC. Total annual bill to run HVAC system with DDRC is \$630.73. Residents who live in a medium house pay less money for cooling and heating due to the smaller house size. Customers spend \$353.56 when the heavy internal load is set. For DDRC case, the cost is decreased to \$318.49 and 9% of electricity bill is saved. With the normal load, the energy cost for HVAC system with DDRC is \$247.74 but the conventional thermostat has an annual cost of \$281.22. DDRC saves 11.9% of money by changing the set-point temperature.

A large house with heavy loads spends \$662.31 for HVAC system while the indoor temperature is set to maintain the set-point temperature. However, DDRC reduces the energy cost to \$621.43 and by 6.2%. For normal load case, \$684.83 of energy cost is spent when the set-point temperature is fixed. DDRC decreases expense to use HVAC system by \$642.53, 6.2%. Residents in a medium house spend less money to use air conditioner and heater than a large house. The operation of HVAC system requires \$167.38 of annual cost with heavy load and fixed set-point temperature setting. The energy cost that DDRC controls HVAC system is \$160.91 and it is 7.4% of cost savings. For normal load, DDRC needs \$152.15 to run air conditioner and heater for a year. However, the fixed set-point mode requires \$164.38 for cooling and heating. DDRC gives 7% of money savings to customers. The energy cost comparisons between DDRC and fixed SP mode in two locations are illustrated in Figure 4.17.

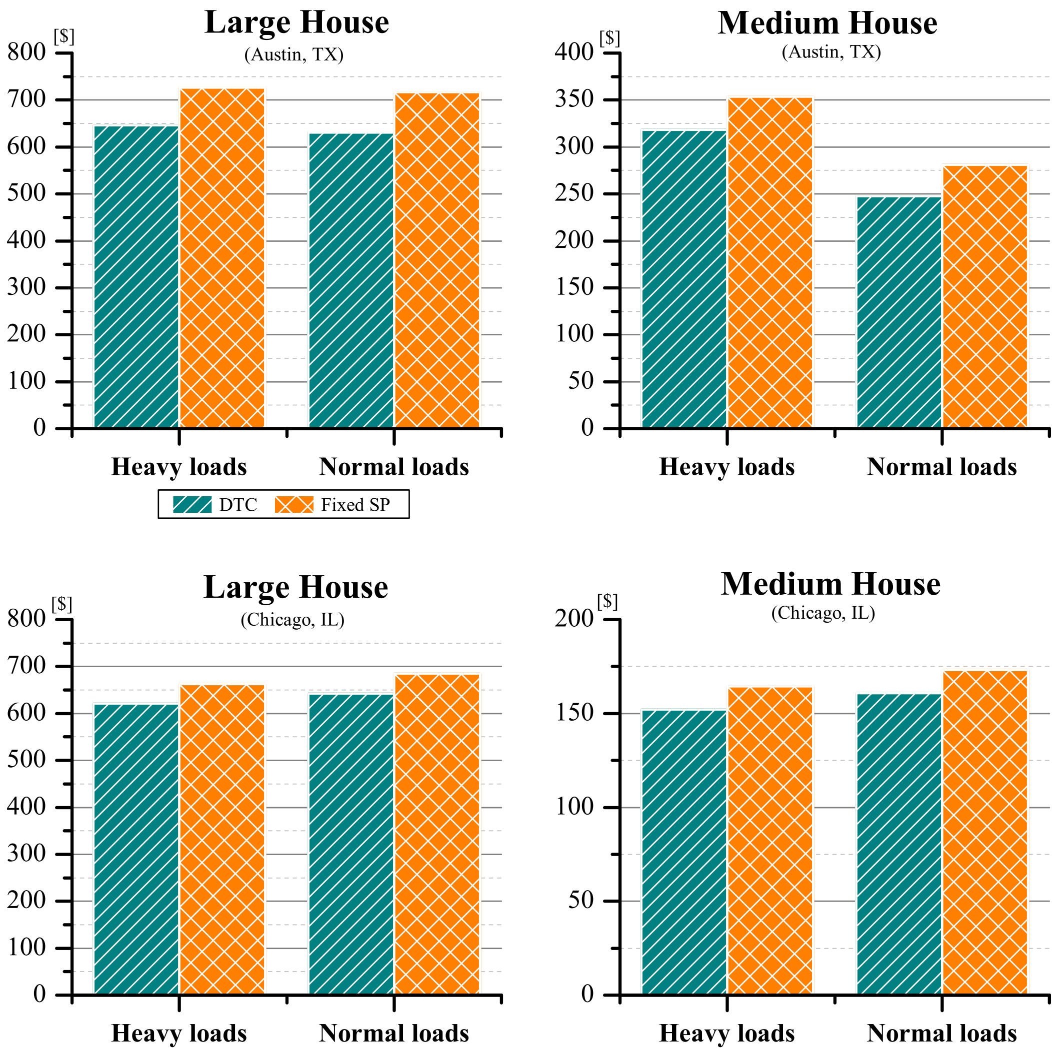


Figure 4.17: Energy cost comparisons between DDRC and fixed SP mode in two locations

The proposed Dynamic Demand Response Controller (DDRC) provides economic benefits to customers in Chicago even if the energy price in PJM is lower than in ERCOT market. If utilities provide the incentive program to their customers who want to take DR programs, the energy cost savings in Chicago will be close to Austin. For Austin, high cost savings with DDRC accrue to residents who live in a large or medium house no matter of internal load size.

4.3.4 The Thermal Comfort

Thermal comfort is important for the indoor environment. If the indoor temperature is over or under the desired temperature for a long time, people feel discomfort. But other researches [72, 79, 80] do not reflect it on the control methods. To minimize the thermal discomfort, the Dynamic Demand Response Controller (DDRC) considers thermal comfort based on ASHRAE Standard 55 [39]. The high change of the set-point temperature by high price of electricity causes severe thermal discomfort. This may increase the resistance of households to participation in DR programs. In this research, the preset set-point temperature for cooling is 25°C and the heating temperature is set to 21°C. So, we assume that residents feel comfort when the indoor temperature maintains a preset temperature (25°C) or below during AC mode. Opposite to AC mode, the indoor temperature in heating mode remains the preset temperature (21°C) or higher. DDRC increases or decreases the set-point temperature when DR signal is enabled by 1°C step. Figure 4.18 shows the indoor thermal comfort of a large house with normal loads when DDRC is applied for Austin, TX.

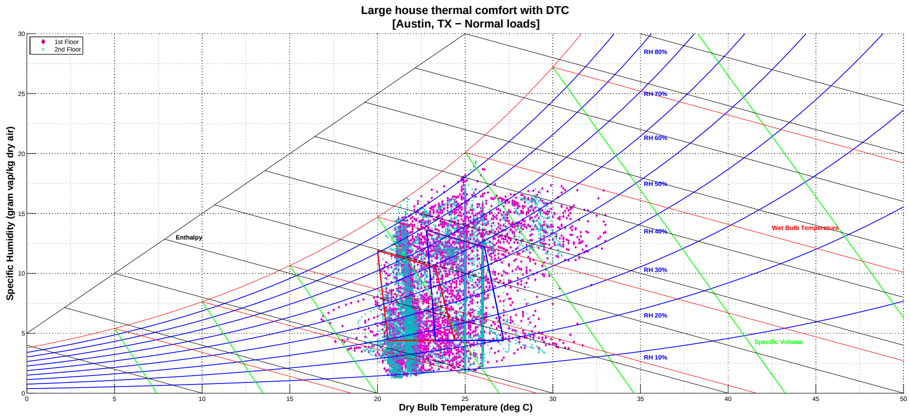


Figure 4.18: Indoor thermal comfort of a large house with normal loads when DDRC is applied – Austin, TX

To calculate how much indoor temperature is over or below the preset temperature for cooling and heating modes during certain amount of time, Equation (4.1) and (4.2) are used as follows below. First, the thermal discomfort is calculated as the product of hours and temperature difference between the indoor temperature and the preset temperature. Next, the summation of thermal discomfort is divided by total hours of cooling or heating for normalization by period. Total hours of cooling and hearing in Austin, TX are 5,880 (245 days) and 2,800 (120 days). For Chicago, IL, they are 4,416 (184 days) for cooling and 4,344 (181 days) for heating.

$$T_{discomfort} = \begin{cases} \dfrac{\Sigma\left[(T_{in} - T_{sp}^{cool}) \times hr_{discomfort}\right]}{\Sigma\, hr_{cooling}} & \text{for } T_{in} > T_{sp}^{cool} \quad (4.1) \\ \dfrac{\Sigma\left[(T_{sp}^{heat} - T_{in}) \times hr_{discomfort}\right]}{\Sigma\, hr_{heating}} & \text{for } T_{in} < T_{sp}^{heat} \quad (4.2) \end{cases}$$

Table 4.3 explains how much DDRC causes thermal discomfort when it changes the set-point temperature. For all cases, the indoor environment does not exceed more than 1 C°from the preset temperature where customers feel comfort. In results, DDRC minimizes the thermal discomfort even if the set-point temperature is reset because of high electricity price. Furthermore, different environments such as cold/hot weather and different internal load sizes do not significantly impact on thermal comfort when DDRC controls HVAC systems.

Table 4.3: Normalized thermal discomfort by days of cooling and heating when DDRC is applied [C^o] - The temperature difference from the indoor temperature without DDRC

Austin, TX

Thermal zones	Heavy Heavy internal loads		Normal Heavy internal loads	
	Cooling	Heating	Cooling	Heating
Large house				
1st floor	0.3	0.0	0.3	0.0
2nd floor	0.3	0.1	0.3	0.1
Medium house				
Main floor	0.3	0.1	0.3	0.1

Chicago, IL

Thermal zones	Heavy internal loads		Normal Heavy internal loads	
	Cooling	Heating	Cooling	Heating
Large house				
1st floor	0.4	0.0	0.2	0.0
2nd floor	0.2	0.0	0.2	0.0
Medium house				
Main floor	0.4	0.2	0.4	0.2

4.4 Summary

4.4.1 DDRC with dynamic price of electricity

Electricity retail price based Dynamic Demand Response Controller (DDRC) shows that heating and cooling electricity consumption on both the coldest month, January and the hottest month, August are considerably reduced by about 12% and 21% each. The electricity cost to operate for both the coldest and hottest months are curtailed by about 29% and 31% each. In annual cost savings, DDRC provides 14% electricity cost reduction to customers with real-time retail pricing tariff. Moreover, DDRC can contribute to save annual electricity consumption up to 9%. In respect of comfort level, indoor air temperatures are between 22 and 24 degrees Celsius with fixed thermostat control. The percentage of temperature which is out of thermostat dead-band for cooling mode is 24.4% and for heating mode is 4.9%. The percentage of time when there is more than 2 Celsius degree deviation from the temperature dead-band is 0.3%. DDRC robustly demonstrates that HVAC loads are curtailed during peak and electricity cost savings are provided to customers on real-time tariffs. The electricity saving of AC using a thermostat controller in [18] is 15.23% to 17.33% and cost savings are 15.54% to 34.79% for summer. The temperature differences by the controller are about $4C^o$ (from 23.9 to 26.1°C).

4.4.2 DDRC with various price types and floor plans

This case demonstrates that our proposed Dynamic Demand Response Controller (DDRC) contributes to reduce peak loads and to saving both annual electricity and costs. Furthermore, it minimizes thermal discomfort for houses with different sizes and floor plans. Our DDRC brings significant peak load curtailment of 12.8% to 24.7%. Annual electricity HVAC use is decreased by 4.3% for a large house and 4.0% for a medium house. In addition, our controller provides advantage to customers in respect of cost savings. Customers can save from 7.7% to 10.8% of their annual electricity bill depending on price types. The weather condition from July 2012 to June 2013 is more moderate than year 2011 which was the hottest year in Austin, TX. So, the electricity price at Electric Reliability Council Of Texas (ERCOT) market at this period was lower than in 2011. As a result, the annual electricity savings are little lower than our previous study [16] that used 2011's ERCOT wholesale price data. The proposed DDRC thermostat can save a significant amount of electricity when the price of electricity is high. The indoor air temperature mostly stays within inside the thermal comfort zone. For 10 % of total hours of a year in average becomes 2 C°above the AC set-point temperature. Thus, our controller avoids significant thermal discomfort while the set-point temperature is changed due to high price of electricity.

4.4.3 DDRC with different internal loads and climate zones

In this case, our Dynamic Demand Response Controller (DDRC) demonstrates that the electricity consumption and energy cost to use HVAC system are decreased while considering the thermal comfort. First, the electricity consumptions are reduced by changing the set-point temperature in a thermostat by 3∼6% even if the internal loads and house sizes are different in two locations. In Austin, TX where the electricity price is high, DDRC reduces more annual energy consumption by about 5∼6%. In addition, it provides 6∼12% of energy cost savings to customers when DDRC is installed at homes. If the electricity price is high, DDRC brings more cost savings to customers who participate in DR programs. In the PJM wholesale market, the energy cost savings could be increased when utilities provides DR incentives to their residential customers. Finally, DDRC mostly keeps the indoor temperature comfortable. Residents experience about 1C°(2F°) deviates of the indoor temperature from the preset set-point temperature on average for a whole year.

4.4.4 Comparison of Results

We introduce two control policies for the proposed Dynamic Demand Response Controller (DDRC) in Chapter 3. The base control algorithm which is introduced in Chapter 3.1 is used for results in Chapter 4.1 and 4.2. The annual electricity consumption with the base control algorithm of DDRC with 2011 Day Ahead Price (DAP) in the ERCOT market is 4.3% for a large house and 4% for a medium house. DDRC with this control policy provides 10.8%

of cost savings for a large house and 10.5% for a medium house. However, the base control policy is limited to Austin, TX because it requires historical price and weather data to calculate the linear regression coefficient (a, Eq 3.7 and 3.8) which converts to temperature. So, the DDRC would require adaptation to use in another location. However, the improved DDRC control policy does not have the linear regression coefficient, which removes the limitation of home locations. So, the DDRC can be deployed in various climate zone and wholesale electricity market. The improve control algorithm gives 6% of annual electricity savings for a large house with 2011 DAP in the ERCOT market and 6.2% for a medium house. The energy cost with the improved DDRC are reduced by 12% for both large and medium houses. The DDRC with improved control policy has high performance compared with the DDRC with the base algorithm. There are improvements in both annual energy cost and electricity savings by the improved control policy. Table 4.4 presents the comparison of the DDRC performance between the base and improved control algorithms. The improved DDRC can reduce the HVAC electricity consumption and increase the annual energy cost savings more than the DDRC with base control algorithm.

Table 4.4: The improvement of DDRC performance by enhanced control policy

Control Type	Base DDRC [%]	Improved DDRC [%]	Improvement [%]
	Annual Electricity Savings		
Large house	4.3	6.0	39.5
Medium house	4.0	6.2	55
	Annual Energy Cost Savings		
Large house	10.8	12.0	11.1
Medium house	10.5	11.9	13.3

Chapter 5

Development of Hardware for Dynamic Demand Response Controller

This chapter shows the development of the proposed Dynamic Demand Response Controller based on embedded controller including sensing environment and wireless communication capability.

5.1 Arduino Due embedded controller

Embedded micro-controllers are widely used in industries. In this research, we used high performance embedded controller to build the Dynamic Demand Response Controller (DDRC) based on the Arduino board. Arduino[1] is an open-source electronics platform based on easy-to-use hardware and software. The compiler, Arduino IDE, is provided for free to build embedded codes based on C++ language. In hardwares, Arduino has various products with different CPUs. Two major CPUs are used in Arduino boards; AVR and ARM CPUs. Most Arduino boards use Atmel[2] AVR 8 bit micro-controller. But, Arduino Due board is 32 bit micro-controller based on Advanced RISC Machines

[1] http://arduino.cc
[2] http://www.atmel.com

(ARM) Cortex−M3.

Arduino Due[3] board has a 32-bit ARM core that can outperform typical 8-bit AVR micro-controller boards. The most significant differences are:

- A 32-bit core, that allows operations on 4 bytes wide data within a single CPU clock.
- CPU Clock at 84Mhz.
- 96 KBytes of SRAM.
- 512 KBytes of Flash memory for code.
- DMA (Direct Memory Access) controller, that can relieve the CPU from doing memory intensive tasks.

Arduino Due has 54 GPIO (General Purpose Input Output) pins (of which 12 can be used as PWM outputs), 12 analog inputs, 4 UARTs (hardware serial ports: RX/TX), a 84 MHz clock, an USB OTG capable connection, 2 DAC (Digital to Analog Converter), 2 TWI (Two Wire Interface: SCL/SDA, SCL1/SDA1), a power jack, an SPI (Serial Peripheral Interface) header, a JTAG (Joint Test Action Group) header, a reset button and an erase button. Figure 5.1 shows Arduino Due board based on 32 bit micro-controller

[3] `http://arduino.cc/en/Main/ArduinoBoardDue`

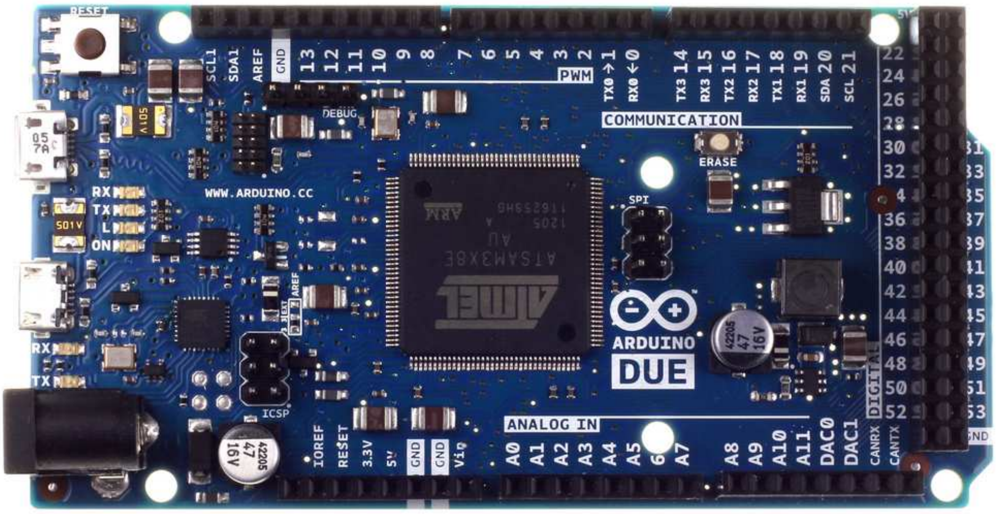


Figure 5.1: 32bit ARM CPU based Arduino Due Board

DDRC has 7 inch resistive touch TFT (Thin Film Transistor) LCD screen to visualize graphic interface for easy control. SPI port is allocated for TFT LCD. Real-Time clock and temperature/humidity sensor use TWI pins to transfer data to Arudino Due. To improve response time of DDRC, another Arduino Due board for WiFi communication to receive demand response signal (price data) is used. The two Arduino Due boards communicate with each other using UART (Universal Asynchronous Receiver/Transmitter) port. Voltage level to transmit and receive is set to 3.3V from power supply with common ground. To measure outdoor environment, 8 bit AVR based Arduino Uno is used with 433 Mhz wireless communication for weather station.

5.2 Sensing of Temperature and Humidity: HTU21D

The indoor environment is very important in Heating Ventilating and Air Conditioning (HVAC) system control. A thermostat maintains the indoor environment thermal comfort by comparing the indoor temperature with the set-point temperature. To measure indoor temperature and relative humidity, the sensor module, HTU21D[4], is used for DDRC and shown in Figure 5.2. HTU21D module can measure relative humidity from 0 to 100% with ±2% accuracy. The indoor temperature is measured from -40 to 125°C with ±0.3°C accuracy.

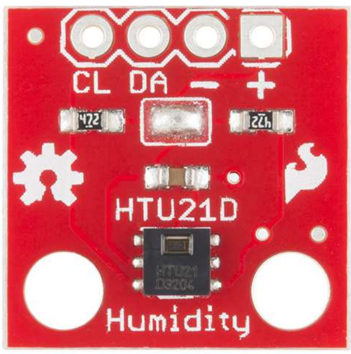


Figure 5.2: Temperature and humidity senor: HTU21D

HTU21D uses TWI (Two Wire Interface) to transfer measured temperature and relative humidity data to Arduino Due board. SDA/SCL ports are reserved for HTU21D in Aruduino Due board.

[4]https://www.sparkfun.com/products/12064

5.3 Wireless Ethernet Connection

In Demand Response, the price signal reflects the status of power grids. When the price of electricity is high, the power grid is stressed due to peak loads. Ethernet connection is required to get the electricity price from Electric Reliability Council of Texas (ERCOT) website. Day Ahead wholesale price of electricity is parsed to get the price data. Ardunio provides WiFi shield to connect Internet via wireless technology. In our research, Arduino WiFi Shield[5] is used and supports IEEE 802.11b/g networks up to 54 Mbit/s (or 6.75 MByte/s) speed. Figure 5.3 presents Arduino WiFi shield.

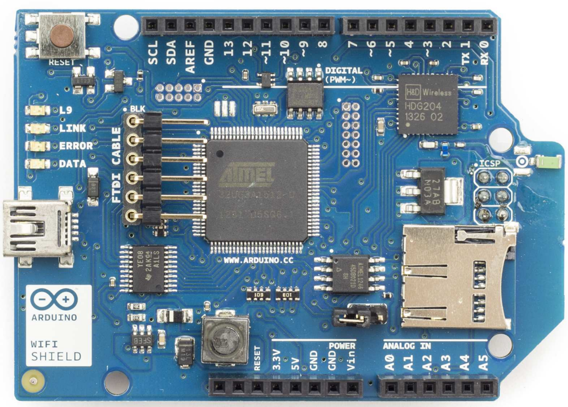


Figure 5.3: WiFi board for Arudino Due micro-controller board

Arduino Due has one SPI (Serial Peripheral Interface) on the board.

[5]`http://arduino.cc/en/Main/ArduinoWiFiShield`, additional accessory boards such as WiFi, Ethernet, and GPS are called to shield.

TFT LCD with touch screen uses SPI port to display information and buttons. So, SPI port must be shared by both TFT LCD and WiFi Shield. Once instruction by WiFi shield on queue, TFT LCD cannot use SPI port until WiFi Shield finishes a job. Therefore, the response time to operate functions such as changing set-point temperature and threshold price is going to be slow. To solve slow response time, two separate Arduino Due boards are used to improve the performance of DDRC.

5.4 Real-Time Clock: DS3231

Our proposed Dynamic Demand Response Controller runs in real-time to control Heating Ventilating and Air Conditioning loads. The price of electricity changes every hour or more often depending on supply and demand of electricity. To perform demand response, Real-Time Clock (RTC) is used to generate clock. DS3231[6] board is connected with Arduino board via TWI. SDA1/SCL1 ports are reserved for RTC. A backup battery is installed to run RTC even if the power to DDRC is cut off. RTC for DDRC is shown in Figure 5.4.

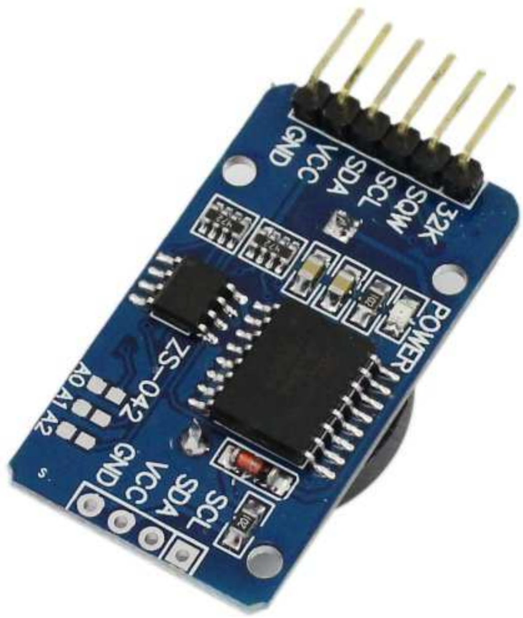


Figure 5.4: Real-Time Clock (RTC): DS3231

[6]http://www.maximintegrated.com/en/products/digital/real-time-clocks/DS3231.html

5.5 DDRC Graphic User Interface

The Dynamic Demand Response Controller (DDRC) uses graphic user interface for easy use. There is no physical button and all functions are designed to work based on touch screen technology. Figure 5.5 illustrates the layout of DDRC main display.

Figure 5.5: Graphic User Interface (GUI) of DDRC

The main display has five sections. The first section is HVAC control functions and located in center. The set-point temperature with C/F unit convertible information is shown on this area. HVAC operation mode buttons are located below the set-point temperature. There are four HVAC modes; cooling, heating, fan only and off. The upper section of the main display shows indoor temperature and humidity by sensing from HTU21D module.

Next, the right side illustrate outdoor temperature and humidity from the weather station. Consumers can set DDRC mode when they want to participate in demand response programs. DDRC is automatically turned on when the threshold price is below the current price of electricity. The normal mode works as a conventional thermostat where the indoor temperature is maintained at the set-point temperature independent of the electricity price. The default mode is DDRC.

The left side of the main display of DDRC presents the current price of electricity and threshold price. Consumers can change threshold price depending on their preferences. The default value of threshold price is \$0.04/kWh. The top line shows the current time and status of WiFi. The setup menu to change the current time and WiFi connection is located on right top corner by clicking a setup icon.

5.6 Assembling modules with Arduino boards

Dynamic Demand Response Controller (DDRC) has several modules to control HVAC system such as a heat pump. The main controller is Arduino Due and visualizes price and environment data on the screen. Demand response control algorithm is also implemented in the main controller. The auxiliary controller is added to receive price data from Electric Reliability Council of Texas (ERCOT) site. The two controllers communicate each other via UART (RX2/TX2 port are allocated).

A power board is installed to supply 15W power for all modules including Arduino boards, sensor, RTC, and relay. 12V input power is supplied to DDRC from wall charger. Arduino boards have been limited to supply up to 5V, 1A. So, WiFi module cannot be combined with 7 inch TFT LCD screen due to lack of power. In addition, three circuit relays to control a heat pump consume more than 150mA to trigger relay. Since DDRC requires more than 5V with 1A, power board is added and supplies 5V, 2A and 3.3V, 1A to all modules

Generally, a heat pump control circuit uses 24V AC system. In other words, Arduino Due board can supply digital signal with 3.3V, 20mA from General Purpose Input Output (GPIO) pins. Three circuits of relays are needed to trigger air conditioner, heater and fan. Each Relay requires high current more than 50mA so that the booster circuit to control from Arudino GPIO pins is designed.

Temperature sensor and real-time clock are installed with the main control board. Radio wireless (433Mhz) module is connected with auxiliary board to receive outdoor weather data from weather station.

Chapter 6

Conclusion

This dissertation describes the methodology to reduce peak loads when the power grid is stressed because of heavy electricity demand. Our research designed the control algorithm of the Dynamic Demand Response Controller (DDRC) and evaluated its performance using a building energy simulation tool. Based on dynamic price of electricity at wholesale electricity markets including Electric Reliability Council of Texas (ERCOT) and PJM Interconnection, demand response signal is generated to reduce the power grid stress.

The controller reduces Heating Ventilating and Air Conditioning (HVAC) loads by demand response. The set-point temperature in DDRC changes by comparing the current electricity price with a threshold price for demand response. Electricity loads during peak period are curtailed, reducing the annual electricity consumption. In respect of energy cost, DDRC brings energy cost savings with dynamic price tariffs in different locations. In addition, we evaluate the indoor thermal comfort based on ASHRAE standard 55 when DDRC changes the set-point temperature during peak time.

In chapter 1, we introduced the background of electricity consumption in residential buildings and general type of HVAC systems for homes. In this chapter, we presented the scope and objective of our research. The proposed Dynamic Demand Response Controller can contribute to decrease electricity loads during peak period in order to increase the power grid efficiency as well as to decrease the stress of the power grid due to heavy demand.

In chapter 2, we presented the modeling of two different size of single family homes using a building energy modeling tools. Based on architectural blueprint, house models are designed using EnergyPlus and OpenStudio. The attributes of building envelopes such as insulation, windows, and basement used International Energy Conservation Code (IECC) 2009 for Climate Zone 2 (Austin, TX) and Climate Zone 5&4 marine (Chicago, IL). The dynamic retail prices of electricity were generated based on the historical wholesale price of electricity in the Electric Reliability Council of Texas (ERCOT) and Pennsylvania, New Jersey, and Maryland (PJM) Interconnection markets. The two different wholesale electricity prices are used to design dynamic retail prices; Day Ahead Price (DAP) and Real-Time Price (RTP).

In chapter 3, we suggested the control policies of the Dynamic Demand Response Controller (DDRC). The DDRC changed the set-point temperature by comparing the current price of electricity price with a threshold price. Two different control algorithms were introduced; the base and improved DDRC control algorithm. The base control policy considered the indoor environment and thermal comfort when the set-point temperature is changed during peak periods. However, it required the linear regression coefficient to convert price/HVAC load to temperature. This coefficient was calculated based on the historical price and weather data in Austin, TX. Therefore, the DDRC with the base control policy is limited to install at homes in Austin, TX. On the other hand, the improved DDRC was designed to deploy in various location and wholesale markets without the limitation. Detailed building information such as the capacity and efficiency of heat pump were considered to change the set-point temperature.

In chapter 4, we illustrated the performance of the Dynamic Demand Response Controller (DDRC). The DDRC with the base control algorithm significantly reduced the peak load by 31% during hot summer. Annual electricity consumption reduction is by 9% and cost savings is 14% with real-time price (RTP) of electricity based tariff. The DDRC provided the energy cost savings up to 10.8% and 4.3% of annual electricity consumption under both RTP and DAP. In addition, the DDRC with improved control policy provided up to 10.8% of energy cost savings with dynamic pricing in two different locations and markets while avoiding significant discomfort due to temperature change. Also, the results present potential for saving considering peak load by 24.7% and total electrical energy saving for HVAC in homes by 4.3% annually. Comparing the base and improved control algorithm, the improved DDRC provided better performance than the DDRC with the base control policy. Regarding annual electricity consumption, the consumption was decreased by 39.5∼55% of more than the base algorithm. The improved DDRC saved 11.1∼13.3% more energy costs.

In chapter 5, we developed the hardware for the Dynamic Demand

Response Controller (DDRC) based on an implemented controller. The control algorithm of DDRC is implemented with an 32 bit ARM micro-controller. DDRC measures indoor and outdoor temperature and relative humidity. In addition, it has the capability to connect to the Internet for getting price data through ERCOT price information site. DDRC can work with general heat pump equipment by relay control. Demand response function is enabled automatically when the current price of electricity is higher than the threshold price.

With regard to future work, we offer the following comments.

- DDRC is developed based on an embedded controller. Generally, a hardware is tested before the deployment using Hardware In the Loop (HIL) technology. The target residential house is modeled using building energy simulation tool, EnergyPlus. DDRC connects a target model to control Heating, Ventilating, and Air Conditioning (HVAC) system via Ethernet socket exchange. Using HIL test method,the hardware of DDRC will be estimate its performance before it is installed in a real house.

- The proposed DDRC will be installed in UTest house[1]. The UTest house is a fully instrumented 1,300ft^2 size manufactured home which is used for education and research in indoor environmental science and engineering. The house has seven building rooms/zones and two heating ventilation

[1] `http://www.caee.utexas.edu/prof/Novoselac/atila_files/Laboratories.html#UTestHouse`

and air-conditioning (HVAC) systems; the first one with ceiling and the second with floor air distribution system. Even though there are several similar test houses in the U.S., none of them is equipped to perform such detailed monitoring of indoor air quality and energy performance. Our DDRC hardware will be evaluate the performance of demand response during summer season when air conditioning loads are heavy due to hot weather.

- The retail shops and small office buildings are also contributors to cause peak loads during summer season due to heavy air conditioner uses. These buildings have similar HVAC system to residential buildings. Multiple heat pumps are used for cooling and heating. Therefore, DDRC is easily retrofitted with their HVAC system for having demand response capability. We will study energy consumption and behaviors of small retails and office building to estimate the performance of the proposed DDRC is not limited to residential buildings.

Appendices

Appendix A

Thermal Comfort on Pychrometric Chart

The indoor environment is important to measure thermal comfort when using Heating, Ventilating, and Air Conditioning (HVAC) equipment such as heat pump, centralized chilled water cooling system, and hot water heating system. The American Society of Refrigerating, Heating, and Air conditioning Engineer (ASHRAE) sets the thermal comfort zone that residents feel comfort when the indoor environment (temperature and humidity) meets ASHRAE Standard 55. The thermal comfort zone is drawn on Pychrometric chart. The vertical axis is the humidity ratio between dry air and water vapor in the air. This ratio can be converted to relative humidity which is usually called RH. Generally, the air is fluid, mixed gas and liquid. The air contains humidity or water vapor. The air with humidity is called to moist air. If the humidity or water vapor does not exist in the air, this air is called dry air. Thus, the moist air is defined as follow below:

$$\text{The moist air} = \text{dry air} + \text{water vapor}$$

The horizontal axis is dry bulb temperature which is generally and widely used in weather forecasting. The blue box is a thermal comfort box for summer season. The red one is for winter.

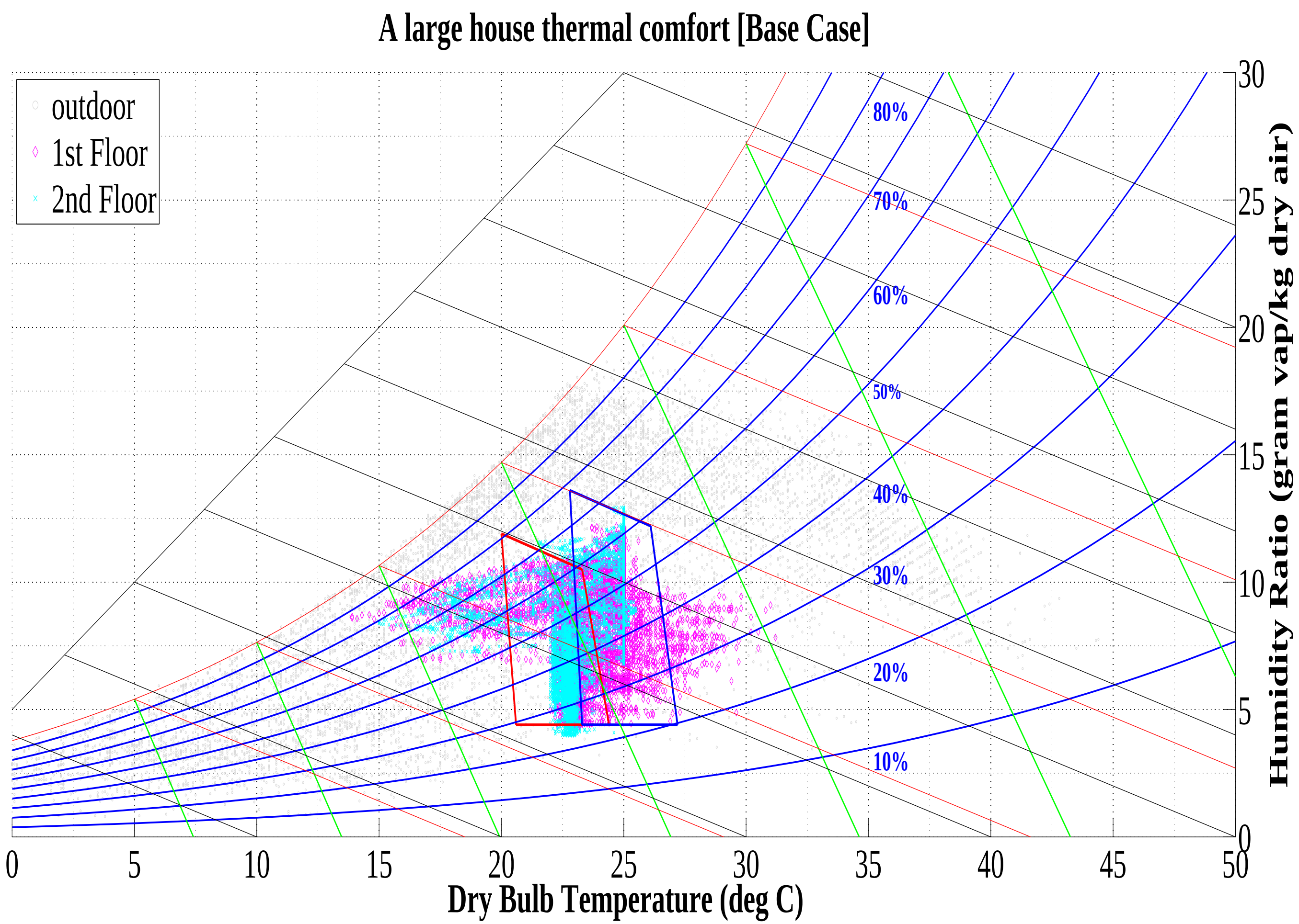


Figure A.1: The indoor environment in a large house with Base Case

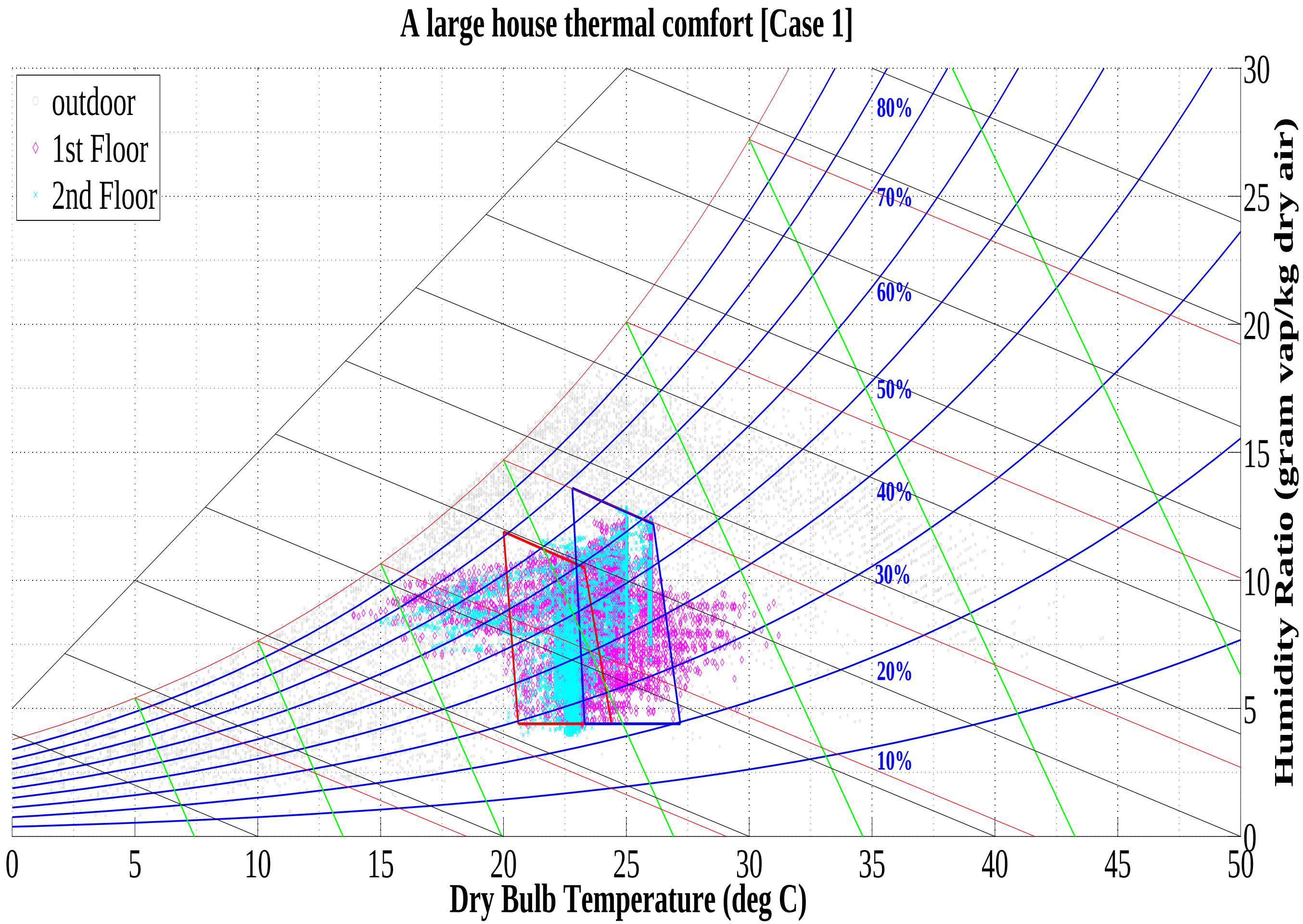


Figure A.2: The indoor environment in a large house with Case 1: Real-Time Price

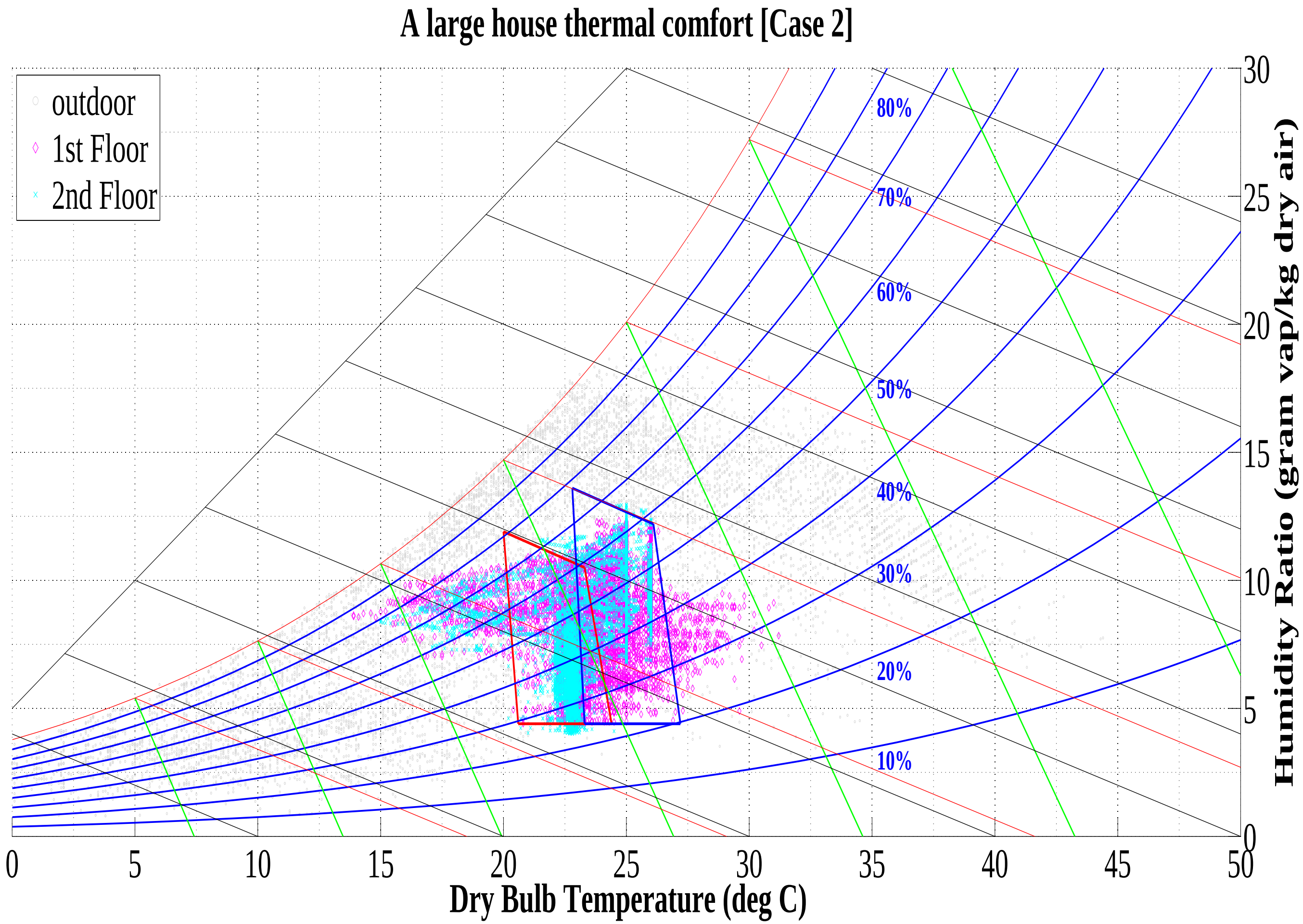


Figure A.3: The indoor environment in a large house with Case 2: Day Ahead Price

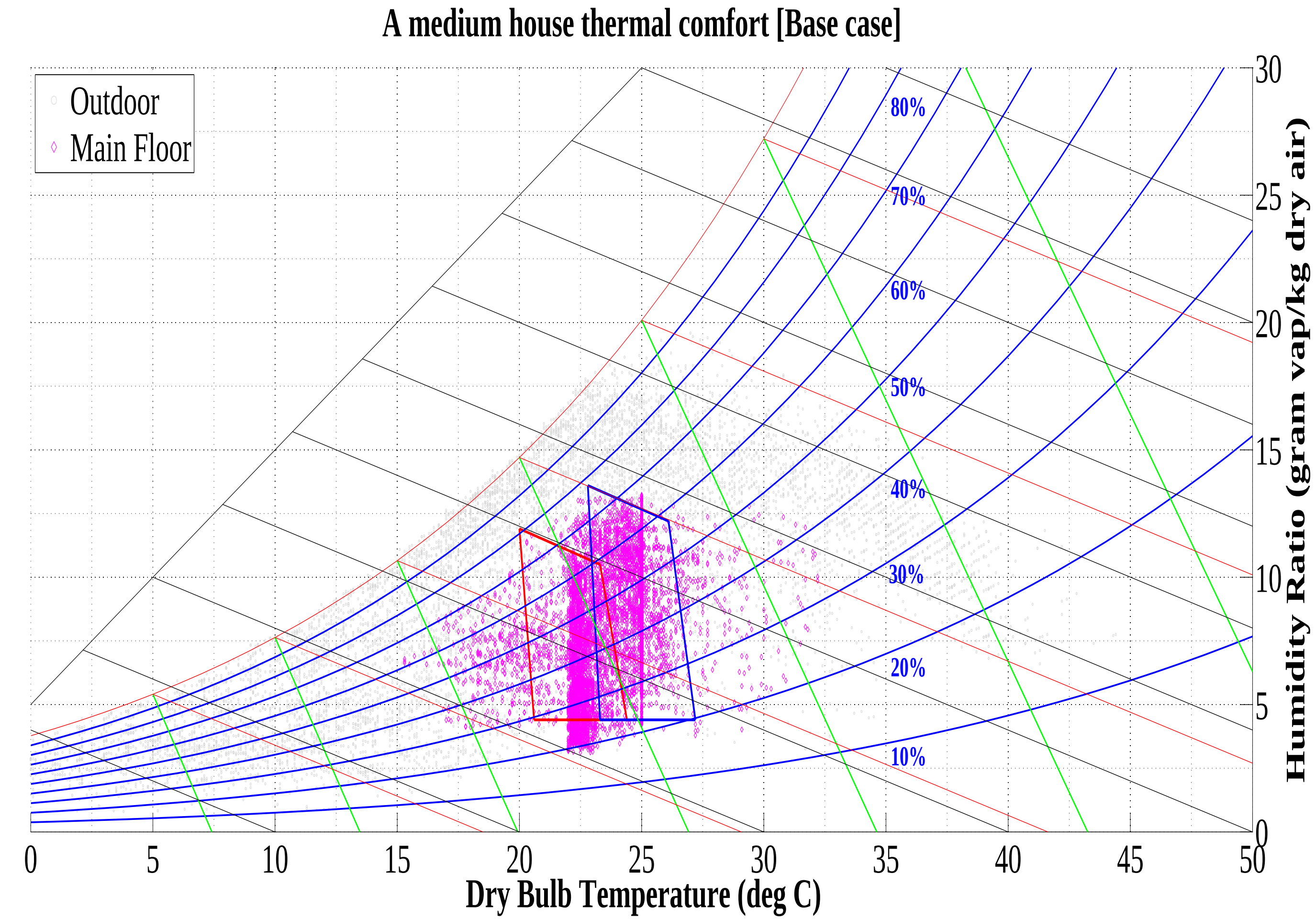


Figure A.4: The indoor environment in a medium house with Base Case

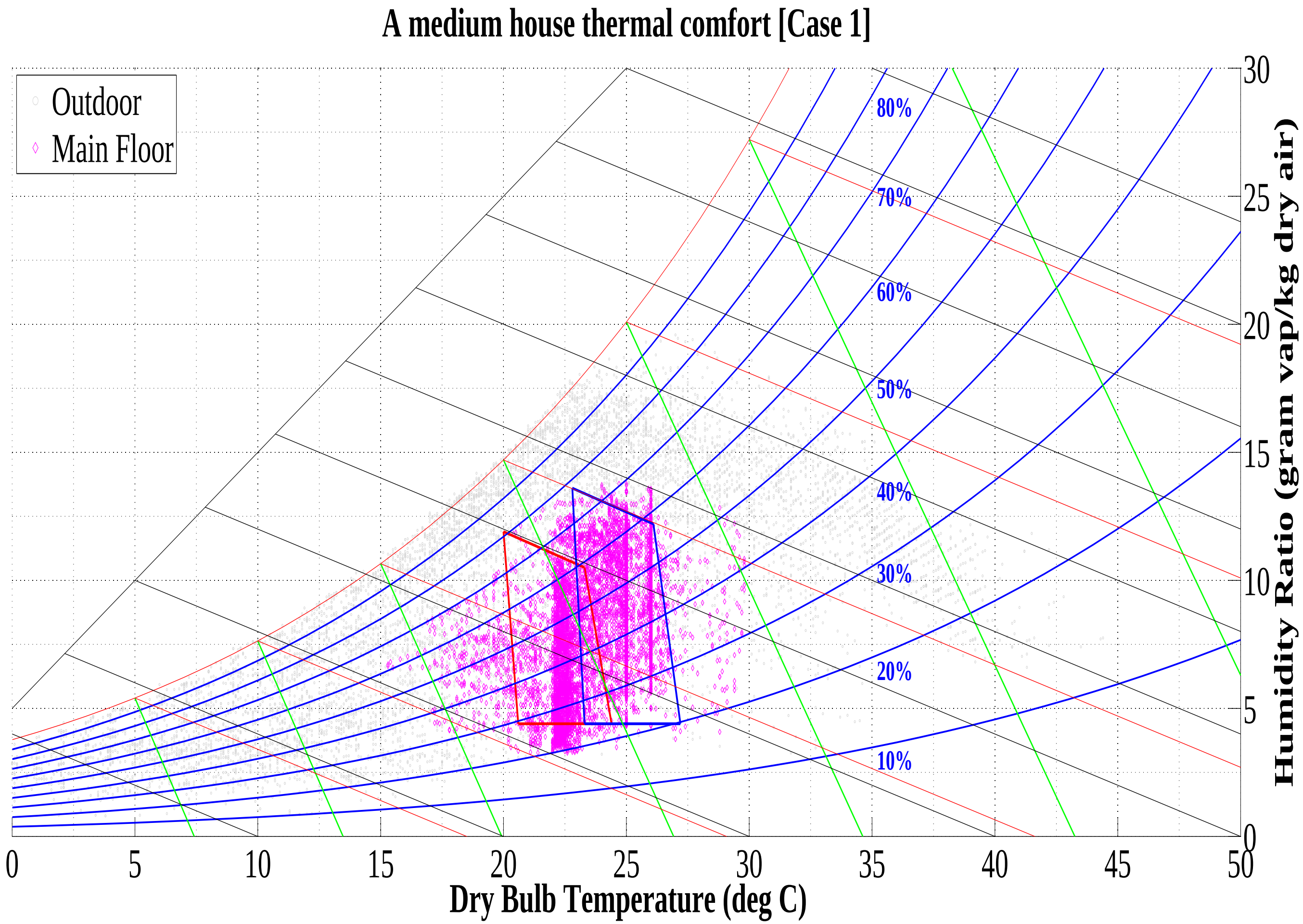


Figure A.5: The indoor environment in a medium house with Case 1: Real-Time Price

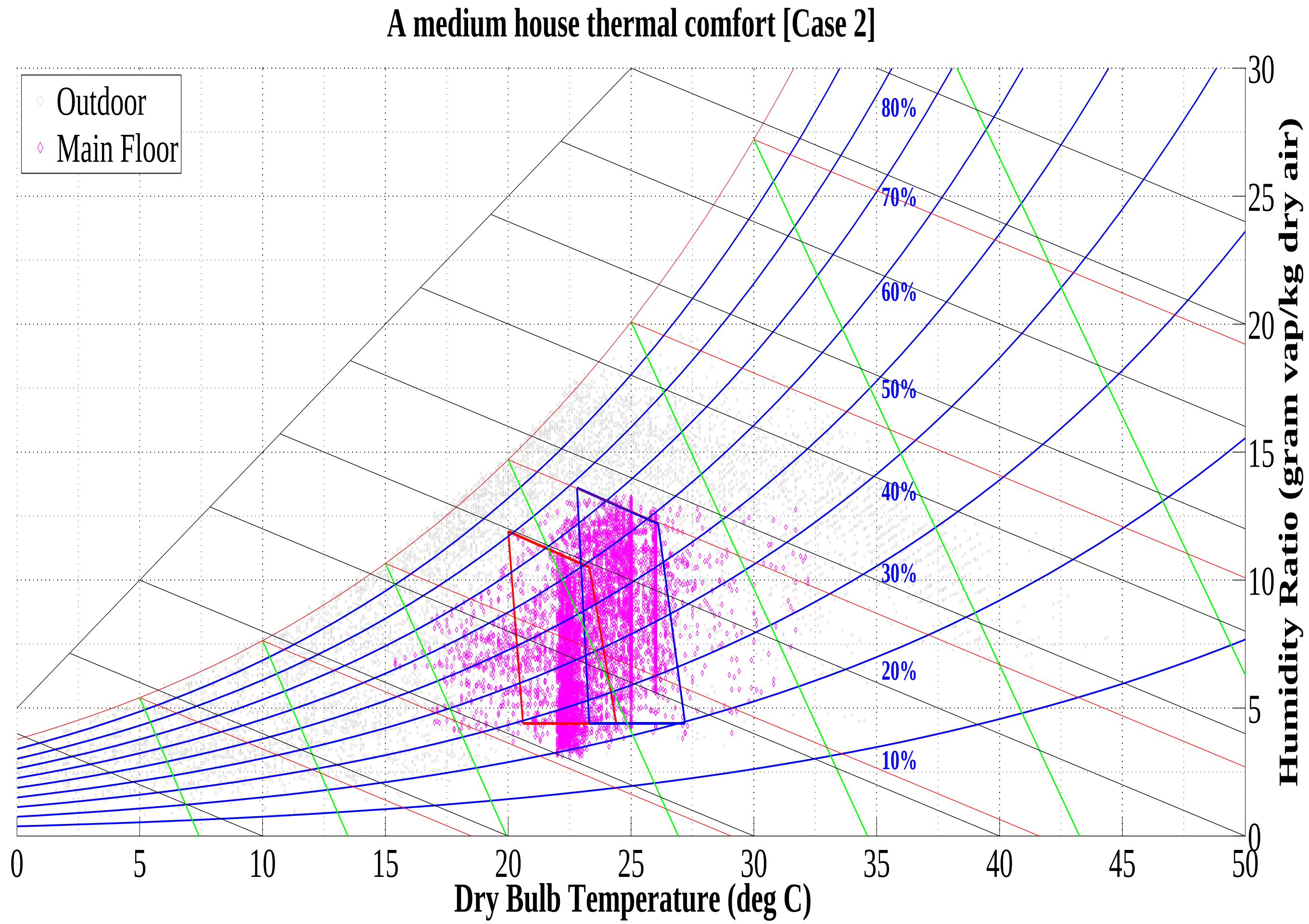


Figure A.6: The indoor environment in a medium house with Case 2: Day Ahead Price

Appendix B

Battery Backup System for residential buildings

The battery backup systems are widely used with Photovoltaic (PV) power generation system as the renewable energy source for residential buildings. PV system consists of three parts; PV panel, inverter, and backup battery. The solar inverter generally has the function to control of batteries with low costs. In this appendix , we suggest the battery backup system using AGM batteries with a solar inverter for DDRC.

B.1 The Layout of Battery Backup System

DDRC controls the battery backup system depending on the dynamic price of electricity. When peak load is occurred, DDRC sets the battery mode to discharge for supplying power to residential building. The batteries are charged during the night time when the electricity price is low. The battery backup system is not connected with utility's grid. So, the electrical power from batteries is consumed at residential buildings. In order to reduce the initial investment cost, the capacity of batteries is designed to supply the power during peak hours only. Figure B.1 shows the layout of the battery backup system for DDRC.

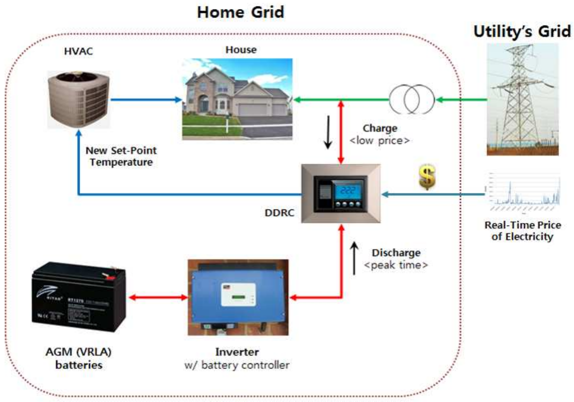


Figure B.1: The layout of the battery backup system for DDRC

The battery type is Absorbed Glass Mat (AGM) battery and its capacity is 1,500Wh. Due to life cycle of the battery, Depth of Discharge (DoD) is set to 50% with 600 battery cycle. The electric power that can use from the battery is limited to 750Wh due to DoD. Therefore, two AGM batteries are used to supply electricity during peak period and connected in parallel to supply 1,500Wh.

Figure B.2: Absorbed Glass Mat (AGM) battery

The solar inverter that has the battery charge and discharge function are chosen. To charge batteries with total 1,500Wh capacity, the inverter output is 1,500W. The inverter supplies the electric power to distribution circuit at a residential building. So, the stored electricity in batteries are not sent to power grid during off-peak. This electric power is reserved for peak time.

Figure B.3: The inverter with the battery charge and discharge function

B.2 Economics on the Battery System

The battery system for DDRC is designed low cost system to assistant the performance of DDRC. The initial investment and battery replacement for maintenance are very important for end users. The solar inverter under 2,000Wh capacity is under $1,000 nowadays [90]. The unit cost of AGM battery with 1,5000Wh is about $285 [91]. We assume that the batteries discharges with 150 cycle at 50% of DoD. Two batteries are needed to replace every 4 years. The life span of an inverter is generally 16 years. During the life span of an inverter, eight batteries are used to supply the electric power for peak time. The initial investment cost of the battery backup system for DDRC is about $3,200 for sixteen year use. The extra costs such as administration or installation fees are expected 10% of the initial investment. The estimated total cost for the battery backup system is $3,600. When DDRC saves the energy cost over $225 per year, the installation cost for the battery backup system will be payback with 16 year use. Table B.1 presents the specification and costs of the battery backup system during the inverter life span.

Table B.1: The estimate cost of the battery backup system for 16 year use

Battery

Type	Voltage [V]	Current [Ah]	Rated Energy [kWh]	Quantity [EA]	Unit Cost [$]
AGM	12	125	1.5	8	285

Inverter

Type	Voltage [V]	Current [A]	Rated Power [kW]	Quantity [EA]	Unit Cost [$]
Solar	120	16	1.5	1	850

Total Costs [$]

Battery	Inverter	Other fees	Total	Cost / yr
2,280 (x8)	850	470	3,600	225

Appendix C

Case Study: Demand Response Experiences with Utilities

Demand response (DR) programs are served in some utilities in the United States. Their DR programs used the electricity wholesale market price or the generation costs to design real-time price. In this appendix, we introduced the experiences of DR program from several utilities in different locations.

C.1 Gulf Power

Gulf Power is subsidiary of Southern Company and covers Northwest Florida. Its service territory is shown in Figure C.1.

C.1.1 DR Program - Energy Select

Energy Select is residential service with variable pricing (RSVP). It has FOUR tiers; low (off-peak), medium (partial-peak), high (on-peak), and critical prices (emergency). When the special event is occurred (ex. emergent peak), the critical price is served. For the normal operation, the critical price is NOT included on the price period. These prices are decided depending on

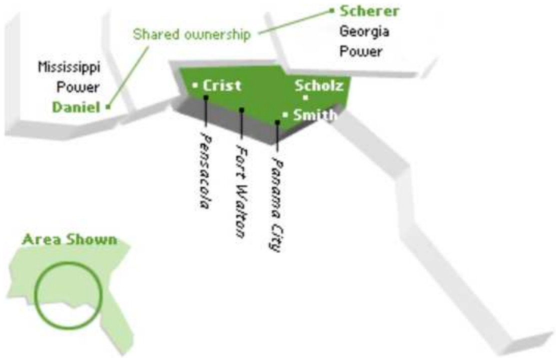


Figure C.1: Gulf Power Service Territory

the power generation cost based on day ahead. This residential tariff is time constrained rate. During the certain point of times, the price is fixed. So, this tariff is very similar to Time of Use (TOU) from Pacific Gas and Electric (PG&E) but the price rate in Energy Select is changed. Figure C.2 presents price period of RSVP for summer and winter season.

The average prices for each tiers as shown below;

<Four price tiers>

Tier 1: low price (Off-Peak) ≈ \$0.079 / kWh

Tier 2: medium price (Partial-Peak) ≈ \$0.092 / kWh

Tier 3: high price (On-Peak) ≈ \$0.169 / kWh

Tier 4: critical price (Emergent Event) ≈ \$0.696 / kWh

The percent of hours that each tier price is provided for a year is display in Figure 3. Most of hours (87% of total hours), the current price maintained under \$0.1/kWh. High and critical prices when DR requested were about 13%.

Figure C.2: Price Period for Residential Service with Variable Pricing (RSVP)

C.1.2 Number of Customers with Energy Select

Until August 15th, 2012, there are about 10,600 customers with Energy Select program.

C.1.3 Results with Energy Select

Energy Select tariff contributed to reduce 12 $\sim$ 15% of annual power consumption. Also, Gulf Power mentioned about 1.7 $\sim$ 1.8kW peak load demand reduction for summer and 2.5 $\sim$ 3kW for winter. However, there was no information that how to measure the peak demand during certain interval. If the interval is an hour, the power curtailment is very severe.

C.1.4 Load Control

Energy Select provides options to control HVAC, electric water heater, pool pump, and appliances. All customers with Energy Select must have the customized thermostat with this program in free. Customers set the schedules to do action when the current price is high or critical prices. The set-point temperature is changed by the customers preferences based on the tier. For example, a customer set the thermostat that the set-point temperature is changed from 78°F to 86°F when the current price is the critical price. This is manual setting and no graduate temperature change. To change the set-point temperature, the preference based on the tier is only considered. Building envelop, characteristics of HVAC system, and indoor environment are not influenced to change the set-point temperature. Thermostat manufacturer is Comverge. Figure C.3 illustrates the thermostat for Energy Select.

Figure C.3: Thermostat for Energy Select

C.2 Commonwealth Edison

Commonwealth Edison is subsidiary of Exelon Corporation and covers Chicago and West Chicago Area include Naperville, Illinois. Its service territory is shown in Figure C.4.

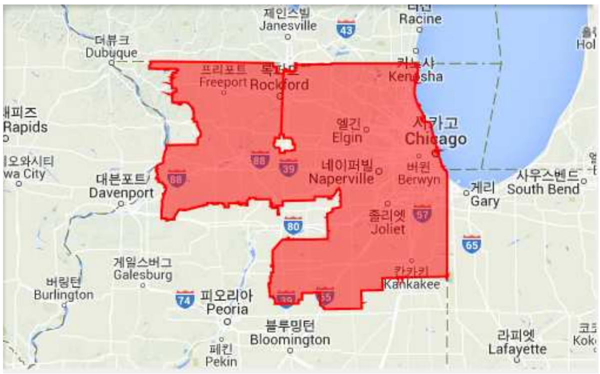


Figure C.4: Commonwealth Edison Service Territory in Chicago area

C.2.1 DR Program - Smart Return

Commonwealth Edison (ComEd) introduced Smart Returns program since 1996. Smart Return has four specific programs.

(a) Voluntary Load Response (VLR)

- Nonresidential customer (C&I Commercial and Industry)
- Minimum reduction is 10kW
- $0.15/kWh incentive for load reduction
- No firm commitments and noncompliance penalties

(b) Early Advantage

- C&I customer
- Minimum reduction is 1MW
- Large incentive during high price or emergency events

(c) The Alliance and Energy Cooperative

- Customers who are taking service under rate 6L or 6T
- More frequent load reduction request
- Substantial incentive payment

C.2.2 Real-Time Price (RTP)

ComEd used Hourly Energy Pricing (HEP) in RTP tariff. Two pricings are peak price and off-peak price. RTP is announced by 7 pm of the previous day on ComEd website.

(a) Peak Price

: Used two year historical data of real-time hourly PJM West price to generate day-ahead hourly peak price.

(b) Off-Peak Price

: Used daily transaction data of the day-ahead spot market for off-peak prices to calculate an average of daily transaction midpoints for the preceding month.

C.2.3 Number of Customers

About 40 of the 350 eligible customers took und HEP tariff in 2004.

C.3 Cincinnati Gas & Electric

Cincinnati Gas & Electric was merged to Duke Energy. Now, Duke Energy covers City of Cincinnati and around Cincinnati, Ohio. Its service territory is illustrated in Figure C.5.

Figure C.5: Cincinnati Gas & Electric Service Territory in Cincinnati, Ohio

C.3.1 DR Programs - PowerShare

Cincinnati Gas & Electric (CGE) provided voluntary RTP program based on day-ahead price. However, Public Utility Commission (PUC) of Ohio approved fixed price rate based on the cost of generation instead of RTP. Therefore, CGE provided fixed rate DR programs to C&I customers.

- Voluntary program since 1996

- PowerShare: incentive based demand response

(a) Call Option

: Higher incentive payment with firm commitments and penalties for nonperformance

(b) Quote Option

: Completely voluntary, no firm commitments and lower incentives

- PUC Ohio (PUCO) approved one-part RTP tariff

: The on-part tariff with a price floor equal the generation rates in the fixed-prince default service. (Dispatch cost of the highest cost generation unit/purchased power to serve CG&Es load)

C.3.2 Number of Customers

About 140 customers in 2004.

C.4 Portland General Electric

Portland General Electric (PGE) mostly covers City of Portland, Oregon. Its service territory is presented in Figure C.6.

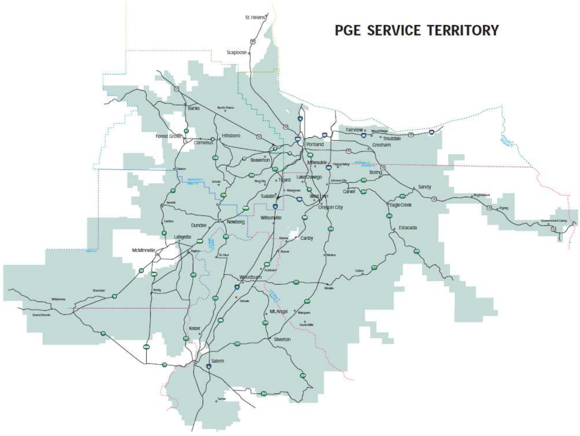


Figure C.6: Portland General Electric Service Territory in Portland, Oregon

C.4.1 DR Programs

In 2004, Portland General Electric (PGE) provided DR programs to non-residential customer without load demand size.

(a) Demand Buyback

: Customers pay market-based price for curtailing when called

(b) Longer-term Buybacks

: A few customers paid to reduce their electricity usage over several months in 2001

(c) Blackout Protection

: Customers can avoid rotating outage by curtailing 15% of their load when called

(d) Dispatchable Standby Generation

For residential customers, Time of Use (TOU) rates is offered. Also, direct load controls of residential electric water heater and spacing heating were tested.

C.4.2 Real-Time Price

Daily rate of RTP is based on the Dow Johnson Mid-C (hub) Daily on an off peak electricity firm indenx (DJ Mid-C Firm Index) for the previous day with the Customer Baseline Load (CBL). A CBL is derived based on each customers historical usage.

C.4.3 Number of Customers

None in 2004

C.5 Duquesne Light Company

Duquesne Light Company mostly covers City of Pittsburgh, Pennsylvania. Its service territory is shown in Figure C.7.

C.5.1 DR Program

Duquesne Light Company (DLC) provided two different voluntary DR programs.

Figure C.7: Duquesne Light Company Service Territory in Pittsburgh, Pennsylvania

(a) Energy Exchange

: For large commercial and industry customers (C&I)

(b) Direct Load Control Pilot Program

: For residential and commercial customers to control central AC system

C.5.2 Real-Time Price

DLC used RTP for Energy Exchange program

• For C&I customers, and minimum load is 300kW

• One part RTP tariff used real-time Pennsylvania-New Jersey-Maryland

(PJM) Locational Marginal Price (LMP) based on the PJM daily capacity market

C.5.3 Number of Customers

59 customers took RTP tariff in April, 2005.

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