An Approach to Mitigate Electric Vehicle Penetration Challenges through Demand Response, Solar Photovoltaics and Energy Storage Applications in Commercial Buildings

Fakeha Sehar

Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Electrical Engineering

Rahman, Saifur
Pipattanasomporn, Manisa
Broadwater, Robert P.
Silva, Luiz A
Ghandforoush, Parviz

May 10th, 2017
Arlington, Virginia

Key Words: Smart Grid, Demand Response, Commercial Buildings, Electric Vehicles, Photovoltaics, Distribution Network, Ice storage

An Approach to Mitigate Electric Vehicle Penetration Challenges through Demand Response, Solar Photovoltaics and Energy Storage Applications in Commercial Buildings

Fakeha Sehar

Abstract (academic)

Electric Vehicles (EVs) are active loads as they increase the demand for electricity and introduce several challenges to electrical distribution feeders during charging. Demand Response (DR) or performing load control in commercial buildings along with the deployment of solar photovoltaic (PV) and ice storage systems at the building level can improve the efficiency of electricity grids and mitigate expensive peak demand/energy charges for buildings. This research aims to provide such a solution to make EV penetration transparent to the grid.

Firstly, this research contributes to the development of an integrated control of major loads, i.e., Heating Ventilation and Air Conditioning (HVAC), lighting and plug loads while maintaining occupant environmental preferences in small- and medium-sized commercial buildings which are an untapped DR resource. Secondly, this research contributes to improvement in functionalities of EnergyPlus by incorporating a 1-minute resolution data set at the individual plug load level. The research evaluates total building power consumption performance taking into account interactions among lighting, plug load, HVAC and control systems in a realistic manner.

Third, this research presents a model to study integrated control of PV and ice storage on improving building operation in demand responsive buildings. The research presents the impact of deploying various combinations of PV and ice storage to generate additional benefits, including clean energy generation from PV and valley filling from ice storage, in commercial buildings.

Fourth, this research presents a coordinated load control strategy, among participating commercial buildings in a distribution feeder to optimally control buildings' major loads without sacrificing

occupant comfort and ice storage discharge, along with strategically deployed PV to absorb EV penetration. Demand responsive commercial building load profiles and field recorded EV charging profiles have been added to a real world distribution circuit to analyze the effects of EV penetration, together with real-world PV output profiles. Instead of focusing on individual building's economic benefits, the developed approach considers both technical and economic benefits of the whole distribution feeder, including maintaining distribution-level load factor within acceptable ranges and reducing feeder losses.

An Approach to Mitigate Electric Vehicle Penetration Challenges through Demand Response, Solar Photovoltaics and Energy Storage Applications in Commercial Buildings

Fakeha Sehar

Abstract (General Audience)

Utilities generally meet peak demand through expensive peaking units which are operated only for short periods of time. At the same time the growing demand for Electric Vehicles (EVs) in the U.S. impacts the already burdened distribution feeder during peak hours. EVs are active loads as they increase the distribution feeder's demand when charging. EV charging may bring about several challenges to the distribution feeder, including reduced load factors, potential transformer overloads, feeder congestion and violation of statutory voltage limits.

On the other hand, building owners want to make buildings demand responsive so that they can participate in a demand response program offered by a regional electric grid operator to earn additional revenues. Allowing buildings to be demand-responsive by controlling buildings' major loads, including HVAC (Heating, Ventilation and Air Conditioning), lighting and plug loads based on demand reduction signals from the grid has proven to provide tremendous savings. Additionally, optimized peak demand reductions at the building level by means of coordinated control of building loads, solar photovoltaic (PV) and ice storage systems can play a major role in flattening the building load shape, thereby decreasing its peak electricity consumption and at the same time mitigating grid stress conditions when needed.

This study discusses the impacts of EV charging on a distribution feeder serving demand responsive commercial customers and develops a mitigation strategy to make EV penetration transparent to the grid. The mitigation strategy relies on coordinated control of major loads in demand responsive commercial buildings, ice storage discharge, along with strategically deployed PV. The analysis presented in this study shows that the developed approach can help mitigate EV penetration challenges by reducing the peak distribution system load, reducing feeder losses and improving distribution system load factor.

Dedication

Dedicated to my family and friends.

Acknowledgement

I pay my utmost gratitude to Allah for his grace and blessings.

It has been a very long journey… a lot of hard work and dedication!

It would not have been possible without the support Prof. Saifur Rahman, my academic advisor, has extended to me at every stage during my tenure at ARI. He set tough benchmarks, which I strived to meet. He provided an excellent research atmosphere. He gave me the opportunity to develop my own individuality and self-sufficiency by being allowed to work independently. I got an opportunity to work on different types of projects which allowed me to gain wider breadth of experience while still a graduate student.

I would like to thank Dr. Manisa Pipattanasomporn for her guidance, understanding, patience, and most importantly, her friendship during my graduate studies at ARI. She sees in her students not what they are but what they can become. I am very thankful for her meaningful inputs, valuable discussions and accessibility. Her keen scientific insight has contributed towards my rewarding graduate experience. She gave me intellectual freedom in my work, engaged me in new ideas, supported my attendance to seminars and conferences, and demanded a very high quality of work in all my endeavors.

I express my sincere thanks to Dr. Broadwater and his student Kaveh for their training on DEW. They were always available to help me in any way. I am very thankful to Dominion Power for providing the real-world EV charge profiles for my research, making it more meaningful and answering patiently to a lot of my queries. I am grateful to National Science Foundation, who funded my PhD research. I would like to thank Dr. Robert Broadwater, Dr. Luiz D. Silva and Dr. Parviz Ghandforoush for serving on my committee.

I would like to thank various members of ARI's research group. Yonael, thanks not only for the IT support but also for your warm friendship. You have a very caring personality which I have experienced occasionally. I don't know what we'll do without you! I am thankful to Dr. Murat, who has the ability for solving seemingly intractable practical difficulties, with whom I worked for a short time but it was a great learning experience. I am very grateful for the friendship of Sneha, Avijit, Desong, Waradom, Shibani and Hamideh – Thanks Guys!

Lastly, I express my deep love and affection for my family and friends, without whom I wouldn't be where I am today! I would like to thank my husband. His support, encouragement, quiet patience and unwavering love has kept me strong for the last eight years. At difficult times he would always assure me of his support and encourage me not to give up. My kiddo, who showed remarkable patience at times when I had a lot of work load or was under stress. I thank my parents, for allowing me to be as ambitious as I wanted. They raised me with a love of science and supported me in all my pursuits. It was under their watchful eye that I gained so much drive and an ability to tackle life's challenges head on. Also, I thank my husband's parents for their encouragement and constant prayers. I thank my elder sister, who herself had gone through the same phase, for providing me with unending encouragement and support. She was always there to guide me when I had tough times or couldn't figure out how to best solve an issue. She kept me motivated throughout my PhD. My brother and younger sister for their encouragement.

Table of Contents

1 Introduction ... 1
1.1 Background ... 1
1.2 Objectives and Scope of the Dissertation ... 4
1.3 Contributions ... 8
1.3.1 An approach to improve the distribution feeder's performance with EV penetration through coordinated control of demand responsive commercial buildings, ice storage and PV ... 8
1.3.2 An integrated control for commercial building DR applications that can evaluate DR potential for commercial buildings by load type ... 8
1.3.3 Development of dynamic plug load models integrated with EnergyPlus ... 9
1.3.4 Development of real-world EV models integrated with EnergyPlus ... 9
1.3.5 An approach for integrated automation of ice storage and PV in demand responsive commercial buildings ... 10
2 Literature Search ... 11
2.1 EV Penetration in Electric Distribution Feeders ... 11
2.1.1 EV overview ... 11
2.1.2 EV charging infrastructure ... 12
2.1.3 EV models discussed in literature ... 14
2.1.4 Non-residential EV charging ... 15
2.1.5 EV charging strategies ... 17
2.1.6 Impacts of EV charging on the electric distribution system ... 18
2.2 Demand Response (DR) or Load Control Strategies in Commercial Buildings ... 20
2.2.1 DR- definition and types ... 20
2.2.2 Barriers to DR ... 21
2.2.3 Potential role of DR ... 22
2.2.4 DR strategies for commercial buildings ... 23
2.2.5 Lighting, HVAC and plug loads DR strategies in commercial buildings ... 24
2.3 Synergy among DR, Renewable and Storage Energy Systems to absorb EV penetration ... 29
2.3.1 Photovoltaic (PV) systems in commercial buildings ... 29
2.3.2 Ice storage systems in commercial buildings ... 30
2.3.3 Synergy among DR, renewable and energy storage systems ... 32

2.4 Knowledge Gaps ... 34
2.4.1 Design an approach to improve the distribution feeder's performance with EV penetration through coordinated control of demand responsive commercial buildings, ice storage and PV 34
2.4.2 Design an integrated control for commercial building DR applications that can evaluate DR potential for commercial buildings by load type ... 35
2.4.3 Dynamic plug load modeling in building energy simulation tools ... 36
2.4.4 Real-world EV models ... 36
2.4.5 Design an integrated automation of ice storage and PV in demand responsive commercial buildings ... 37
3 Methodology ... 38
3.1 EV Absorption Strategy for the Distribution Feeder ... 38
3.1.1 Strategy to decide level of participation from each demand responsive building ... 39
3.1.2 Load control strategies in commercial buildings ... 41
3.1.3 Strategy for Ice Storage Charge/Discharge Control ... 49
3.2 Simulation Tools used in the Study ... 50
3.2.1 EnergyPlus – Building Energy Modeling and Simulation Tool ... 50
3.2.2 Distribution Engineering Workstation (DEW) - Distribution Feeder Modeling and Analysis Tool ... 51
3.3 Electric Distribution Feeder Model in DEW ... 52
3.4 Commercial Building Models in EnergyPlus ... 53
3.4.1 Small-sized office building model input assumptions ... 54
3.4.2 Medium-sized office building model input assumptions ... 56
3.4.3 Standalone retail building model input assumptions ... 60
3.5 Plug Load Models for Office Buildings ... 62
3.5.1 Beverage vending machines ... 63
3.5.2 Fax machines ... 64
3.5.3 Server computers ... 65
3.5.4 Desktop computers ... 65
3.5.5 Laptop computers ... 66
3.5.6 Liquid Crystal Display (LCD) monitors ... 68
3.5.7 Laser printer ... 69
3.5.8 Copy machine ... 70
3.5.9 Water cooler ... 72

3.5.10 Refrigerator 72
3.5.11 Coffee maker 73
3.5.12 Portable fan 74
3.5.13 Miscellaneous appliances 75
3.6 Integrating the demand responsive commercial buildings to the distribution feeder 75
3.7 PV Models in EnergyPlus and DEW Software 77
3.7.1 PV model in EnergyPlus 77
3.7.2 PV model in DEW 81
3.8 Ice Storage Model in EnergyPlus 81
3.8.1 Ice storage model description 82
3.8.2 Ice storage system size 82
3.8.3 Ice storage system control 83
3.9 EV Models in EnergyPlus 83
3.9.1 Measured EV charge profiles used for modeling EVs as active loads 84
3.9.2 Control of EV charging 85
4 Simulation Results and Discussions 86
4.1 Case study: Distribution feeder load control strategy for EV absorption 86
4.2 Case study: Building level load control (DR) strategy 91
4.2.1 Building end-use loads profile 92
4.2.2 Rooftop PV system potential 92
4.2.3 Ice storage system potential 93
4.2.4 End-use loads control (DR) potential 95
4.2.5 PV, ice storage and DR potential 97
4.3 Sensitivity Analysis 102
5 Conclusions and Future Work 104
6 References 107

List of Figures

Figure 1 Distribution feeder’s excess load due to EV penetration 38

Figure 2 EV absorption strategy for the distribution feeder 39

Figure 3 Distribution feeder model used in this study modeled in DEW software 52

Figure 4 Outdoor dry-bulb temperature for a summer day used in this study 54

Figure 5 Axonometric view of the small-sized office building used in this study [217] 55

Figure 6 Small-sized office building typical weekday schedule used in this study 55

Figure 7 HVAC zoning for small-sized office building used in this study [217] 56

Figure 8 Axonometric view of the medium-sized office building used in this study [215] 57

Figure 9 Medium-sized office building typical weekday schedule used in this study 58

Figure 10 HVAC zoning for medium-sized office building used in this study [215] 58

Figure 11 Axonometric view of the standalone retail building used in this study 60

Figure 12 Standalone retail building typical weekday schedule used in this study 61

Figure 13 HVAC zoning for standalone retail building used in this study 61

Figure 14 Beverage vending machine model 1 weekday power consumption profile used in this study... 63

Figure 15 Beverage vending machine model 2 weekday power consumption profile used in this study... 64

Figure 16 Fax machine weekday power consumption profile used in this study 65

Figure 17 Desktop computer weekday power consumption profile used in this study 66

Figure 18 Laptop computer measured power consumption 67

Figure 19 Laptop computer weekday power consumption profile used in this study 68

Figure 20 LCD monitors weekday power consumption profile used in this study 69

Figure 21 Laser printer measured power consumption 70

Figure 22 Laser printers weekday power consumption profile used in this study 70

Figure 23 Copy machines measured power consumption profile 71

Figure 24 Copy machines weekday power consumption profile used in this study 71

Figure 25 Water cooler weekday power consumption profile used in this study 72

Figure 26 Refrigerator weekday power consumption profile used in this study 73

Figure 27 Coffee maker measured power consumption 74

Figure 28 Coffee maker weekday power consumption profile used in this study 74

Figure 29 Miscellaneous equipment weekday schedule used in this study 75

Figure 30 Scaled down power consumption profiles for the commercial buildings used in this study for a summer day 76

Figure 31 Axonometric view of the simulated medium-sized office building with installed PV panels.... 79

Figure 32 Scaled down building power consumption profiles with EV charging used in this study 85
Figure 33 Distribution feeder's load profiles with and without EV penetration.. 86
Figure 34 Distribution feeder's load profiles without EV and with EV plus load control and ice storage discharge 88
Figure 35 PV profiles for the demand responsive commercial buildings used in this study 89
Figure 36 Distribution feeder's load profiles without EV, with EV, load control, ice storage discharge and PV 89
Figure 37 Power consumption of major end-use loads for the simulated medium-sized office building for the simulation day 92
Figure 38 Power generated by PV and purchased from utility for the simulated building for the simulation day 93
Figure 39 Simulated building power consumption profiles with and without ice storage for the simulation day 94
Figure 40 Simulated building's HVAC power consumption profiles with and without ice storage for the simulation day 94
Figure 41 Simulated building power consumption profiles with and without end-use loads control by EMS for the simulation day 95
Figure 42 Simulated building's HVAC power consumption profiles with and without end-use loads control by EMS for the simulation day 96
Figure 43 Simulated building power consumption profiles with combinations of PV, full ice storage and DR for the simulation day 98
Figure 44 Simulated building surplus PV power generation for Case 5a for the simulation day 99
Figure 45 Simulated building's HVAC power consumption profiles with combinations of PV, full ice storage and DR for the simulation day 99
Figure 46 Simulated building power consumption profiles with combinations of PV, partial ice storage and DR for the simulation day 100
Figure 47 Simulated building's HVAC power consumption profiles with and without PV, partial ice storage and DR for the simulation day 100

List of Tables

Table 1 SAE charging configurations 13

Table 2 Electric range and power consumption of different EVs 13

Table 3 HVAC DR strategies 24

Table 4 Lighting DR strategies 26

Table 5 Designated zone priorities for control of lighting and HVAC in retail buildings 48

Table 6 Control of lighting and HVAC based on zones' priorities in retail buildings 49

Table 7 Plug load equipment inventory for the small-sized office building used in this study 56

Table 8 Plug load equipment inventory for the medium-sized office building used in this study 59

Table 9 Radiant and convective heat gain from office equipment [219, 221] 60

Table 10 Standalone retail building occupant, lighting and plug load densities 62

Table 11 Fax machines modes of operation used in this study 64

Table 12 Desktop computers modes of operation used in this study 66

Table 13 Laptop computers modes of operation used in this study 67

Table 14 Monitors modes of operation used in this study 68

Table 15 Demand Responsive Buildings Peak Demand 76

Table 16 Inverter efficiencies at nominal input voltage and percentage of rated power 80

Table 17 EV Charge Stations for Demand Responsive Buildings 84

Table 18 Demand Responsive Buildings Peak Demand with and without EV 85

Table 19 Demand Responsive Buildings Participation 87

Table 20 Summary of distribution feeder's peak loads, load factors and losses without EV, with EV, load control and PV 90

Table 21 Peak load savings and energy consumption with full and partial ice storage 95

Table 22 Peak load and energy savings for simulated building with and without end-use loads control by EMS for the simulation day 97

Table 23 Peak load savings and energy consumption with various combinations of DR, PV and ice storage 102

Table 24 Sensitivity Analysis considering Different Percent of Buildings with EV Charge Stations 103

1 Introduction

1.1 Background

Utilities meet peak demand through more expensive peaking units which are operated only for short periods of time. At the same time the growing demand for Electric Vehicles (EVs) in the U.S. due to technical advancements and environmental concerns impacts the already burdened distribution feeder during peak hours [1]. EVs are active loads as they increase the distribution feeder's demand during charging. Along with residential plug-in electric vehicle charging, the public charging infrastructure coupled with fast charging is much needed to reduce EVs range anxiety and foster their adoption. Depending on EV penetration, EV can result in negative impacts on an electrical grid [2]. As opposed to Alternating Current (AC) Level 1 charging (rated at 120V [3]), AC Level 2 charging (rated at 208/240V [3]) can quickly increase peak electrical demand [4]. Direct Current (DC) fast charge (with a typical 208/480V AC three-phase input [3]) on the other hand can quickly overload the local distribution circuit. Additionally, EV charging tends to increase transformer losses, voltage deviations, harmonic distortion, peak load and thermal loading on a distribution system [5]. Studies [6, 7] demonstrate that controlled EV charging can improve the distribution feeder's voltage profile and reduce the power losses. However, controlled EV charging delays EV charging to night time which could prevent distribution assets, such as transformers from cooling down overnight, reducing their lifetime [8]. Also at the end of controlled charging some EVs may not have been charged to the desired State of Charge (SOC) level [9]. An expensive way to manage such an impact is to reinforce the grid's infrastructure. However, instead of investing in the electricity infrastructure, impacts of EV charging can be mitigated by exploiting the synergy among EV charging, renewable generation and Demand Response (DR) [10]. Renewable energy and DR programs are considered viable options that can reduce the impacts of widespread EV penetration on the electric grid.

Implementing DR programs or performing load control in commercial buildings provides opportunities for peak demand reduction [11-13] and in doing so helps reduce energy costs [14] and increase renewable energy share [15]. DR provides control of end users' electrical demand in response to grid signals [16]. DR changes the time pattern and magnitude of utility's load and results in increasing the efficiency and use of system assets [17]. Most large commercial buildings (100,000ft^2 or more) are equipped with an Energy Management System (EMS) which provides opportunities for peak load reduction [18, 19]. The use of EMS is not widespread in small and medium-sized commercial buildings (< 100,000 ft^2) [20, 21]. These buildings represent 94% of all commercial buildings, and consume 44% of the total energy of the commercial buildings in the U.S. according to the Commercial Building Energy Consumption Survey (CBECS) 2012 [22]. Due to the lack of controls significant amount of energy consumed in these buildings is wasted [20] with building owners typically missing building specific DR opportunities [23]. They do not approach DR strategy development systematically and are unable to correctly estimate DR effectiveness [24, 25].

Based on the literature, it can be concluded that there is a lack of optimal DR management that can control all major loads, including Heating Ventilation and Air-Conditioning (HVAC), lighting and plug loads, and quantify DR potential in small and medium-sized commercial buildings. While some large-sized commercial buildings are reported to already participate in DR programs with a DR aggregator, like EnerNoc, very few number of small- and medium-sized commercial buildings participate due to the limitation on their small size and the lack of software solutions to manage buildings' peak demand. Additionally, previous studies have rarely reported comfort performance; it is important that buildings provide comfortable indoor environment necessary for productivity of occupants [26]. For HVAC control, literature review shows that mostly buildings apply global temperature adjustment to achieve HVAC energy savings. This scheme may not be able to meet occupant comfort satisfaction as all thermal zones do not behave the same. For lighting control, typically daylight control with automatic light switching or loosely coupled photoelectric dimming is implemented in buildings. For plug load control, there are a limited number of studies discussing control of plug loads at building level. Building's plug loads are usually modeled by lumping all plug loads together, and the total plug load power consumption is determined by using a constant plug load density (i.e., W/ft^2) together with the plug load schedule. There is a need to explore load duration curves of key plug loads in order to better map how usage patterns affect consumed power [27] and help in automating DR management in peak load scenarios [28]. There is also a knowledge gap with regard to impacts of controlling commercial building's plug loads on the building load profiles [29].

With respect to EV impacts on the distribution feeder, a thorough literature search shows that, while majority of previous work pays attention to the impacts of EV penetration in residential distribution feeders, there is a lack of studies analyzing impacts of EV penetration in distribution feeders serving primarily commercial customers.

Literature review also shows that mostly controlled EV charging is performed to reduce EV impacts on the grid; or in some cases solar photovoltaic (PV) located at specific sites may be deployed to address the issue. However, there is no study which analyzes the synergy between PV and DR of buildings' end-use loads to mitigate the impacts of EV charging demand in commercial buildings.

DR or performing load control strategies till now have been implemented and analyzed in individual commercial buildings for their own economic benefits. However, researchers have overlooked DR/load control implementation to a group of commercial buildings to efficiently reduce grid's peak load and improve distribution system load factor.

To address the above knowledge gaps, this study presents an integrated control of major loads in commercial buildings, i.e., HVAC, lighting and plug loads that can maintain occupant environmental preferences – mainly thermal and lighting. The integrated control approach was designed using the Energy Management System (EMS) feature in EnergyPlus, a whole building energy simulation tool. Each zone's space temperature set points were optimally adjusted to maintain thermal comfort. Lighting levels, with and without daylight availability, were tightly controlled to maintain desired illuminance levels. Unlike other studies, this research contributes to improvement in functionalities of EnergyPlus by incorporating a 1-minute resolution data set at the individual plug load level. The integrated automation enables a smart building to minimize its power and energy usage, taking into account the interaction among lighting, HVAC, plug loads and control systems in a realistic manner, both among themselves and with building occupants. The developed approach was validated by experimentation conducted on simulated small and medium-sized office buildings and a standalone retail building modeled in EnergyPlus, which reflect existing commercial buildings in Virginia, U.S. The developed approach can be applicable to any type and size of commercial buildings.

Realistic driving and charging behaviors of different types (e.g., Nissan Leaf, Chevrolet Volt) and classes (e.g., Sedan, SUV) of EVs were considered in this study. Real-world EV data were derived from AC Level 1 and Level 2 charge stations located at various residential sites and EV DC fast charging stations located at a retail site's on-street parking area. Approximately 12 months of EV charge data was collected and analyzed to determine EV charge patterns and associated power consumption. The monitored data represents varying driving distance, vehicle class (sedan, small car, SUV, etc.), driving cycle (city, highway, congested) and the driver style (aggressive, passive) for residential and public EVs. As EVs are being integrated to the electric grid, it is essential to understand their charging behavior so that the grid can be managed to accommodate higher EV penetration.

In this study instead of controlling or delaying EV charging to reduce grid's stress conditions, a coordinated load control strategy for controlling end-use building loads including ice storage discharge, along with strategically deployed solar rooftop PV systems in groups of participating commercial buildings were employed to absorb EV penetration using real world charging scenarios. A real world electricity distribution feeder model developed in Distribution Engineering Workstation (DEW) software was used in order to assess impacts of integrating EVs to the grid. Having been validated on several types of commercial buildings in a distribution feeder with summer peaks, the developed strategy has been proven to be scalable and applicable to any type, size and number of commercial buildings in a distribution feeder. Results of implementing the developed strategy in a distribution feeder show the improvement in overall system load factor and reduction of system losses due to EV penetration.

1.2 Objectives and Scope of the Dissertation

In order to make EV penetration transparent to the grid, DR or load control strategies (including ice storage discharge) along with strategically deployed PV are introduced in the demand responsive commercial buildings. In this study, the main objective of the developed strategy is to keep the distribution feeder's peak demand unchanged with EV penetration, improve the feeder's load factors and reduce the losses.

In order to achieve this objective, a threshold value is selected, which is the distribution feeder's original peak demand (kW) without EV penetration, load control, PV and ice storage systems. If the distribution feeder's peak demand gets higher than this threshold due to EV penetration, the excess load is shed by performing control of major loads in participating demand responsive commercial buildings. The control of major loads is arranged to spread over the day, and hence minimizing demand restrike which refers to a sudden increase in building load due to set point adjustments after a building participation in load control.

The dissertation's main objective is segmented into multiple objectives with associated tasks and sub-tasks. Following is the description of the tasks to meet the dissertation objectives.

***Objective 1*: Address the issue of lack of optimal DR management that can control all major loads, including Heating Ventilation and Air-Conditioning (HVAC), lighting and plug loads, and quantify DR potential in small and medium-sized commercial buildings.**

This objective involves the design of an integrated automation for optimal control of major loads in demand responsive commercial buildings (including HVAC, lighting and plug loads) considering occupant environmental preferences in the EMS integrated with EnergyPlus. Specifically, the followings were performed:

1.1. Developed models of small and medium-sized office buildings and a standalone retail store in EnergyPlus. Building operations were based on the already validated small- and medium-sized office building models available in [30] and the already validated stand-alone retail building model available in [31]. These models are explained in detail in [32, 33].

1.2. Developed simulated load profiles of major loads in commercial buildings including HVAC, lighting and plug loads. HVAC and lighting load models were developed in EnergyPlus based on the reference commercial building models, discussed in 1.1. Dynamic plug load models with 1-minute intervals were developed for individual plug loads in EnergyPlus using published research and measurements of electrical equipment with a power analyzer.

1.3. Developed an integrated automation for optimal control of major loads in demand responsive commercial buildings. This includes: (i) optimally adjusted each thermal zone's temperature set points to maintain the Predicted Mean Vote (PMV) index within comfortable range of -0.5 to +0.5; (ii) optimally adjusted lighting levels in each zone to maintain the required standard illuminance levels; and (iii) controlled low priority plug load to avoid occupant inconvenience.

1.4. Validated the developed approach by experimentation conducted on simulated office buildings and a standalone retail store reflecting existing commercial buildings in Virginia, U.S.

1.5. Performed simulations to evaluate total building performance taking into account interdependencies among lighting, plug load, HVAC and control systems in a realistic manner, and determined the DR potential of a building, i.e., the amount of electrical demand (kW) by load type that can be shifted or shed.

Objective 2: **Address the issue of lack of EV models representing real world charge scenarios at building level.**

To achieve this objective, real-time EV models were developed representing different types, classes and charging levels of EVs, using EnergyPlus. These models were integrated to the existing electric demand of demand responsive commercial buildings representing grid level penetration. Specifically, the followings were accomplished:

2.1. Developed EV models representing real world driving and charging behaviors of different types (e.g., Nissan Leaf, Chevrolet Volt) and classes (e.g., Sedan, SUV) of EVs currently available in the U.S. market, like Nissan Leaf, Chevy Volt and Tesla Model S.

2.2. Developed aggregate AC Level 2 charging profiles for workplace charge stations located at small and medium-sized office buildings and DC fast charging for public charge stations located at retail sites.

2.3. Integrated the developed aggregate EV charge profiles for workplace and public stations to the modeled demand responsive buildings' existing electric service representing EV integration to the grid.

Objective 3: **Address the issue of lack of studies analyzing the integrated automation of ice storage and PV in demand responsive commercial buildings to meet the utility's demand reduction target through viable combinations of load control, PV and ice storage.**

This task was achieved by investigating the ability of grid-tied rooftop PV and packaged ice storage air conditioning systems at the building level to shift the building's peak load. Specifically, the followings were performed:

3.1. Developed the models of PV and ice storage systems in EnergyPlus for integration with the small and medium-sized demand responsive commercial building models developed in 1.1.
3.2. Performed sizing of rooftop PV systems based on available building roof space for selected demand responsive commercial buildings.
3.3. Quantified peak load reduction and energy savings potentials of commercial buildings through the use of viable technologies (i.e., DR, PV and ice storage systems).

Objective 4: **Address the issue of lack of studies analyzing the synergy between PV and load control in commercial buildings (including ice storage discharge) to make EV penetration transparent to the distribution feeder serving a number of commercial buildings.**

This objective involves the development of a load control strategy for the distribution feeder to absorb EV penetration through control of major loads, ice storage discharge, and PV in demand responsive commercial buildings. The followings were performed:

4.1. Developed a real world distribution feeder model serving a number of small and medium-sized commercial buildings along with some residential buildings using Distribution Engineering Workstation (DEW) software.
4.2. Quantified the impacts of integrating real world EVs charging on the distribution feeder.
4.3. Developed a coordinated load control strategy for controlling building major loads including ice storage discharge, along with strategically deployed solar rooftop PV systems in groups of participating commercial buildings to absorb EV penetration and improve the distribution feeder's load factors, and losses due to EV penetration.
4.4. Performed sensitivity analysis by varying the EV penetration levels among demand responsive commercial buildings to analyze how the load control strategy can contribute to reducing distribution feeder peak load with EVs, thereby making the EV penetration transparent to the grid.

1.3 Contributions

Major contributions of this work can be summarized as follows:

1.3.1 An approach to improve the distribution feeder's performance with EV penetration through coordinated control of demand responsive commercial buildings, ice storage and PV

This study presents impacts of EV using real world charging scenarios at a distribution feeder level and develops a mitigation strategy to make EV penetration transparent to the grid. The developed coordinated load control strategy is proven to absorb EV penetration by controlling end-use building loads including ice storage discharge, along with strategically deployed solar rooftop PV systems in groups of participating commercial buildings. A real world electrical distribution feeder serving a number of commercial buildings is used for analysis purposes. Instead of focusing on individual building's economic benefits, the developed approach considers both technical and economic benefits of the whole distribution feeder, including maintaining distribution-level load factor within acceptable ranges and reducing feeder losses.

This study performs sensitivity analysis by varying EV penetration levels among demand responsive commercial buildings to identify how the developed load control strategy can contribute to reducing distribution feeder peak load with EVs.

Research findings indicate that improvement in distribution feeder's load factors can be achieved with the developed approach. This helps increase system operating efficiency, better utilization of existing power distribution assets and defer investments in distribution system upgrades.

1.3.2 An integrated control for commercial building DR applications that can evaluate DR potential for commercial buildings by load type

This study develops an integrated control of major loads in commercial buildings, i.e., cooling, lighting and plug loads that can maintain occupant environmental preferences, mainly thermal and lighting. Unlike other studies instead of applying global temperature adjustment to achieve HVAC savings, in this study each zone's space temperature set points are optimally adjusted to maintain thermal comfort. Unlike other studies which typically implement daylight control with automatic light switching or loosely coupled photoelectric dimming, in this study lighting levels, with and without daylight availability, are tightly controlled to maintain desired illuminance levels. Unlike other studies which lump all plug loads together, this research explores the load duration curves of key plug loads in order to better map how usage patterns affect consumed power and controls them during DR events.

This study estimates DR potential for demand responsive commercial buildings by load type – HVAC, lighting and plug loads. This information can serve as inputs to decision makers to assess the current state of DR in small and medium-sized commercial buildings as they become accessible to increased adoption of EVs. Additionally, this study also benefits researchers in academia and industry as it demonstrates how an EMS can be developed and integrated with EnergyPlus for analyzing peak load and energy consumption in buildings, taking into account comfort perspective. Use of building energy simulation tool provides more accurate DR savings unlike other studies which estimate building's load profiles using baseline methods.

1.3.3 Development of dynamic plug load models integrated with EnergyPlus

In this study instead of considering plug loads as static devices with pre-determined parameters which leads to simulation results exhibiting low fidelity, dynamic plug load models were developed in EnergyPlus, contributing to improvement in its functionalities and accuracy of simulation results, by incorporating a 1-minute resolution data set at the individual plug load level, representing near realistic equipment behavior. The impacts of controlling different plug loads, in a demand responsive commercial building, on the aggregate plug load and building load profiles were investigated and quantified.

1.3.4 Development of real-world EV models integrated with EnergyPlus

In this study EV models indicating real world charge scenarios were developed in EnergyPlus and integrated to the building's existing electric service. For EV model development, unlike other studies, real-time EV charge profiles, both AC level 2 and DC fast charging, monitored over a year at both residential and public charging stations representing varying driving distance, vehicle class (sedan, small car, SUV, etc.), driving cycle (city, highway, congested), multiple charging events over the day, dynamics of EV arrivals and departures in real time, and the driver style (aggressive, passive) were used. As EVs are being integrated to the electric grid, it is essential to understand their charging behavior so that the grid can be managed to accommodate higher EV penetration.

In this study instead of controlling or delaying EV charging, EV charging was given priority, and the synergy between PV and DR of buildings' end-use loads were exploited to mitigate their impacts.

1.3.5 An approach for integrated automation of ice storage and PV in demand responsive commercial buildings

Unlike other studies which discussed integration of renewable and storage at the utility side, this study developed an integrated automation of DR, PV and ice storage to enable a building to meet the utility's demand reduction target through viable combinations of DR, PV and ice storage. The developed approach is expected to serve as a stepping stone towards net-zero energy buildings. The study also quantifies peak load reduction and energy savings potentials of a commercial building through the use of viable technologies (i.e., DR, PV and ice storage systems).

This study is expected to benefit building owners/operators by providing an improved understanding of building's load shapes as a result of performing DR, install PV and ice storage systems to maximize their building's economic benefits while being sensitive to occupant thermal and visual comfort.

2 Literature Search

The objective of this chapter is to establish the relevance of this dissertation with the past research work related to the methodology developed in this dissertation and identify the knowledge gaps. Section 2.1 discusses the in-depth research work related to EV penetration and its impacts on electrical distribution feeders. Section 2.2 discusses the in-depth research work related to DR or load control strategies in commercial buildings. Section 2.3 discusses the synergy among DR, renewable and storage energy systems to absorb EV penetration. Section 2.4 summarizes the past research and presents the knowledge gaps.

2.1 EV Penetration in Electric Distribution Feeders

2.1.1 EV overview

EV penetration is increasing due to technical advancements and environmental concerns. EVs will play a key role in the U.S. transportation future as they reduce petroleum dependence and greenhouse gas emissions [34]. However, there are some barriers to EV adoption, including EV cost, range anxiety and availability of charging infrastructure [35]. A study [36], discusses in detail the key factors such as advanced battery research, development and deployment of EV technologies, deployment of charging infrastructure, standardization of industry protocols of plugs and chargers, public education, government policies and others needed for smooth transition towards transportation electrification.

EVs include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). BEVs solely operate on electricity stored in a battery; like Nissan LEAF, BMWi3, Ford Focus Electric and Volkswagen-e-Golf. In contrast PHEVs have an internal combustion engine that can supplement the electric power train; like Ford C-MAX Energi, Chevy Volt and Toyota Prius Plug-in.

BEVs always start charging from 20% SOC and stop at 80% SOC and have driving range of 129 to 161 km, while a few luxury models have ranges up to 402 km. BEV operates in charge depleting (CD) mode only in which electric motor converts the energy stored in the battery to power up the vehicle. The battery pack needs to be connected to the electric grid to recharge the BEV.

For PHEVs due to the hybrid mode, charging can start from 0%. PHEVs run on electricity for shorter ranges around 10 to 64 km, upon depletion of battery the operation is switched over to an internal combustion engine running on gasoline [37]. PHEV operation can be divided into charge depleting (CD) and charge sustaining (CS) mode. In CD mode the EV gradually depletes the electric energy of its battery pack. Total distance a PHEV can travel in CD mode with its battery being initially fully charged is defined as its charge-depleting range (CDR). When the battery reaches its minimum SOC, vehicle switches to CS mode, and is operated by the gasoline engine so that SOC can be maintained around its minimum limit. PHEV electric performance is designated by the nomenclature of "PHEV-XX", where XX represents approximate battery storage capacity in miles, such as PHEV-40. For PHEV-40 the vehicle travels on battery for 40 miles before the gasoline engine is turned on for the first time. For PHEVs external electricity can be used to provide energy to the batteries unlike hybrid electric vehicle (HEV).

2.1.2 EV charging infrastructure

As EVs are being integrated to the electric grid, it is essential to understand their charging behavior so that the grid can be managed to accommodate higher EV penetration. EV charging can be performed using Alternating Current (AC) level 1, AC level 2 and DC fast charging [38]. AC level 1 charging is suitable for homes. Charging is provided through a 120V AC plug and 3.2 to 8 km of range can be delivered per hour of charging. AC level 2 charging, suitable for workplace and public charging, is done through a 240 V (for residential) or 208 V (for commercial) plug. About 16 to 97 km of range can be delivered per hour of charging. DC fast charging, suitable for public charging stations, is provided through a 480V AC input and can deliver 97 to 161 km of range in about 20 minutes [39]. Table 1 defines the charging configurations specified in [38].

Charge Method	Voltage (V)	Current (A)	Power (kW)	BEV Charging Time				PHEV Charging Time			
				3.3 kW Charger	7 kW Charger	20 kW Charger	45 kW Charger	3.3 kW Charger	7 kW Charger	20 kW Charger	45 kW Charger
AC Level 1	120 VAC	12/16	1.4/1.92	17 hrs.				7 hrs.			
AC Level 2	240 VAC	80	Up to 19.2	7 hrs.	3.5 hrs.	1.2 hrs.		3 hrs.	1.5 hrs.	22 mins.	
DC Level 1	200-450 VDC	80	Up to 36			1.2 hrs.				22 mins.	
DC Level 2	200-450 VDC	200	Up to 90				20 mins				10 mins

Table 1 SAE charging configurations

Table 2 summarizes electric range and power consumption of different EVs available in the U.S. market [40-44]

	Battery capacity (kWh)	All electric range (km)	AC Level 1		AC Level 2		DC fast charging	
			Power consumption (kW)	Charging duration (hours)	Power consumption (kW)	Charging duration (hours)	Power consumption (kW)	Charging duration (minutes)
Toyota Prius Prime	8.8	40.2	1.4	5.5	3.3	2.17	-	-
Chevrolet Volt PHEV 2017	18.4	85.3	1.4	13	3.84	4.5	-	-
Mitsubishi i-MiEV 2017	16	100	1.4	14	7.2	6	50	30
Nissan Leaf 2016	24	135	1.8	18-20	3.3 6.6	6-8 4-5	48-50	20-30
	30	172	0.8-1.2	26	3.3 6.6	5.5 9.5	48-50	20-30
Tesla Model S	100	506.9	1.1	90	12	9-10	120	30-40

Table 2 Electric range and power consumption of different EVs

DC fast charging is done through different connectors including CHAdeMO, an abbreviation for "CHArge de MOve" equivalent to "charge for moving", Society of Automotive Engineers (SAE) Combo Charging System (CCS) and Tesla Supercharger [45]. Nissan Leaf and Mitsubishi i-MiEV use CHAdeMO [46], which only supports DC fast charging. Chevrolet Volt, BMW i3, Chevrolet Spark and Volkswagen e-Golf use SAE CCS [46], which supports both slow and fast charging. Tesla Supercharger can only be used with Tesla vehicles and through vehicle adaptors can use CHAdeMO connectors.

2.1.3 EV models discussed in literature

It is important that EV models represent varying driving distance, vehicle class (sedan, small car, SUV, etc.), driving cycle (city, highway, congested) and the driver style (aggressive, passive). EV models used in many studies are based on assumptions ignoring either vehicle types, diversity of usage, multiple charging events over the day, dynamics of EV arrivals and departures in real time, or driving habits [47].

Authors in [48] state that precise determination of EV's stochastic profiles are needed for accurately assessing their impacts on distribution feeders. The various uncertainties highlighted in the study include; arrival times and daily distance traveled by each vehicle, EV penetration levels and their types and level of charging. A simplified EV model developed by authors in [49] assumes that all EVs travel about 33 miles each day, which is an average daily distance traveled by vehicles in the U.S., and assumed an average consumption rate of 0.35kWh/mile. Batteries were assumed to present a constant load of 3.3kW (220V at 15A) while being charged. Model presented by authors in [50] assumes that a PHEV fleet travels 40% of its distance using electricity. The model neglects the fact that all PHEVs in the fleet travel different distances. The usable battery capacity for the fleet is assumed to be an average of 10.2 kWh. Authors in [51] have used a large scale planning model to investigate the impacts on investment cost and losses in distribution feeder. They assumed that 85% of all the vehicles are charged during off-peak hours mostly in slow and normal charge mode. During peak hours, 40% of the vehicles are connected to the grid of which 90% are being charged, some in fast charging mode. The model does not consider the fact that drivers have different driving habits, not all the vehicles arrive at their homes the same time. Authors in [52] assume that all vehicles begin charging around 6pm which is not the case as indicated by [53, 54] and the batteries SOC is considered 30% upon arrival. Authors in [55] assume that all vehicles are charged for 4 hours daily, ignoring how much distance each vehicle has traveled, as some might require more charging. Authors in [56] assume that EV charging always occur at peak time. This is not true as indicated by studies [53, 54]. This leads to an overestimation of the impacts of EVs on the distribution feeder. Also the model considers a random charging profile for each vehicle, ignoring their traveled distances.

Authors in [57] use stochastic approach to model EVs for office, retail and residential buildings. The study assumes only two charging technology types and battery sizes. Office buildings are assumed to be equipped with 1.4 kW chargers. One EV per charger arrives the office building randomly between 7am to 9am with a random battery SOC between empty and half of its capacity. Vehicles begin immediate charging till the batteries are full. Retail buildings are assumed to be equipped with 7.6kW chargers. Using traffic volume data [44] it is assumed that vehicles arrive at the retail sites every half an hour throughout the day. Residential EV models use the U.S. National Personal Transportation Survey [58, 59]. These residential models assume that owners travel to work each day and make other trips while at work or evening. Authors in [60, 61] assume that all batteries begin charging from fully discharged state and that all PHEVs are equipped with 11kWh batteries charged by 4kW chargers ignoring fast charging. EV charging in small office buildings is also examined, vehicles are charged between 10am to 4pm but only one vehicle per office can be charged. Authors in [62] state that from a computational perspective it is too difficult to model the driving habits and battery SOC of each individual vehicle, so some models choose to aggregate all the vehicle batteries into one large unit and use historical data to predict vehicle availability which leads vehicles to charge faster than would actually be realistic or aggregate vehicles by size and battery range.

2.1.4 Non-residential EV charging

Residential charging is problematic for those who either use on-street parking or rent their homes and have no authority to install EV charger [35]. For such EV owners workplace and public charging infrastructure is much needed. Non-residential charging provides benefits such as extending the EV range, reducing range anxiety, and promoting widespread adoption of EVs [63]. Most EV drivers charge at home at present, due to lack of non-residential charging infrastructure, which causes them to have range anxiety.

For commercial buildings the peak demand occurs during the afternoon hours when the cooling demand is high. This time coincides with EV charging time, typically from 9am to 6pm. Workplace charging could shift the evening peak load due to residential EV charging to morning and afternoon times and can increase the electric range of EVs. Authors in [64] analyze that mid-day EV charging can alleviate evening residential peak load. Authors in

[65] forecast PHEV's daily electric energy use to increase from 24% to 29% with non-residential EV charging. A study [49] concludes that EV charging, although uncontrolled, occurring both at residential and non-residential sites, distributes the peak load evenly between distribution feeders serving residential and commercial customers and lasts for shorter duration than with residential charging alone. Authors in [66] state that as number of PHEVs continue to increase, charging locations away from homes would be needed. The existing residential metering infrastructure would be insufficient to monitor and control PHEV charging along with DR use. Although non-residential PHEV charging will make it more difficult to predict how DR programs may interact with PHEVs.

A study [67] shows that EV drivers who charged their cars away from home averaged 72% more daily miles on electricity alone than drivers who never charged away from homes. Drivers used a mix of charging equipment types when charging away from home, including AC level 1, AC level 2 and DC fast charging. EV drivers adjusted their charging habits based on conditions such as fees and rules for use. Drivers were less likely to charge if they had to pay to charge and the average time for charging increased as drivers stayed connected longer to get their money's worth.

Public charging infrastructure is essential for encouraging EV adoption. Public charging stations offer EV owners the convenience of 24-hour accessibility [4]. A case study [68] was performed in Tokyo and results indicated that with charging available at homes only, the drivers would come back home with 50% of the charge still remaining due to range anxiety. Installation of public chargers throughout Tokyo reduced the range anxiety and EV driving distances increased. A retail outlet, for instance, can install EV chargers to attract customer visits and generate additional revenue. Visitors may shop while their EVs are being charged and encouraging an extended stay benefits retail's business [69]. A study [70] shows that 83% EV owners prefer to shop at locations which offer EV charging while 89% of EV drivers make a purchase while charging at retail sites. Stations with DC fast charging are most suitable for places where drivers park for less than half an hour, such as retail outlets [69].

On the other hand, there are studies which suggest daytime charging is undesirable. A report [71] suggests that public day time charging is expensive and undesirable, only one public charging station would be sufficient for 100 EVs to overcome range anxiety along with majority of charging taking place at residential sites. Authors in [72] predict that EV penetration at workplace may not drive the need for upgrades to the distribution feeder serving commercial customers. Commercial transformers are capable of handling greater electric load; it is unlikely that clustering of several EVs at a workplace will cause transformer issues as with residential transformers.

2.1.5 EV charging strategies

EV charging can be either uncontrolled, which occurs whenever the EV owner is within reach of an outlet or performed with a time delay in the evening to minimize electricity costs. EV charging when performed at off-peak hours optimizes grid utilization during low-load hours. Controlled EV charging helps minimize power losses in the distribution grid and improves its performance. Smart EV charging enables variety of technologies that involve grid-enabled vehicles to interact with the electrical grid beyond simple charging. However, controlled EV charging delays EV charging to night time which could prevent distribution assets, such as transformers from cooling down overnight, reducing their lifetime [8]. Also at the end of controlled charging some EVs may not have been charged to the desired SOC level [9].

There are various studies which discuss charging control strategies and algorithms with different objectives but for mainly residential distribution feeders. Authors in [73] propose methodologies to estimate the energy and power consumption for uncontrolled charging at any time when vehicle is parked at home, a shopping mall, work etc. by light-duty plug-in electric vehicles. Results show that uncontrolled charging increases power system's peak load. Authors in [74] show that with smart charging device, which prevents charging at peak hours, the impact of EVs on distribution feeder over a time frame could be manageable. Authors in [75] propose EV charging algorithms to decrease the impact on distribution system by preventing distribution transformer overloading and under frequency conditions. Authors in [76] show that energy control strategies, controlling duration and rate of EV charging, can provide peak energy savings and flatten the overall load profile for a residential area. Authors in [61] apply coordinated EV charging to minimize power losses and maximize distribution feeder's load factors serving residential customers. Authors in [77] show controlled charging is more effective than the uncontrolled charging for integrating EVs in a distribution feeder on a moderate level. Authors in [60] propose a coordinated charging scheme to minimize the feeder power losses and maximize grid load factors. Authors in [78] propose EV charging control strategies which allow the integration of larger number of EVs in the system, allow feeder operation in less stressed conditions, with improved voltage profiles and lower congestion levels. Authors in [79] have developed a novel Smart Load Management algorithm for coordinating the scheduling of multiple EVs to maximize residential grid performance by maintaining voltages within tolerances, reducing system losses and achieving peak load shaving. The study considers different EV penetration levels, EV battery sizes and owner charging time preferences. Authors in [80] have developed three optimal EV charging algorithms to perform coordinated PHEV charging and to minimize the impacts of PHEVs on the connected distribution system. Authors in [81] demonstrate that optimized charging rates of EVs on a test feeder can deliver the maximum amount of energy to the EVs within a set charging period subject to feeder constraints, while ensuring that the underlying residential load remains unaffected.

2.1.6 Impacts of EV charging on the electric distribution system

In the early stages of EV integration, the number of EVs is expected to be small and EV owners can charge them at home without any controlled scheme [82]. As the number of EVs increase, efficient management of the charging infrastructure along with analysis tools would be needed to determine the effects of adding large numbers of active mobile loads to the grid [83]. Uncontrolled charging of a cluster of EVs during peak periods significantly stresses the distribution feeder, slows EV visibility and requires infrastructure investments [84]. Mature stages of EV integration would require advanced EV charging control algorithms, DR algorithms along with renewable and storage systems to absorb EV penetration and optimize the feeder operation.

Earlier studies focused on the impact of EV fleet charging on large scale electric power systems and showed only slight increase in the system peak load. These studies also focused on determining generation capacity needed to absorb the growing EV load. A study [85] by Electric Power Research Institute (EPRI) states that only 8% increase in generation would be needed if PHEVs replace half of the vehicles in U.S. by 2050. Another study [86] states that the existing U.S. electricity infrastructure can support about 70% of the existing U.S.

light duty vehicle fleet including, cars, pick-up trucks, vans and SUVs, under coordinated EV charging. Authors in [87] predict an increase in electricity demand, generation, prices and emissions due to large scale EV penetration. Authors in [88] conclude, large deployments of PHEVs may significantly increase the grid's peak load due to overlapping of residential EV charging in the evening with the domestic demand. Authors in [89] investigate the impacts of PHEV charging on electric energy generation and usage of primary fuel. The study concludes that PHEV charging can shift petroleum utilization to other fuel types depending on the generation mix of the electric utility. Authors in [65] state "*PHEVs with all-electric ranges as low as 10, 20 and 40 miles allow drivers in the US to cut their gasoline consumption by more than half by shifting 45–77% of miles traveled from gasoline to electricity*".

Research on impacts of EV penetration has now turned towards the electric distribution feeder [90-93]. However, studies have mainly focused on analyzing the impacts of EV penetration on distribution feeders serving residential customers [6, 94-97]. Significant EV penetration is likely to cause implications to the already burdened distribution feeder [98, 99]. Authors in [74] show that the existing Pacific Northwest distribution infrastructure can support a 50% penetration of 120V smartly-charged PHEVs, which equates to approximately 21.6% of the Washington state Light Duty Vehicle fleet. A study [100] shows that EV charging in small residential areas causes more severe problems due to cluster effect than at commercial and industrial sites. Authors in [101-104] study the impacts of EV charging on distribution transformer life. Authors in [48] state that secondary distribution transformers are the bottleneck blocking the widespread adoption of PHEVs. Authors in [89] show 93% reduction of the expected life of a residential distribution transformer for a specific scenario.

There are studies, although lacking, which have investigated the impacts of EV penetration on commercial and industrial distribution feeders. Authors in [105] demonstrate overloading of feeders in a 10 kV real distribution system in commercial area due to simultaneous charging of EVs during peak afternoon period. Authors in [57] investigate three distribution feeders including urban, suburban and rural feeders to show that EV charging significantly increases the peak demand on all feeders causing larger voltage drops and increasing the probability of transformer overloading. Authors in [106] study the impacts of EV penetration in distribution feeders serving residential, industrial and commercial customers. The study shows that 10% and 20% EV penetration with uncontrolled charging may increase the residential feeder's peak load by 17.9% and 35.8% respectively. Similar EV penetration with uncontrolled charging may increase the industrial feeder's peak load by 5.9% and 11.8% respectively and commercial feeder's peak load by 7.3% and 14.6% respectively.

2.2 Demand Response (DR) or Load Control Strategies in Commercial Buildings

2.2.1 DR- definition and types

DR is defined by Federal Energy Regulatory Commission (FERC) [107] as " *Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*".

As per 2012 FERC survey different types of DR programs are as follows [107]:

Incentive-based programs - Customers receive incentives or discounts to participate in these DR programs. Customers reduce their loads at times requested by the program sponsor when grid reliability is being jeopardized or electricity prices are high. Different types of programs are:

- Demand Bidding and Buyback
- Direct Load control
- Emergency DR
- Interruptible Load
- Load as Capacity Resource
- Non-Spinning Reserves
- Regulation Service
- Spinning Reserves

Time-based programs - Customers receive time varying rates that reflect the value and cost of electricity in different time periods. With this information customers use less electricity when the electricity prices are high. Different types of programs are:

- Critical Peak Pricing with Control
- Critical Peak Pricing
- Peak Time Rebate
- Real-Time Pricing
- Time-of-Use Pricing
- System Peak Response Transmission Tariff

Incentive-based DR program types represent bulk of reported DR potential but in 2012 time-based program types significantly increased. As per FERC survey data, DR capability in the U.S. has increased from 2010 to 2012. Over this time, DR potential peak reduction increased by more than 10,000 MW from 53,062 to 66,351 MW. Commercial and industrial customers showed largest potential peak reduction increase of 31 percent. FERC suggests this increase is due to new and expanded DR programs, along with improved reporting of existing programs. From 2010 to 2012, the potential peak reduction for wholesale entities and residential customers increased by 26 percent and 13 percent respectively.

2.2.2 Barriers to DR

Federal Energy Regulatory Commission (FERC) in its report [107] identifies several outstanding barriers to DR.

- There are a low number of retail customers who purchase electricity based on time-based rate which slows the development of new technologies and programs and the fulfillment of DR potential.
- Some progress has been made towards consistency in the measurement and verification of demand reductions and demand responsive specific cost effectiveness tools.
- There is a lack of uniform standards for communicating DR pricing, signals and usage information.
- Customers need to be effectively educated and informed about DR opportunities and impacts at the customer level.

- New tools and methods need to be developed to directly incorporate DR into dispatch algorithms and resource planning models. Also tools and methods are needed to forecast and model the capability of demand resources to adjust consumption in near real-time. Current DR planning and forecasting tools are not sufficiently robust to adequately model DR capability to alleviate transmission congestion.

2.2.3 Potential role of DR

DR offers financial and operational benefits to electricity consumers, load serving entities and grid operators [25]. DR is crucial since 1) electric power systems need to maintain a balance between supply and demand at real time, 2) grid conditions and demand levels change constantly and unexpectedly and electric system is highly capital intensive, and 3) generation and transmission system investments have long lead times and economic lifetimes. Implementing Demand Response (DR) programs in buildings provides opportunities for peak demand reduction [11-13] and in doing so help reduce energy costs [14] and increase renewable energy share [15]. DR provides control of end users' electrical demand in response to grid signals [16]. DR changes the time pattern and magnitude of utility's load and results in increasing the efficiency and use of system assets [17].

Customers participating in DR programs can save their electricity bills and also earn incentives. Distribution utilities can also improve their reliability by smartly managing various DR schemes. With planned DR programs transmission and distribution companies can benefit too by avoiding purchase of bulk power from generating units at high prices and instead maximize utilization of their already existing resources and infrastructure. The DR programs avoid construction of new infrastructure to meet the ever increasing demand growth and therefore the avoided or deferred cost is passed on to customers as bill savings. DR lowers the consequences and likelihood of forced outages that impose financial costs and customer inconvenience. DR may also provide environmental benefits by reducing the emissions of generation plants during the peak period [25]. DR not only curtails peak load on the demand side but DR also impacts the distribution feeder by improving the voltage profile, minimization of loss and valley filling [108]. Some types of DR can be used to fulfill resource adequacy requirements, whereby these resources can be used to meet demand for emergency purposes [109].

2.2.4 DR strategies for commercial buildings

Some work has been done in developing DR strategies for the residential buildings. Authors in [110, 111] propose a DR strategy as a load shaping tool to help the distribution feeder serving residential customers to accommodate EV penetration. The proposed DR strategy is an energy management tool within a home area network (HAN) that takes into account consumer's preferences, load priorities and privacy.

Lawrence Berkeley National Laboratory (LBNL) has performed studies [112, 113] which identify various DR strategies for lighting and HVAC and estimates their demand savings potential for commercial buildings. These DR strategies were field tested in 28 commercial buildings, located mostly in California and New York. Different types of commercial buildings used for DR testing purposes include; office buildings, retail sites, supermarket, public assembly buildings, cafeteria, post office, museum, high school, data centers, and laboratory buildings. The study points out that the DR strategies listed in Tables 3-4 are not an exhaustive list and that further research is needed to better understand their full potential for various building types, climates and occupancy patterns. It further states that research is needed to develop improved methods to estimate peak demand savings for various strategies. Another LBNL study [34] field tested DR strategies at ten sites in California. The sites included small offices, restaurant, pre-school and convenience store. One or more DR strategies tested at these sites included changing cooling set point, compressor cycling, turning down lights or dimming them, turning down miscellaneous electric equipment (MEL) and anti-sweat heaters. Results showed limited DR savings. The reasons suggested are lack of customer awareness towards DR, non-optimized DR strategies for sites with less savings, loads (e.g. lighting and MELs) being controlled were too small to distinguish from whole building load and HVAC systems not being able to maintain DR strategy for extended period of time. The study recommends that there is a need to develop useful strategies for different kinds of customers and identify methods to determine peak load reductions during DR events. Vendors and manufacturers of DR technologies have to identify more effective DR strategies for end-uses, limitations and possible opportunities to control end-use differently in response to DR event and ways to evaluate the efficacy of these strategies. Authors in [114] present summary of results of a series of field tests of automated DR in large commercial buildings in the Pacific Northwest. Twelve DR strategies including global temperature adjustment, duct static pressure decrease, pre-heating, cycle electric heaters, dimmable ballast etc. were able to improve the electric load shape both in summer and winter.

Small and medium-sized commercial buildings have a diverse mix of businesses and types of buildings. These customers are not targeted to the extent as large commercial and industrial customers for DR applications. These buildings represent 94% of all commercial buildings, and consume 44% of the total energy of the commercial buildings in the U.S. according to the Commercial Building Energy Consumption Survey (CBECS) 2012 [22]. Due to the lack of controls significant amount of energy consumed in these buildings is wasted [20]. There is lack of information on how DR works for these buildings [25].

2.2.5 Lighting, HVAC and plug loads DR strategies in commercial buildings

There are studies that discuss possible DR strategies for controlling major commercial buildings' end-use loads including; HVAC, lighting and plug loads. These studies are summarized below:

HVAC-based DR strategies **-** Different HVAC-based DR strategies include global temperature adjustment of zones and systemic adjustments to the air distribution and cooling systems [112] as presented in Table 3.

Category	DR Strategy	Definition
Zone Control	Global Temperature Adjustment	Increase zone temperature set points for an entire facility.
	Passive thermal mass storage	Decrease zone temperature set points prior to DR operation to store cooling energy in the building mass, and increase zone set points to unload fan and cooling system during DR.
Air distribution	Duct static pressure decrease	Decrease duct static pressure set points to reduce fan power.
	Fan variable frequency drive limit	Limit or decrease fan variable frequency drive speeds or inlet guide vane positions to reduce fan power.
	Supply air temperature increase	Increase SAT set points to reduce cooling load.
	Fan quantity reduction	Shut off some of multiple fans or package units to reduce fan and cooling loads.
	Cooling valve limit	Limit or reduce cooling valve positions to reduce cooling loads.
Central plant	Chilled water temperature increase	Increase chilled water temperature to improve chiller efficiency and reduce cooling load.
	Chiller demand limit	Limit or reduce chiller demand or capacity.
	Chiller quantity reduction	Shut off some of multiple chiller units.

Table 3 HVAC DR strategies

A study [115] concludes that usually commercial buildings are overcooled. Studies [112, 113] suggest global temperature adjustment of zones to be the priority DR strategy that best achieves DR goal. At the end of DR event, the system should be slowly brought to normal conditions in order to avoid unwanted demand restrike caused by immediate increase of cooling load [116-118]. Authors in [119] correlated cooling energy usage with thermostat operation to better understand relationship between energy consumption and thermal comfort. Authors in [120] provided a summary of some case studies analyzing energy consumption with changes in summer set point temperatures. Authors in [121] showed that applying global set point changes during peak hours results in poor distribution of HVAC capacity across zones and an uneven distribution of occupant satisfaction across the building. Authors in [122] reported demand savings associated with closure of air-conditioning units or rise in cooling set points for different types of buildings. Authors in [123] showed that although global temperature adjustment was able to achieve more peak load savings but is unable to maintain thermal comfort in all zones across a building. Authors in [112] state that further field investigation is needed in diverse climate conditions and seasons other than summer for HVAC DR strategies. Authors in [124] estimate about 1 kWh lighting savings induces 0.48 kWh cooling savings for existing commercial buildings. Authors in [125] show energy savings for two big box retail buildings. First store's cooling set point was raised by 2.9°C and second store's cooling set point was raised by 1.83°C to achieve annual cooling energy savings of 48% and 22% respectively. Authors in [126] show the reduction in annual electricity consumption in the range of 0.96% to 1.84% for 1°C indoor air temperature set point modification for retail stores located in seven U.S. climate zones. Authors in [127] raised the temperature by 1°C during a DR event to achieve 6% load reduction in big box retail buildings.

***Lighting-based DR strategies* –** Control of electric lighting adapting to changes in occupancy and daylight while maintaining illumination comfort can reduce building energy consumption. Due to the availability of dimmable sources like light emitting diodes (LEDs), lighting systems have become attractive controllable loads to offer DR services. Lighting systems are being increasingly equipped with embedded sensing, communication and control functionalities. Some field tested lighting DR strategies [112] are presented in Table 4.

DR Strategy	Definition
Zone switching	Switch off luminaires where daylight is available.
Fixture/lamp switching	Four light levels; all off, 1/3 off, 2/3 off or full lighting
Stepped dimming	Lamps are controlled in a fixture together to provide one, two or three light levels
Continuous dimming	Continuous variation in light level from maximum to about 10% light output

Table 4 Lighting DR strategies

Authors in [128-132] discuss different types of lighting control strategies for peak load reduction including harvesting daylight, continuous dimming and on/off strategies implemented in commercial buildings. Authors in [133] show peak demand savings of 0.23MW achieved in a group of eight buildings with de-lamping for a typical summer day. Authors in [131] demonstrate poor light performance for lighting control integrated with occupancy and HVAC in cooling dominated spaces. Authors in [134] provide an overview of occupant behavior from studies examining occupant preferred light levels in office buildings with natural daylight available and light controls. Authors in [135-137] indicate that occupants prefer illuminance levels lower than recommended values. Authors in [138-141] indicate occupants electric lighting use is seldom affected by daylight availability, higher levels of electric light use have been observed with higher external illuminance [141, 142]. In order to get benefits from daylight control, automatic controls either providing automatic lights switching or photoelectric dimming are needed to avoid the risk of more energy usage. Upon reception of a simulated shed signal authors in [39] dim building lights for one hour in response to available daylight. Further 10% reduction during DR event was unnoticeable by the occupants. Conclusions were drawn that small changes in light levels accomplished through dimming are inconspicuous than opposed to switching.

Authors in [117] performed demand responsive lighting control in a supermarket in California. A demand shed signal switched off about 50% of the overhead lighting during the DR event. Customer complaints were received since there was a noticeable change when lights were shutdown. Authors in [143] performed demand responsive lighting control in three buildings in California. These buildings included two chains with light switching system as per California Title 24 and a building controls company with dimmable lighting. Findings showed lighting has a major impact on electricity demand in commercial buildings comparable to HVAC. Dimming controls enable building lighting controls to be elastic but are not widely used due to high costs. Results also highlighted that utilities only have little reliable data as to how much energy and load savings result from lighting DR strategies in different building types. Hence utilities cannot properly rebate lighting control systems in their efficiency programs. Energy has to be measured both before and after the installation of controls for accurate savings calculations. Authors in [144] performed uniform and simultaneous dimming of all the luminaires in a building. All load shedding ballasts reduced lighting power by 33% upon receiving the shed signal. The study ignored the fact that a building facility is usually sub-divided into different areas, like office space, corridor, and cafeteria etc., each having their own illumination requirements. Uniform dimming can lead to consumer inconvenience. Authors in [145] discuss control algorithms for distributing load reduction across multiple lighting system controllers. Upon receiving a DR request, light controllers reduce power consumption based on their load shedding flexibilities. The load shedding flexibilities reflect the amount of power reduction that can be achieved without compromising the occupant illumination requirements in that area. Authors in [146] extended the work by [145] to determine DR capacity of automatic lighting control systems in commercial buildings. Authors in [127] shutdown 50% main sales lighting in big box retail buildings during a DR event to achieve 10% load reduction.

***Plug loads-based DR strategies* -** In commercial buildings about 30% to 50% plug loads have yet to be controlled [147]. To consider plug loads as a DR resource is challenging since these loads are widely deployed within every physical space in a building and it is not immediately known what these loads are. Authors in [148] report plug load data from twelve commercial buildings in California, Georgia, and Pennsylvania including two health care buildings, two large-sized offices (> 500employees each), three medium-sized offices (50-500 employees), four education buildings, and five small-sized businesses. The report provides an inventory of equipment with trends in usage patterns typical in commercial buildings. The report indicates that office equipment is often idle and is left on when not in use. Authors in [149] measured office equipment usage. The study inventoried nearly 7,000 plug load devices and collected meter data for 470 plug load devices. Results showed plug lads consumed about 30% of total electricity consumption in the participating sites. Computers and monitors consume about 66% energy of all plug loads and office electronics about 17%. Mostly the energy is consumed during weekends and night time when the buildings are unoccupied. There is a dire need for active plug load power management to cater this. Authors in [150-153] provide insights on usage patterns of office equipment and to achieve plug load reduction.

Authors in [154] analyzed different plug load intervention techniques including occupancy sensing and load sensing plug strips intervention, educational and behavior based strategies, and installing Energy Star equipment. Occupancy and load sensing plug strips interventions achieved most savings as they shut down equipment during unoccupied periods or when equipment is idle. Authors in [147] also discuss similar ideas to control plug loads. Authors in [155] studied three plug load control strategies at eight office sites. These strategies included load-sensing plug strips, schedule timer controls and both controls applied at the same time. Printers and miscellaneous equipment achieved most savings with load sensing plug strips and schedule timer control. While the combined control achieved control in all categories of plug loads except monitors. Largest savings were shown by loads that run 24 hours a day; 7 days a week unnecessarily. Authors in [156] present a software architecture to enable plug loads as a DR resource to be automatically actuated. The architecture uses Smart Power Strips and is implemented by Energy Information Gateways (EIGs). Authors in [70] discuss the coordinated optimal control of plug loads during DR event. The optimal control algorithm utilizes software architecture presented in [156] to manage few local office plug loads to meet load shed target. The algorithm minimizes the inconvenience associated with the loss of operation of the actuated plug loads. Devices are actuated which consume largest amount of energy while also have lowest priority set by the consumer. Authors in [157] provide control of plug loads by designing energy metering and management system specifically targeted for DR. The designed smart energy meter can actuate its connected device. The DR server tied to this meter with its web-based user interface provides visibility and control of plug-loads to building managers, allowing them to deal with DR situations through user specified actuation policies.

2.3 Synergy among DR, Renewable and Storage Energy Systems to absorb EV penetration

2.3.1 Photovoltaic (PV) systems in commercial buildings

Buildings can be equipped with renewable energy technologies, such as PV or micro-wind generators. Field trials of urban building mounted micro-wind generators show that they generate less energy than predicted owing to insufficient wind resource [158, 159]. In addition, micro-wind generators suitability for roof mounting is questionable in urban environment due to complexity of wind distribution. PV is a well-known technology and authors in [160] highlight its emerging trends and advanced applications. Hence particular attention is given to PV in this study. PV, located either on building rooftop or integrated to building façade, produces electricity during daytime. PV has potential to reduce building peak demand; however, a large fraction of PV electricity generation occurs when the demand is moderate.

Photovoltaic modules are solid state devices which directly convert sunlight into electricity. Power from the sun intercepted by the earth is around 1.8×10^{11} MW, which is many times larger than present consumption rate from all energy sources [161] . PV devices are rugged and simple, and require little maintenance.

The costs of PV panels have fallen due to manufacturing in China [162]. U.S. is a clear leader in terms of research and development public funding for PV. U.S. Department of Energy (DOE) accelerates the development and deployment of all PV technologies through its Solar Energy Technologies Program (SETP). In February 2011, DOE launched a program, Sun Shot Initiative, which is focused on driving innovation to make solar energy systems cost competitive. The total PV capacity in the U.S. has increased by 1867 MW in 2011. By the end of 2011, approximately 214,000 distributed, grid connected PV systems were installed in U.S. PV capacity reached 0.4% of total national electricity generation [144]. DOE's SunShot Vision study lays out a scenario in which solar energy is projected to be 14% of total U.S. contiguous demand by 2030 [163].

2.3.2 Ice storage systems in commercial buildings

The renewable energy sources, like wind and solar, have variable and uncertain output which has led to an increase call for the deployment of energy storage systems. Onsite or local energy storage systems are not new to commercial buildings. Most building scale storage technologies are either thermal or electrochemical. These storage technologies provide grid operators the flexibility in grid operation to increase integration of additional intermittent renewable energy capacity and avoid capital investment for upgrading transmission and distribution infrastructure. From a building owner's perspective, storage systems help shift peak demand to off peak periods in order to optimize energy costs while maintaining occupant comfort.

A PNNL study [164] presents insights gained by literature review on thermal and electric energy storage systems for buildings. The study states that thermal energy storage (TES) is a proven technology, is less expensive and control strategies exist to integrate use into building energy management systems. The study also highlights that so far only a little effort has been made to explore the potential of thermal energy storage system with intermittent renewable energy smoothing. While batteries are expensive and there is only little experience using batteries for time shifting and load balancing services, it can be argued that excess renewable generation could be put back into the grid and utilized by another building but this approach leads to losses and there by storage is crucial.

For commercial buildings, space cooling presents a significant end use for electricity. In TES system for a commercial building, the chiller modulates its output in accordance with cooling load requirements and grid needs. Authors in [165] investigate the energy consumption and peak demand savings by ice storage systems for large and medium-sized office buildings in diverse climate zones. The findings indicate that ice storage system's energy savings depend upon climatic conditions.

Extensive research has been performed in the field of thermal energy storage systems. A research study [166] provides an elaborate review of various types of thermal energy storage technologies currently available in the market. Different thermal storage systems include chilled water storage systems, phase change materials and ice storage systems. Chilled water storage systems, although are compatible with existing chillers but there disadvantage is that they require large storage tanks [167]. Phase change materials also allow the use of standard chilling equipment but their disadvantage is that the tank typically cools the water for the distribution system to only 48–50°F, which accomplishes less dehumidification of the building and requires more pumping energy [166]. The ability to provide low chilled water temperatures, reducing fans and ducts sizes, introducing less humid air in occupied spaces and less storage tank's volume makes ice storage systems ideal candidate for thermal energy storage [166].

The different types of ice storage systems include ice-on-coil internal melt, ice-on-coil external melt and encapsulated ice. Ice storage systems can be operated as either full or partial storage. In a full storage system, entire cooling peak load is shifted to off peak periods. The chiller is not operational during peak hours and cooling load is completely met by storage. In partial ice storage systems, chiller and storage together meets the peak cooling demand.

Authors in [164] conclude that thermal storage is a load management tool and its use can be integrated into building HVAC control systems to generate value for electricity provider in exchange for a financial reward for the building owner. Authors in [168] analyze thermal energy storage potential in load profile management which has not been systematically developed as yet. Authors in [169] couple thermal energy storage with a conventional AC system to perform energy-demand management in Saudia Arabia, where cooling load is high. Reduced energy consumption, lower operation costs and downsizing of chiller plant are achieved as a result. Authors in [170] evaluate the application of cool storage AC in commercial buildings as a demand side management program used to improve system load factor and efficiency of electricity usage. Results show that the technology is a viable resource in generation power expansion planning and can reduce the need for new generation resources. Authors in [171] analyze performance of different energy storage devices in a building energy system, whose operation is formulated as an energy cost minimization problem, in a micro grid environment and conclude that thermal storage provides effective energy cost savings in multiple scenarios of demand and solar radiation profiles. Authors in [172] present cost analysis of a hybrid cooling system that uses thermal energy storage and AC powered by PV to meet a residential building's cooling load during peak hours. Historically ice storage systems have been applied to large commercial buildings and have been integrated with chillers. Mostly small and medium-sized commercial buildings have packaged AC units and if ice storage systems can be integrated with these, its deployment potential could be high [173].

2.3.3 Synergy among DR, renewable and energy storage systems

In order to absorb the increasing EV penetration, expanding the existing electric system would require construction of large plants far from the load centers, and upgrade of the existing transmission and distribution systems. This can be costly and time consuming, instead smaller power plants based on renewable energy systems can be deployed. EVs will create a significant new class of electricity demand from renewable energy sources such as PV. Due to variability of renewable energy output, storage systems can be utilized.

There are studies, highlighted below, which discuss the interaction of DR with PV or integration of PV and energy storage systems with EV charging stations. However, there are no studies which discuss EV absorption with PV and storage systems in demand responsive commercial buildings.

Studies in [174-176] report that DR can facilitate the integration of intermittent renewable generation and provide required ancillary services. Authors in [177] develop the load behavior of office buildings, which demand electrical energy during high daytime prices. Demand side management is utilized to shift demand to low prices and a PV system can be utilized to reduce demand during high tariffs. Authors in [178] evaluate the impact DR capability on PV penetration for residential customers. Customers with higher DR capability are able to accept more PV capacity due to slow decrease in the marginal revenue for new installed PV.

Authors in [179] investigate large scale deployment of both PHEVs and PVs to mitigate negative impacts on the grid. Their findings indicate that PVs can provide a potential generation source for mid-day PHEV charging, while PHEVs provide a dispatchable load for unusable PV generation during low demand periods. Hence, depending upon penetration of each technology, PV could meet the increased capacity requirements associated with PHEV deployment and PHEVs could absorb much of the curtailed PV generation. PHEV mid-day charging by PVs can increase its traveling distance using low cost electricity and potentially reduce the battery size. With respect to the integration of PV into a EV charging system, authors in [180] provide a review of EV charging methods using PV-grid and standalone PV systems. Authors in [181] show a PV system with battery storage powering a residential EV to reduce CO_2 emissions. Authors in [4] indicate that solar-assisted EV charging could reduce the peak load, but it is not a cost effective solution. Authors in [182] indicate that installation of PV panels to supply daytime charging of EVs could not meet EV's driving needs in winter. Authors in [183] study a public charging infrastructure integrated with PV and their results show that in urban environment, the high variability of renewable generation causes charging waiting delays.

Authors in [184]` analyze distributed energy storage (DES) systems for distribution feeders serving residential customers. The DES comprises fleet of battery based energy storage units at customer sites to provide flexibility for voltage control and reliability aspects. Optimal operation of these DES systems prevents the impacts of high EV penetration such as voltage deviations, increased losses and circuit overloading.

Authors in [185] study the impacts of solar and wind generation and combination of the two technologies with battery storage to control residential peak demand growth due to EV penetration in urban environment. The study shows that solar configuration produces more total energy but since this energy is produced during daytime it has no effect on the evening peak residential demand. However, coupled with battery storage system, solar generation is able to meet the evening peak residential demand. Although the wind configuration produces energy during night time but it shows less benefit even when coupled with battery storage system due to less energy production by wind resource in cities.

Authors in [186] provide more realistic simulations than [185] by using the 2020 and 2030 future PHEV and distributed energy resource (DER) projections, system effects due to the addition of PHEV, solar generation and wind generation. Monte Carlo simulations of DER adoption analysis is introduced. Locations for placing DER generation were based on minimizing overloading conditions. Findings indicate that DER generation along with storage can sufficiently manage load growth for a residential circuit in 2030 scenario but not in 2020 scenario.

Authors in [187] analyze wind and solar energy potential for PHEV charging. Availability of wind energy production to the grid would enable people to charge their EVs upon arriving home. The vehicles would start charging if there is excess capacity from the grid otherwise they would have to wait. Solar panels, unlike wind turbine generators can be easily installed on building roof or wall and present an attractive option for EV charging. The study presents a scenario of how smart grid can use wind energy resource for EV charging and a method for sizing PV panel for EV charging stations.

2.4 Knowledge Gaps

Based on the literature search presented in this section, the following knowledge gaps have been identified:

2.4.1 Design an approach to improve the distribution feeder's performance with EV penetration through coordinated control of demand responsive commercial buildings, ice storage and PV

Load control or DR strategies till now have been implemented and analyzed in individual commercial buildings for their economic benefits. However, researchers have overlooked load control to a group of commercial buildings to efficiently reduce grid's peak load, which is its main concern. No systematic studies are available on: firstly, developing coordinated load control strategies for a group of small and medium-sized commercial buildings in order to relieve the grid's peak load due to individual building's peak demand; and secondly, DR's ability to absorb EV penetration at commercial building level which has been identified as a research gap in Federal Energy Regulatory Commission's (FERC's) National Action Plan on DR.

Literature review indicates that most studies have analyzed either EV charge stations integrated with either PV systems, control of EV charging, especially for EV fleets in residential areas, or control of end-use loads for commercial buildings to achieve building demand savings. For EVs being charged at home, the charging process is controlled to shave the distribution feeder's peak load or improve the power quality. However, controlling or delaying public EV charging in commercial buildings to reduce their impacts on the grid is not applicable, especially when dealing with fast charging, where EVs can be fully charged within half an hour. As number of EVs increase, non-residential charging becomes vital.

Daytime EV charging can increase EV's traveling distance, potentially reduce battery size and increase EV visibility.

One promising solution to mitigate the impacts of EV charging demand in commercial buildings is to deploy the synergy between PV and DR of buildings' end-use loads and thus releasing the grid's stress has not been discussed in previous studies. There is a knowledge gap as to how a coordinated load control strategy in commercial buildings, ice storage discharge, and strategically deployed solar rooftop PV systems in groups of participating commercial buildings can absorb EV penetration using real world charging scenarios instead of delaying or controlling EVs.

2.4.2 Design an integrated control for commercial building DR applications that can evaluate DR potential for commercial buildings by load type

Small and medium-sized commercial buildings have not historically played much role as a DR resource both due to lack of hardware and software tools, and awareness. Most large commercial buildings (100,000 sq. ft. or more) are equipped with an EMS which provides opportunities for peak load reduction. However, the penetration of EMS is low in small and medium-sized commercial buildings (< 100,000 sq. ft.). Due to limited availability of DR methods and tools, building owners typically miss building specific DR opportunities. They do not approach DR strategy development systematically and are unable to correctly estimate DR effectiveness.

Existing studies have not estimated DR potential for commercial buildings by load type. There is a lack of data available as to how much peak load can be shaved with optimal control of building's major end-use loads including HVAC, lighting and plug loads taking into account occupant comfort preferences.

For HVAC control literature review reveals that an optimal control of each thermal zone's cooling load is needed since all thermal zones do not behave the same, they may not be able to evenly share the DR shed burden. Higher increase in the cooling set points for zones with high solar gains drastically effects occupant thermal comfort. For lighting control, typically daylight control with automatic light switching or loosely coupled photoelectric dimming is implemented in buildings. For plug load control, there is a knowledge gap with regard to evaluating impacts of controlling individual plug load, in a commercial building, on the aggregate building load profile.

2.4.3 Dynamic plug load modeling in building energy simulation tools

For plug loads there are only few studies that provide 1) energy usage patterns of different commercial plug loads; 2) demonstrate potential benefits of using energy efficient appliances; and 3) perform control of few commercial equipment for energy conservation purposes.

In order to control the plug loads in commercial buildings for evaluation of DR strategies, their models have to be developed based on individual plug load's characteristics. Plug load models should be of short time interval, as some usually run for only few seconds or minutes to perform a job, e.g., printing and faxing. Considering hourly data for plug loads is too rough for their control. Existing simulation tools lump all plug loads together and the total plug load power consumption is determined by using a constant plug load density (i.e., W/m^2) together with the plug load schedule, leading to simulation results exhibiting low fidelity. For plug load modeling, load duration curves of key plug loads have to be explored in order to better map how consumed power is affected by usage patterns.

2.4.4 Real-world EV models

Research studies use simplified EV models by either fixing the distance traveled by EVs in a fleet, assuming same battery size for all EVs, ignoring different driving habits, diverse arrival times, types of EV charge stations, and aggregating all vehicle batteries into one large unit and using historical data to predict vehicle availability.

In order to accurately determine the impacts of EVs on the distribution feeder, EV models indicating real world charging scenarios are needed. EV models used in many studies are based on assumptions ignoring either vehicle types (Nissan Leaf, Toyota Prius), vehicle class (sedan, small car, SUV, etc.), driving cycle (city, highway, congested) and the driver style (aggressive, passive), diversity of usage, multiple charging events over the day, dynamics of EV arrivals and departures in real time, or driving habits.

2.4.5 Design an integrated automation of ice storage and PV in demand responsive commercial buildings

Building owners want to make buildings demand responsive so that they can participate in electricity market. Literature review shows that there are studies which discuss coupling of thermal storage with conventional AC, generating power with a rooftop PV or employing DR strategies at the consumer side to reduce peak demand. However, no work has been carried out to study the impact of deploying various combinations of PV and ice storage to generate additional benefits, including clean energy generation from PV and valley filling from ice storage, from demand responsive buildings. Building owners can take advantage of different electricity prices during peak and off-peak hours and utilities can spread the demand over whole day. DR, on-site renewable and storage can reduce the investment cost, installed capacity of power plants and its CO_2 emission.

Historically ice storage systems have been applied to large commercial buildings. Studies to date have not demonstrated integrated control approaches for ice storage and PV systems or quantify how the coordinated control of ice storage system, end-use loads and PV system can optimize a building's load profile.

3 Methodology

This Section presents the load control strategy for EV absorption. Section 3.1 defines the absorption strategy for the distribution feeder. Sections 3.2 – 3.9 discuss the simulation tools for building and distribution feeder modeling, electric distribution feeder model, commercial building models, plug load models, PV, ice storage and EV models respectively.

3.1 EV Absorption Strategy for the Distribution Feeder

In order to absorb EV penetration, control of end-use loads and ice storage discharge along with PV were introduced in the demand responsive commercial buildings including small- and medium-sized office and retail buildings. In this study, the objective of the proposed strategy was to keep the distribution feeder's peak demand unchanged with EV penetration. To accomplish this, a threshold value was selected, which is the distribution feeder's original peak demand (kW) without EV, load control, PV and ice storage systems. If the distribution feeder's peak demand got higher than this threshold due to EV penetration, the excess load was shed by performing control of major loads in participating demand responsive commercial buildings. See Figure 1. The control of major loads was arranged to spread over the day and hence minimizing demand restrike– Here, demand restrike refers to a sudden increase in building load due to set point adjustments after a building participation in load control [123].

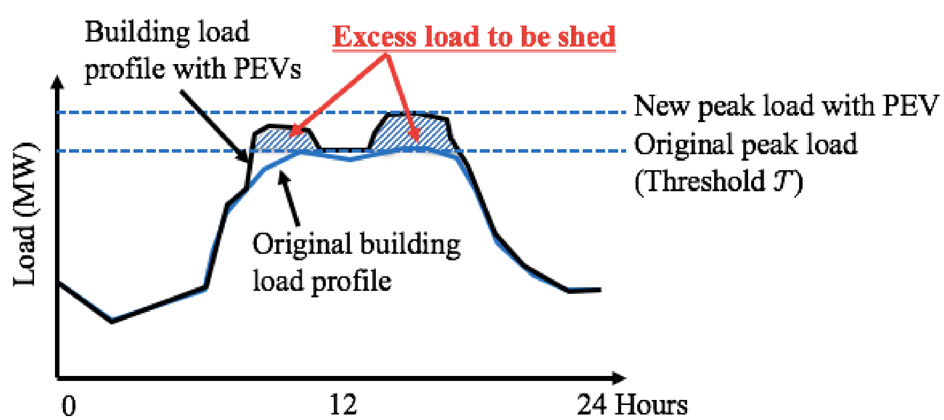

Figure 1 Distribution feeder's excess load due to EV penetration

Upon receiving a load control signal from the utility, participating buildings managed their end-use loads (i.e., HVAC, lighting, and plug loads, including EVs) in an optimal manner so that peak demand reduction could be achieved while a comfortable indoor environment was maintained.

The flowchart in Figure 2 illustrates the overall strategy for EV demand absorption in a distribution feeder.

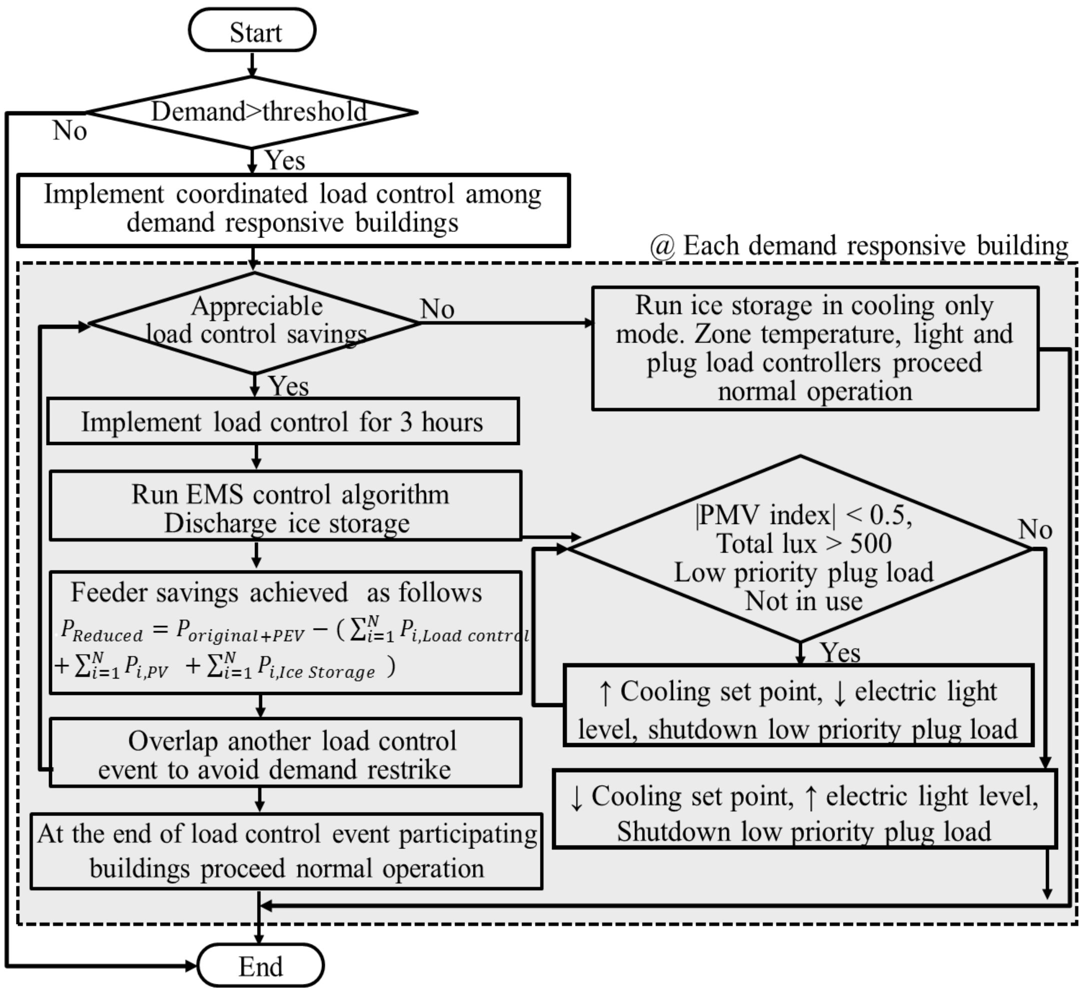

Figure 2 EV absorption strategy for the distribution feeder

3.1.1 Strategy to decide level of participation from each demand responsive building

The level of load control implemented in each building depends if they can provide appreciable load control savings which is mainly based on buildings' operating schedules and load control savings potential during the operating hours. In this study, load control savings potential was evaluated through simulation studies by simulating each building type in EnergyPlus for different time periods of the day with the designed load control algorithm, discussed in Section 3.1.2. Based on this insight, buildings with smaller operating hours were made to participate first in load control and those with longer operating hours participated later in load control. For instance, office buildings need not to participate in load control during late evening hours, when their occupancy is low, and can only provide limited load control savings. Whereas more retail buildings can participate towards late evening hours due to their longer operating hours and ability to still provide appreciable load control savings. This method is further elaborated by using a case study as discussed in Table 19, Section 4.1.

The resulting EnergyPlus simulation also reveals the relationship between the size of a building and the amount of load control savings a building can provide. That is, load control savings of small-sized office buildings are less than other demand responsive buildings. These buildings can absorb only a small portion of excess demand. Hence, they can participate when EV charge impacts are limited. If a building could not provide appreciable load control savings, then it did not participate in load control and continued its normal operation.

Calculation of distribution feeder demand **-** The distribution feeder's demand is reduced per Equation 3.1.1.

$$P_{Reduced} = P_{original+EV} - \left(\sum_{i=1}^{N} P_{i,Load\ control} + \sum_{i=1}^{N} P_{i,PV} + \sum_{i=1}^{N} P_{i,Ice\ Storage} \right)$$

Equation 3.1.1

Where:

$P_{Reduced}$	:	Distribution feeder's reduced demand in kW that needs to be shed due to EV penetration
$P_{original+EV}$	:	Distribution feeder's original demand in kW with EV penetration
$P_{i,Load\ control}$	:	Optimized demand value in kW for the i^{th} demand responsive commercial building participating in load control
$P_{i,PV}$	:	Demand reduction in kW by the PV system for the i^{th} demand responsive commercial building participating in load control

$P_{i,Ice\ Storage}$: Demand reduction in kW by the ice storage system for the i^{th} demand responsive commercial building participating in load control

***Mitigating demand restrike* -** The coordinated load control strategy among demand responsive buildings minimized demand restrike which occurs when buildings after participating in load control proceed their normal operation and instantaneously reduce cooling set points and ice storage switches to conventional cooling, causing an increase in electric cooling consumption. This demand restrike had to be taken into account by the next group of buildings participating in load control by overlapping their end-use loads control with those already participating in load control.

Lastly, if load control strategy (including ice storage control) was not able to absorb EV penetration, the proposed strategy suggested appropriate sizes and number of rooftop PVs to help absorb EV penetration.

3.1.2 Load control strategies in commercial buildings

Upon receiving a signal indicating excess load, participating buildings, including small- and medium- sized office and retail buildings, managed their end-use loads (i.e., HVAC, lighting, and plug loads, including EVs) and controlled ice storage charge/discharge in an optimal manner to achieve maximum demand reduction while maintaining a comfortable indoor environment. This optimal control algorithm was designed using EnergyPlus Energy Management System (EMS). A building was assumed to participate in load control for no more than 3 hours to limit occupant discomfort. The strategy for controlling each major loads, including HVAC, lighting and plug loads, is discussed below.

Minute-by-minute load simulation was performed to enable the most accurate representation of building loads. Note that, while most traditional Building Energy Management (BEM) products enable control of building loads in 15-minute intervals, with the availability of Internet-of-Things (IoT) devices and powerful computers, recently released BEM software platforms, such as Building Energy Management Open Source Software (BEMOSS) [188], are capable of monitoring and control building loads at a fine resolution of 1-minute intervals or less. This justifies the 1-minute resolution end-use load control presented in this study.

The designed control algorithm is explained as follows:

- First, the EMS module and the zone cooling set point, light and plug loads actuators were activated and over rid the normal building operation during load control duration.
- At each time-step the EMS sensors retrieved the PMV index, daylight illuminance levels and cooling set points of each zone on all floors along with light and plug load schedules. This data was then mapped to EMS variables to be used in control algorithms specified in the EMS program.
- At the beginning of each time step the EMS Program Calling Manager called the EMS program - which contains instruction blocks of Erl code - to adjust each zone's cooling set points, lights and plug load levels as per the control algorithm. Building's cooling system attempted to meet the thermal load with the adjusted cooling set points, light and plug load levels for the relevant zones.

In this study, the algorithm designed for space temperature set point control, optimally adjusted each thermal zone's cooling set points to achieve peak load savings and maintained occupant thermal comfort. The algorithm designed for lighting control in EMS provided a tighter control of light levels, integrated with daylight, to maintain the illuminance at the desired set point in order to achieve more savings with good adaptability to the changing daylight conditions. In order to improve the accuracy of building simulation results and gain an insight into how individual plug load operation can be controlled during load control; instead of lumping together all the plug loads, the study developed a 1-minute resolution data set at individual plug load level that was integrated with EnergyPlus. This allowed each key plug load to be individually controlled and shutdown during load control as each equipment's usage pattern affects the power it consumes.

3.1.2.1 Thermal and lighting comfort levels

Fanger's Predicted Mean Vote (PMV) index was used to measure occupants' thermal comfort – with comfortable range between –0.5 and +0.5 – which takes into account air temperature, mean radiant temperature, relative humidity, air speed and two personal factors including activity and clothing [123]. With raised cooling set points, PMV in each zone is kept lower than +0.5 to maintain thermal comfort [189]. Fanger model assumes that the person is thermally at steady state with his environment. The model is based on energy analysis that takes into account all modes of energy loss from the body. It was developed with human subjects in climate chambers exposed to well control environments. The PMV model has been validated in various field studies including the ASHRAE's worldwide research in buildings with HVAC systems situated in cold, temperate and warm climates and during both summer and winter [190]. PMV is calculated using the following relations described in [191, 192].

When PMV is zero, thermal comfort is maintained; + 1, + 2 and + 3 indicate slightly warm, warm and hot conditions respectively, while - 1, - 2 and - 3 present slightly cool, cool and cold conditions respectively. EnergyPlus can handle PMV calculations, considering activity and clothing schedules based on time of day together with thermostats for the zones. In this study, an HVAC system conditions the space based on comfort not just temperature. Internal gains from occupants, light, equipment, infiltration and ventilation that affect thermal zones are also taken into account. In addition, the radiative effect of surfaces is taken into account and inside surface temperatures are generated without which thermal comfort calculations are not possible [193].

In this study illuminance, an index which assesses the quantity of light [194], for building space was used for light control. Ambient lighting levels are varied to maintain an average ambient illumination level of 500 lux [195-197], as recommended by Illuminating Engineering Society of North America (IESNA), in the retail and office buildings.

3.1.2.2 Load control strategy for office buildings

During load control, HVAC, lighting and plug loads were optimally controlled in an office building. Control algorithms for HVAC, lighting and plug loads are described in detail below.

- ***HVAC load control -*** To perform HVAC control, the lower temperature limit in all zones was set at the normal operating cooling set point during occupied periods, or 24°C. Each zone's cooling set points were adjusted repeatedly until a value was obtained at which the PMV index lied in between -0.5 and +0.5 and maximum peak load savings could be achieved. Once judgment had been made as per the EMS program instructions, EMS zone temperature control actuators increased or decreased thermostat cooling set points for all zones as per Equation 3.1.2. It is a schedule-based control since the building's normal operating cooling set point schedule is considered. The “SET” instruction performs control actions on the object to which it is mapped; here zone temperature control actuators. The offset varies at each time step, depending upon how much the cooling set points should be increased or decreased in order to maintain the PMV index within comfortable range. After participating in load control, the normal cooling set points were resumed by setting the temperature control actuators for each zone to “Null”. Null is a special structure that stops the actuator from overriding control.

$$SET \qquad T_{cool}^{Adjusted} = T_{cool}^{Normal} + \beta_{cool} \qquad \text{Equation 3.1.2}$$

Where:

$T_{cool}^{Adjusted}$	:	Adjusted cooling set point (°C)
T_{cool}^{Normal}	:	Normal operating cooling set point (°C)
β_{cool}	:	Adjustment factor for cooling load (°C)

- ***Electric lighting load control -*** The electric lights control algorithm was developed in EMS that provides tighter control of electric lights to maintain an overall daylight plus electric light illuminance (in case of low daylight illuminance levels) at a set point value. This is unlike the daylight control object available in EnergyPlus which linearly reduces light electric power in response to increase in daylight illuminance. The developed EMS control maintains the targeted illuminance levels in both the perimeter zones with daylight illuminance and the core zones which are deprived of daylight illuminance. Dimming and shutting down the lights has an additional benefit as it reduces the cooling load.

  a) In order to optimally utilize daylight, photosensors located in each zone communicate real time illuminance levels to the EMS which was configured with a threshold value of 500lux. This is as recommended by Illuminating Engineering Society of North America (IESNA) for office buildings [198]. For a medium-sized office building as an example, as the perimeter zones are 15ft deep and receive uniform daylight illuminance due to the windows which are distributed evenly in continuous ribbons around the perimeter of the building, the photosensors were located 3ft above ground (at desk height), at the center of each perimeter zone and 10ft away from the windows. EnergyPlus calculates daylight illuminance at the photosensor – which is dependent upon sky conditions (clear, clear turbid, intermediate and overcast), glass transmittance of windows, location of photosensor, window shading devices and reflectance of interior surfaces - through the daylight factor (DF)[194] which is ratio of interior illuminance to exterior horizontal illuminance and the external horizontal For core zones, which do not receive daylight illuminance, at each time step EMS core zone light control actuators increased or decreased the electric lighting levels as per Equation 3.1.5. It is a schedule-based control since the building's normal operating light schedule is considered. The adjustment factor is varied, and for each value electric light input power level is calculated and input in the Equation 3.1.3 to calculate the generated electric illuminance. Electric light input power level was selected which can maintain 500lux. illuminance [199]. The external illuminance is calculated in EnergyPlus through a model developed by [200]. The daylight illuminance available at the photosensor is added to the electric light illuminance - which is determined using Equation 3.1.3 [201, 202] in the EMS program - to determine each perimeter zone's overall illuminance value as shown in Equation 3.1.4.

$$I_{electric} = \frac{P * \eta}{A} \qquad \text{Equation 3.1.3}$$

Where:

$I_{electric}$	:	Electric illuminance (lux)
P	:	Electric light input power (W)
η	:	Luminous efficacy $\left(\frac{\text{lm}}{\text{watt}}\right)$
A	:	Area of a zone (m^2)

$$I_{total} = I_{electric} + I_{sensor} \qquad \text{Equation 3.1.4}$$

Where:

I_{total}	:	Total illuminance (lux)
I_{sensor}	:	Daylight illuminance at the photosensor (lux)

A fluorescent lamp, most common in commercial building, is considered for the modeled office building. Fluorescent lamp efficacy is between 70 to 100 $\left(\frac{lm}{watt}\right)$ and the system – lamp + ballast - decreases by about 5% [203]. An efficacy of 90 $\left(\frac{lm}{watt}\right)$ is considered.

EMS light control operates as follows:

b) For each perimeter zone, at each time step, firstly the daylight illuminance level from the photosensor was read by the EMS program. If this value was greater than 500lux than the zone light control actuator completely shut down all lights by setting the adjustment factor in Equation 3.1.5 to zero. If the daylight illuminance level was less than 500lux than the EMS zone light control actuator increased or decreased the electric lighting level as per Equation 3.1.5 by varying the adjustment factor. Each calculated electric light input power level was input in the Equation 3.1.3 to calculate the generated electric illuminance. This electric illuminance was then added to the daylight illuminance as per Equation 3.1.4 to determine the overall zone illuminance. Electric light input power level was selected which can maintain an overall 500lux. After participating in load control, the normal light levels were resumed by setting the light control actuators for each zone to "Null".

$$SET \quad P_{light}^{Adjusted} = P_{light}^{Normal} \cdot S_{light} \cdot \beta_{light} \qquad \text{Equation 3.1.5}$$

Where:

$P_{light}^{Adjusted}$	:	Adjusted lighting load power (W)
P_{light}^{Normal}	:	Normal lighting load power (W)
S_{light}	:	Normal lighting load schedule

β_{light}	:	Adjustment factor for lighting load

- ***Plug load control -*** During load control, 50% miscellaneous appliances, all portable fans and water coolers were shut down to achieve peak load savings by smart plugs and strips. The designed algorithm did not shutdown critical plug loads. Shutting down plug loads also reduces cooling load. Desktop and server computers/monitors were not shutdown during DR event since a desktop computer should not be de-energized without going through a proper shutdown procedure and a laptop, after de-energizing, if left in idle state can fully discharge before a proper shutdown procedure is performed [204]. Refrigerators, vending machines also remained on in order to maintain food quality and cold beverage temperatures. Other office equipment - like fax machines, copy machines and laser printers - were observed to consume low standby power. Their power consumption is high only when in an active mode - which lasts only for a short duration - therefore there was no need to shutdown these equipment.

  Electric plug loads were shut down by EMS zone plug load control actuators as per Equation 3.1.6. It is also a schedule-based control since for each plug load - to be shut down - its normal operating schedule is considered. The adjustment factor is 0.5, which allows shut down of 50% miscellaneous equipment in each zone, and zero for shutting down all portable fans and water coolers during load control. Plug load control actuators for each zone were set to "Null" after participation in load control.

$$SET \quad P_{plug}^{Adjusted} = P_{plug}^{Normal} \cdot S_{plug} \cdot \beta_{plug} \qquad \text{Equation 3.1.6}$$

Where:

$P_{plug}^{Adjusted}$	:	Adjusted plug load power (W)
P_{plug}^{Normal}	:	Normal operating plug load power (W)
S_{plug}	:	Normal operating plug load schedule
β_{plug}	:	Adjustment factor for plug load

3.1.2.3 Load control strategy for retail buildings

All zones in the retail building were allocated a priority based on which their lighting and HVAC loads were controlled. Lower priority zones' lights and HVAC were controlled first followed by higher priority zones. Table 5 shows the allocated zones' priorities for the application of load control. Priorities were assigned in order of increasing occupant density and also significance of performed activity. All zones other than the vestibule and sales areas were assigned lower priority as these zones do not have the sales potential. That is, these areas are not for display or appraisal of merchandise, and do not need to be appealing as there is no customer influx. Zones like mechanical room, corridor were assigned the lowest priority, "6", due to lowest occupancy. Breakroom and meeting room, with next higher occupant density, were assigned a priority of "5". Office and restroom were assigned a priority of "4" due to high occupant density. Office lighting is as important as any corporate office lighting. Stockroom was assigned a priority of "3" due to its high occupant density and this zone involves the task of reading of labels and identifying merchandise [205]. Vestibule was assigned a priority "2" as a shopper's first impression is shaped at the store's entrance. The lighting here should be pleasing and facilitate safe passage and create sense of security [205]. Sales areas' lights and HVAC were controlled last to as these zones need to be comfortable and should appear attractive to the customers in order to encourage shopping. Perimeter sales areas allowed daylight control as these zones receive natural daylight hence they were controlled first before the main sales area and were assigned lower priority than the main sales area. Sequence of HVAC and lighting control for each zone is discussed below.

Zone	Order of increasing priority	Reason for priority assignment
Mechanical room/Corridor	6	Lowest occupant density
Breakroom/Meeting room	5	Next highest occupant density
Office/Restroom	4	Store offices should reflect the store's image. Lighting as important as in a corporate office. Next highest occupant density
Stock room	3	Reading labels and identifying merchandise are the primary objectives. High occupant density
Vestibule/Perimeter sales area	2	These zones need to be appealing. Daylight control possible as these zones receive daylight
Main sales area	1	Zone needs to be comfortable and attractive, customers should be able to easily evaluate product and hence this zone is controlled the last

Table 5 Designated zone priorities for control of lighting and HVAC in retail buildings

Whenever load control was required, lights and HVAC were controlled the same way as described for office buildings at each time step, i.e., at 1-minute intervals, without sacrificing customers or employees comfort requirements. Summer cooling set points in each zone were raised that did not compromise thermal comfort. Lighting levels were maintained that could still meet the required illuminance levels. The order in which control of lighting and HVAC load was performed is explained in Table 6. For all zones first their HVAC load was controlled and then lights. Lighting for zones with high priorities “1” and “2”, which are sales area, were controlled last as lighting plays an important role in these zones. For sales area (main sales and perimeter sales), only general lights were controlled not the accent lighting so that product visibility was not greatly affected.

Order of control	Load control algorithm for retail buildings
Step 1	Adjust cooling set points first to maintain PMV<+0.5 and next adjust lights to maintain 500lux for zones with lowest priority “6”
Step 2	Adjust cooling set points first to maintain PMV<+0.5 and next adjust lights to maintain 500lux for zones with priority “5”
Step 3	Adjust cooling set points first to maintain PMV<+0.5 and next adjust lights to maintain 500lux for zones with priority “4”
Step 4	Adjust cooling set points first to maintain PMV<+0.5 and next adjust lights to maintain 500lux for zones with priority “3”
Step 5	Adjust cooling set points to maintain PMV<+0.5 for zones with priorities “2” and “1”
Step 6	Lighting for zones with priority “2” is controlled. If daylight illuminance>500lux than shutdown all general lights. If daylight illuminance<500lux than adjust lights so that general light and daylight together produce 500lux
Step 7	Adjust lights for zone with priority “1” to maintain 500lux

Table 6 Control of lighting and HVAC based on zones’ priorities in retail buildings

3.1.3 Strategy for Ice Storage Charge/Discharge Control

Some demand responsive buildings had ice storage systems integrated with their packaged air-conditioning (AC) units which could be controlled to discharge fully or partially [165] and provide space cooling, thereby further reducing the cooling load. For demand responsive buildings with ice storage systems, their mode of operation was changed to discharge-only mode (full storage discharge) or cool and discharge mode (partial storage discharge) as needed so that building’s cooling energy consumption could be reduced through storage discharge.

3.2 Simulation Tools used in the Study

This Section describes the simulation tools, i.e., EnergyPlus and DEW, used in this study. EnergyPlus has been used for modeling and simulating the small- and medium-sized commercial buildings and for developing the integrated automation for load control. DEW has been used for modeling and simulating the electric distribution feeder.

3.2.1 EnergyPlus – Building Energy Modeling and Simulation Tool

In this study EnergyPlus version 8.3 was used for modeling and simulation purposes. EnergyPlus is a building energy simulation program from the creators of DOE.2 and Building Loads Analysis and System Thermodynamics (BLAST) that combines their best features and capabilities [196]. Authors in [206, 207] provide the detailed overview of EnergyPlus. EnergyPlus solves the biggest deficiency of BLAST and DOE-2, sequential simulations, using integrated solution technique. In BLAST and DOE-2 there is lack of feedback from the HVAC module to loads calculations, which leads to inaccurate space temperature prediction. Accurate prediction of space temperatures is needed for proper system and plant sizing and occupant comfort calculations. In EnergyPlus loads are calculated by heat and balance engine and passed on to the building systems simulation module which calculates response from the heating and cooling plant and electrical system. Feedback from the building systems simulation module determines whether loads are met or not and accordingly the space temperatures are adjusted in the next load calculations. EnergyPlus requires an ASCII text based description of the building and underlying mechanical system and calculates the heating and cooling loads needed to maintain thermal control set points, energy consumption and other parameters visualizing actual building performance based on user’s description of building envelope, mechanical systems, location, weather and other inputs [208].

The integrated automation for optimally controlling building end-use loads, was designed with EnergyPlus Energy Management System (EMS) module. The EMS uses a simple programming language, EnergyPlus Runtime Language (Erl), to specify control algorithms. Application guide for EMS [209] provides details of Erl programming. With the EMS control, EnergyPlus can simulate novel control strategies [210]. The core of EMS module is the EMS Manager which co-ordinates activities of EMS objects like sensors and actuators with the overall EnergyPlus simulation. The EMS works by polling a set of sensors and retrieves data about external environmental conditions, internal building conditions, HVAC and other equipment conditions. Sensor data becomes input variable for EMS control algorithms. Control algorithms are specified by programming language based on IF-THEN-ELSE statements and other logic structures. Remote actuators are controlled to make changes to system operations once the EMS passes judgment. The concept is to emulate, inside EnergyPlus, the same type of controls that can be implemented with digital EMS in real buildings. EnergyPlus EMS can turn on or off the lights; change the zone thermostats set points and other actions thereby affecting building operation.

3.2.2 Distribution Engineering Workstation (DEW) - Distribution Feeder Modeling and Analysis Tool

DEW was used for modeling and analyzing the distribution feeder in this study. The distribution feeder is constantly evolving into an active resource with complex modeling needs. Over the years the distribution feeder could contain a complex mix of load, generation, and automated resources all operating on different time scales.

This distribution feeder was modeled in DEW and simulations were performed using its power flow applications [211]. Authors in [212] compare different distribution modeling tools. DEW offers a graphical user interface which enables easy changes to models and scenario development options. DEW allows user to define and arrange different steady state applications like power flow, load allocation, feeder performance, fault location, and system restoration in a queue for different operation and planning studies. DEW can also export results to a built-in graphic tool for data visualization. The DEW software package is the only solution that relies on a non-matrix based solving method, graph theory-based approach, called Graph Trace Analysis (GTA). GTA is a topology search method that iterates from one node to the neighboring node and updates the feeder connectivity and physical characteristics like impedance, voltage drop and current flow. The GTA power flow method in DEW is naturally distributed and can solve the power flow problem in a few seconds.

3.3 Electric Distribution Feeder Model in DEW

A real world distribution feeder model, shown in Figure 3, was used for analysis purposes in this study. The circuit has underground cables, overhead lines, overhead cables and bus bars and load/service points. The main feeder is about 5,272ft long with branching laterals. The 3-phase voltage at the substation is stepped down from 69kV to 13.2kV. The circuit has a total of 97 load buses with both commercial and residential customers. 25 load buses are supplied by phase A, 12 by phase B, 18 by phase C and 42 have a 3-phase supply.

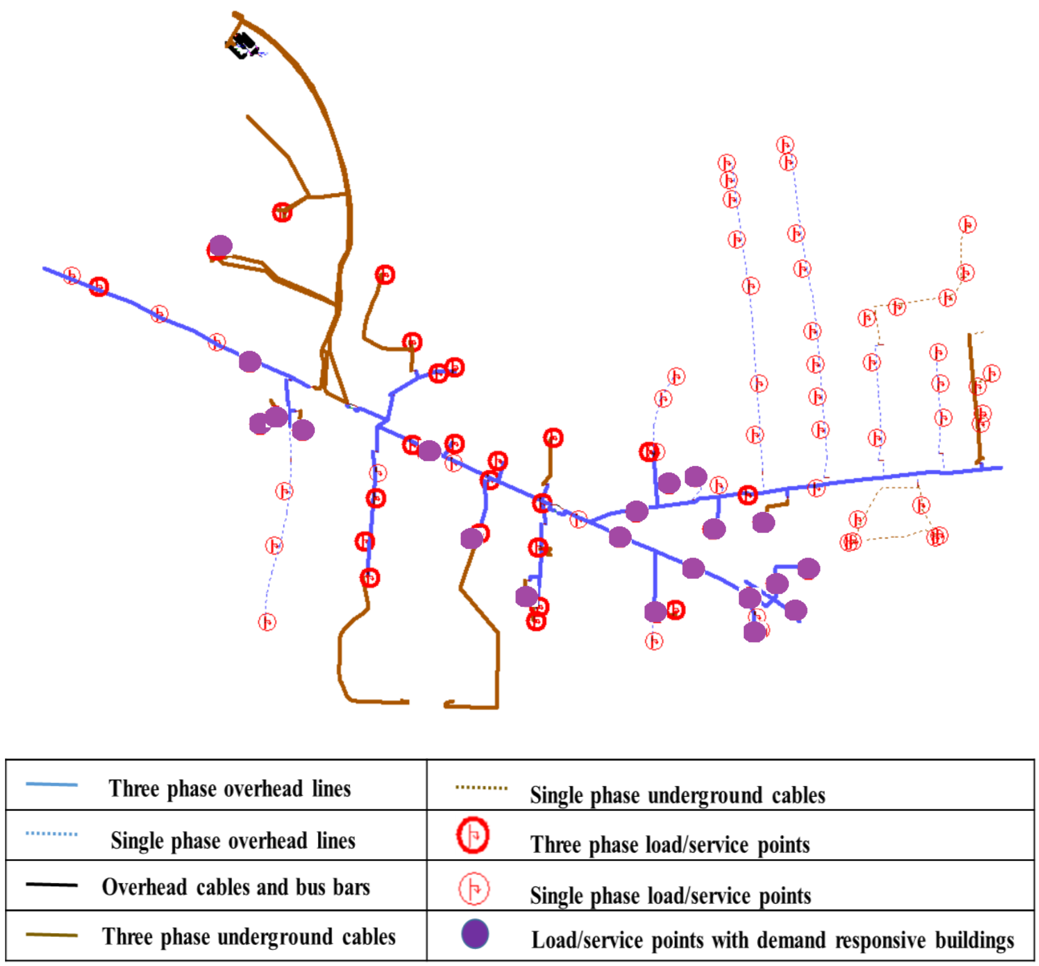

Figure 3 Distribution feeder model used in this study modeled in DEW software

Commercial customers connected to 21 load buses, colored purple, in the feeder were replaced with scaled down dynamic demand responsive building loads as explained in Section 3.4, representing a penetration of about 22%. These demand responsive buildings include 8 medium-sized office buildings, 7 stand-alone retail buildings and 6 small-sized office buildings. In this study, load profiles of these buildings developed in EnergyPlus were integrated into the modeled distribution feeder, and thus their power consumption was scaled down to match with the existing load and distribution transformer ratings. The load buses selected to be replaced by the demand responsive buildings originally had commercial loads connected to them with peak demand similar to that of the new demand responsive buildings and the building transformers can accept additional building load. The demand responsive buildings are connected to the 3-phase load buses except for 2 buildings which are connected to the load buses supplied only by phase A. These buildings' dynamic load profiles were added to the distribution feeder model using the Measurement Selector dialogue in DEW, enabling measurements stored in applicable database tables to be uploaded to the feeder model.

3.4 Commercial Building Models in EnergyPlus

This Section summarizes the simulated small and medium-sized commercial building models used for experimentation in this study. Small and medium-sized office buildings and a standalone retail building were selected for the study. The simulated small and medium-sized office building models are based on Department of Energy (DOE) reference building models and are theoretical buildings whose characteristics are typical of buildings of their size and use. The EnergyPlus input file for these simulated building models are available in [147], of which the description is provided in [197, 213]. The simulated standalone retail building model is based on the prototype medium-sized retail building model available in [32, 214] developed by National Renewable Energy Laboratory (NREL). The retail building model represents a medium box store with average level of retail activity, such as a clothing store and has little plug loads.

Input assumptions about climate conditions, building envelope characteristics, building operating characteristics, internal and external loads for developing the simulated building models in EnergyPlus are discussed below.

- *Climate data* – The weather data used is of Ronald Reagan Washington National airport. Weather data, in the EnergyPlus weather format is available from [24]. Figure 4 shows the outdoor air dry-bulb temperature for a summer day used in this study. The worst hot summer day has been chosen so that the designed strategy works for all other days over the year. From noon to around 6pm outside air temperature is greater than 30°C.

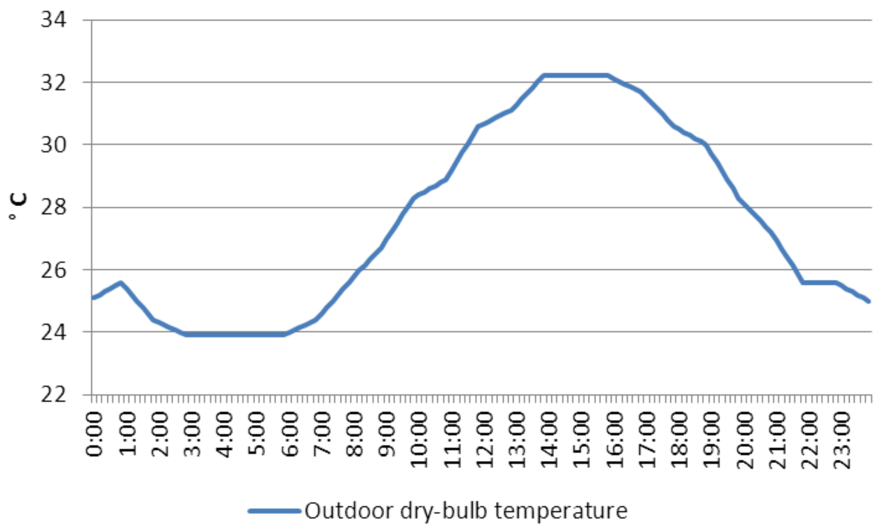

Figure 4 Outdoor dry-bulb temperature for a summer day used in this study

3.4.1 Small-sized office building model input assumptions

- *Building envelope* – The small-sized office building for this study is a 5,500 ft^2 single-story building. The building is rectangular shaped, 90.8 ft. by 60.5 ft. (aspect ratio 1.5). Building envelope constructions include wood-framed walls, attic roof with wood joist and slab-on-grade floors. The windows are 6ft by 5ft punch type and are evenly distributed along the four facades. The window to wall ratio for South is 24.4% and 19.8% for the other three orientations. Figure 5 shows the axonometric view of the small-sized office building used in this study.

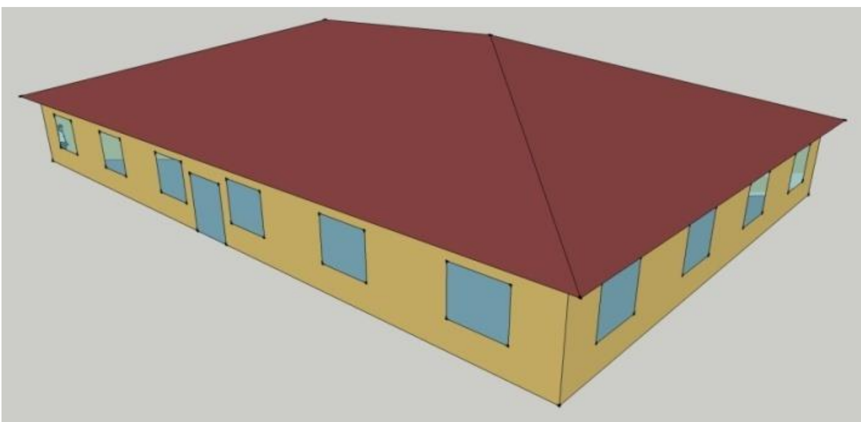

Figure 5 Axonometric view of the small-sized office building used in this study [215]

- *Building operation* – The occupancy, lighting, HVAC and electric equipment schedules on a typical weekday used in this study are shown in Figure 6. The building follows typical occupancy patterns for office building with peak occupancy between 8am to 5pm on weekdays with limited occupancy beginning at 6am and extended until midnight to include janitorial function and after-hours work. From 8am to 5pm, occupancy, lights and equipment usage is at maximum with a decrease during lunch time between 12pm to 1pm. There is 40% usage of miscellaneous electrical equipment after unoccupied hours. HVAC system starts earlier before occupants arrive to bring the space to desired temperature.

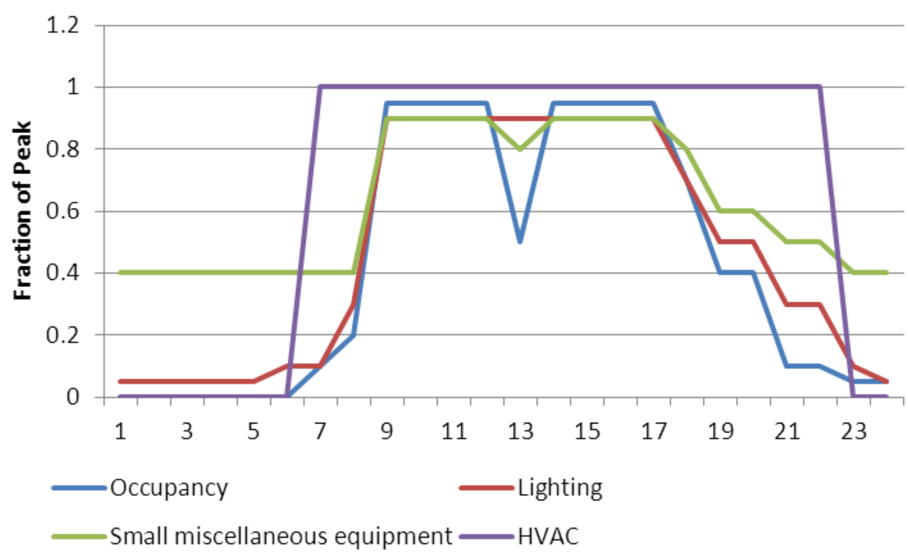

Figure 6 Small-sized office building typical weekday schedule used in this study

- *HVAC load* – The building has five single zone, packaged rooftop units, serving five thermal zones with constant air volume (CAV) distribution. For a summer weekday from 6am to 10pm the normal operating cooling set point is 24°C. During off-hours set back strategy is applied and the cooling temperature set point is 26.7°C. The building has five thermal zones on each floor. A zone is a thermal concept not geometric. It is described as an air volume at a uniform temperature which includes the heat transfer surfaces, such as outside walls, roofs and floors, and heat storage surfaces, such as interior surfaces, bounding or inside that air volume [216]. Each zone has its own thermostat. There are four perimeter zones and one core zone. Each perimeter zone extends from exterior wall inward for 16.4 ft. Figure 7 shows the HVAC zoning.

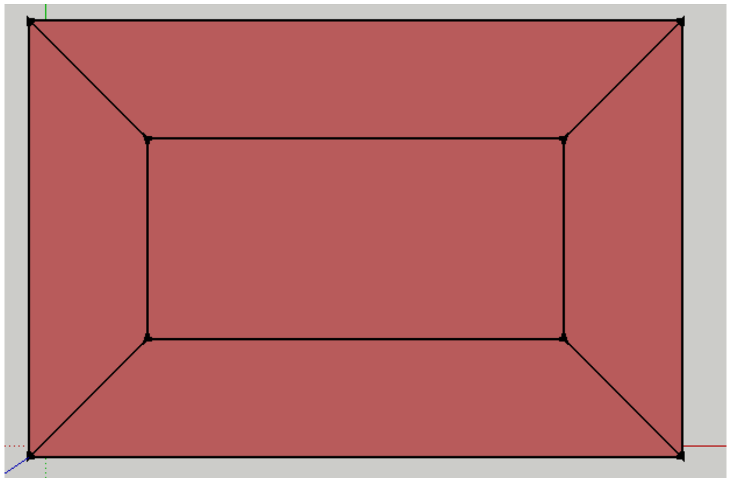

Figure 7 HVAC zoning for small-sized office building used in this study [215]

- *Occupants, lighting and equipment* – Number of occupants in the building are 28. Hence there are 5 persons per 1000 ft^2 of gross floor area. Ambient lighting power density for the entire building is 1 W/ft^2. Office buildings have plug loads, such as office equipment, refrigerators, coffee makers, beverage and vending machines. The electric plug load density is 0.63 W/ft^2 [215]. Table 7 shows the plug load equipment inventory for the small-sized office building.

Equipment	Quantity
Beverage vending machines	1
Fax machines	1
Computers-servers	1
Computers desktop	9
Computers laptop	6
Monitors server/desktop	1/15
Laser printer	1
Copy machine	1
Water cooler	1
Refrigerator	1
Coffee maker	1

Table 7 Plug load equipment inventory for the small-sized office building used in this study

3.4.2 Medium-sized office building model input assumptions

- *Building envelope* – The medium-sized office building for this study is a 53,600 ft^2 three-story building. The building is rectangular shaped, 164 ft. by 109 ft. (aspect ratio 1.5).

Building envelope constructions include steel-framed walls, flat roof with insulation above the deck and slab-on-grade floors. The window to wall ratio is 33%. The windows have a height of 4ft and are distributed evenly in continuous ribbons around the perimeter of the building. Figure 8 shows the axonometric view of the medium-sized office building used in this study.

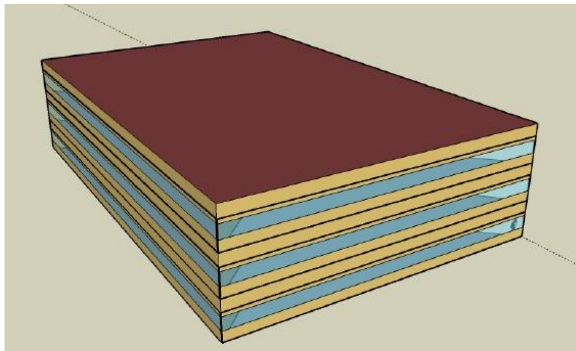

Figure 8 Axonometric view of the medium-sized office building used in this study [213]

- *Building operation* – The occupancy, lighting, HVAC and electric equipment schedules on a typical weekday used in this study are shown in Figure 9. The building follows typical occupancy patterns for office building with peak occupancy between 8am to 5pm on weekdays with limited occupancy beginning at 6am and extended until midnight to include janitorial function and after-hours work. From 8am to 5pm, occupancy, lights and equipment usage is at maximum with a decrease during lunch time between 12pm to 1pm. There is 40% usage of miscellaneous electrical equipment after unoccupied hours. Key plug load models, including vending machines, fax machine, printer, copy machines, refrigerators, water coolers, coffee makers, laptop, desktops and monitors, usage profiles for the medium-sized office building are described in Section 3.5. HVAC system starts earlier before occupants arrive to bring the space to desired temperature.

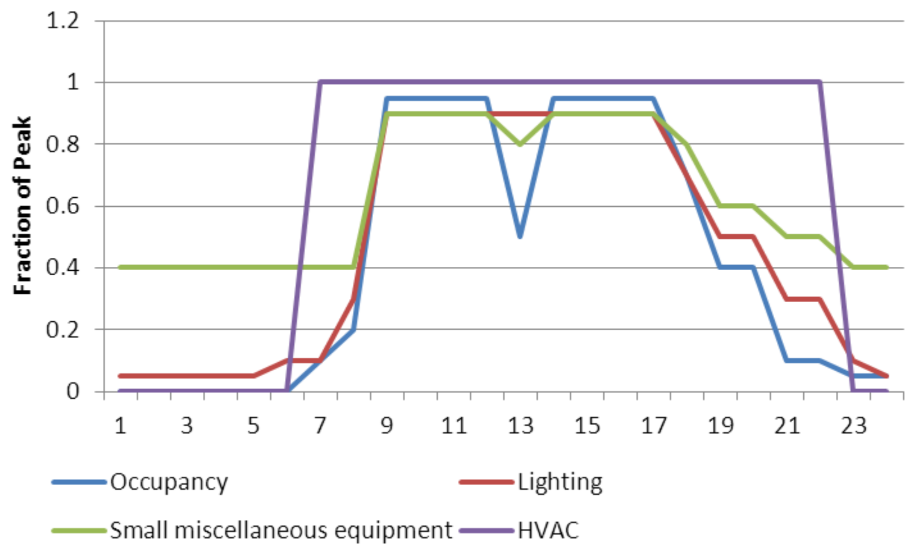

Figure 9 Medium-sized office building typical weekday schedule used in this study

- *HVAC load* – The building has a package rooftop variable air volume (VAV) HVAC system. Each of the three floors has their own HVAC system. For a summer weekday from 6am to 10pm the normal operating cooling set point is 24°C. During off-hours set back strategy is applied and the cooling temperature set point is 26.7°C. The building has five thermal zones on each floor. Each zone has its own thermostat. There are four perimeter zones and one core zone on each floor. Each perimeter zone extends from exterior wall inward for 15 ft. Figure 10 shows the HVAC zoning.

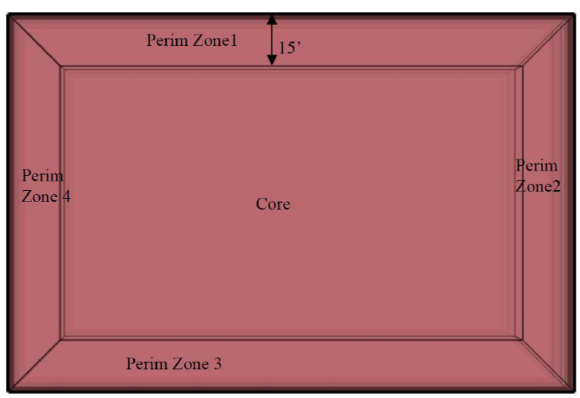

Figure 10 HVAC zoning for medium-sized office building used in this study [213]

- *Occupants, lighting and equipment* – Number of occupants in the building are 268. Hence there are 5 persons per 1000 ft^2 of gross floor area. Ambient lighting power density for the entire building is 1.6 W/ft^2. Office buildings have plug loads, such as office equipment, refrigerators, coffee makers, beverage and vending machines. As there are four tenants in the building, it is assumed that the mid floor has twice as many tenants than other floors [213], which leads to higher number of office equipment and plug load density for the mid floor. To simulate plug loads in the building, instead of lumping all plug loads together, a dynamic plug load model with 1-minute intervals has been developed for individual plug loads discussed in Section 3.5. This results in 0.73 W/ft^{2}plug load power density for the entire simulated building. Table 8 shows the plug load equipment inventory for the medium-sized office building. The simulated medium-sized office building has two elevators, each with 20hp hydraulic motor. These elevators are modeled as an internal zone load. Heat gain from these elevators is added to the bottom floor core zone.

Equipment	Quantity
Beverage vending machines	4
Fax machines	8
Computers-servers	8
Computers desktop	134
Computers laptop	134
Monitors server/desktop LCD	8/268
Laser printer	8
Copy machine	4
Water cooler	8
Refrigerator	8
Coffee maker	4
Portable HVAC	30
Small appliances	250

Table 8 Plug load equipment inventory for the medium-sized office building used in this study

Electric plug loads produce both radiant and convective heat gains which impact the time and magnitude of peak load. Convective heat gain is converted instantly to cooling load while radiant heat gain is first absorbed by building mass and later converted to cooling load [217, 218]. Radiant and convective heat gains are selected for some office equipment based on available experimentation results by [217, 219] and are presented in Table 9. Authors in [218] provide guideline that if no information is available total heat loss from equipment can be estimated as 20% by radiation and 80% by convection. Hence, it is assumed that for vending machine, water cooler, fan and miscellaneous appliances, heat produced is 20% is radiant and 80% convective.

	Heat gain (%)	
	Radiant	Convective
Computer - desktop	10	90
Computer - laptop	75	25
Monitor	40	60
Laser printer	30	70
Copier	22	78
Fax machine	32	68
Refrigerator	25	75
Coffee machine	33.33	66.67

Table 9 Radiant and convective heat gain from office equipment [217, 219]

3.4.3 Standalone retail building model input assumptions

- *Building envelope* – The standalone retail building for this study is a 40499.97 ft^2 single-story building. The building is rectangular shaped with an aspect ratio of 1.25. Building envelope constructions include steel framed walls, flat roof with insulation above the deck and slab-on-grade floors. Windows are located on the south façade with a window-to-wall ratio of 22%. The different zones include sales area, vestibule, stockroom, office, meeting room, break room, restroom, corridor and mechanical room. Figure 11 shows the axonometric view of the standalone retail building used in this study.

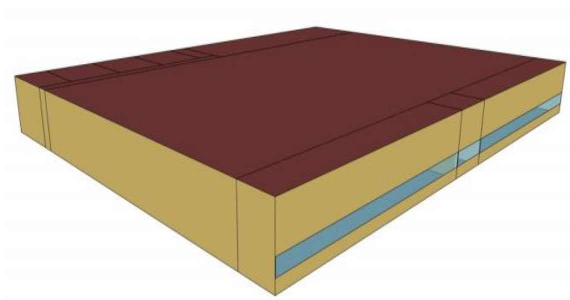

Figure 11 Axonometric view of the standalone retail building used in this study

- *Building operation* – A weekday is considered for simulation purposes -- since on these days other commercial buildings such as office buildings are also operational and grid load is high. The occupancy, lighting, and electric equipment schedules as a fraction of peak densities on a typical weekday used in this study are shown in Figure 12. As shown, the building follows typical occupancy patterns for a retail building with peak occupancy between 11am to 1pm and 5pm to 7pm on weekdays. Lighting (general and accent) and equipment usage is high from 9am to 9pm. HVAC system operates all day.

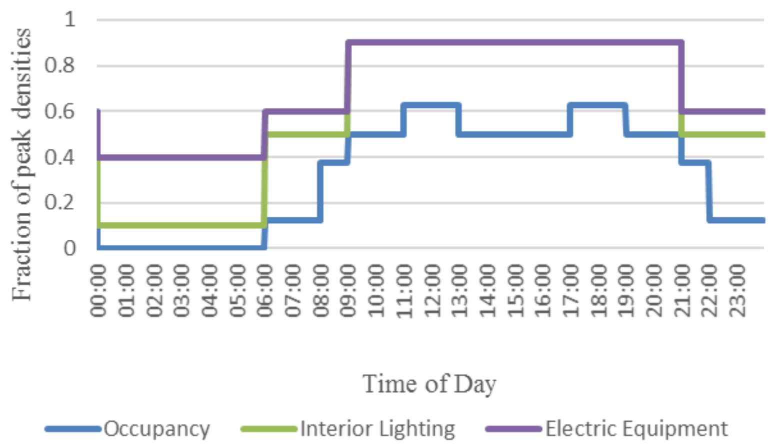

Figure 12 Standalone retail building typical weekday schedule used in this study

- *HVAC load* – Each zone has a single packaged rooftop unit with constant air volume (CAV) distribution. Each packaged unit has a direct exchange (DX) cooling coil and a gas fired furnace. In addition, each zone has an electric baseboard heat to maintain comfort. For a summer weekday from 6am to 12am the normal operating cooling set point is 24°C. From midnight to 6am the cooling temperature set point is 30°C. Figure 13 shows the HVAC zoning.

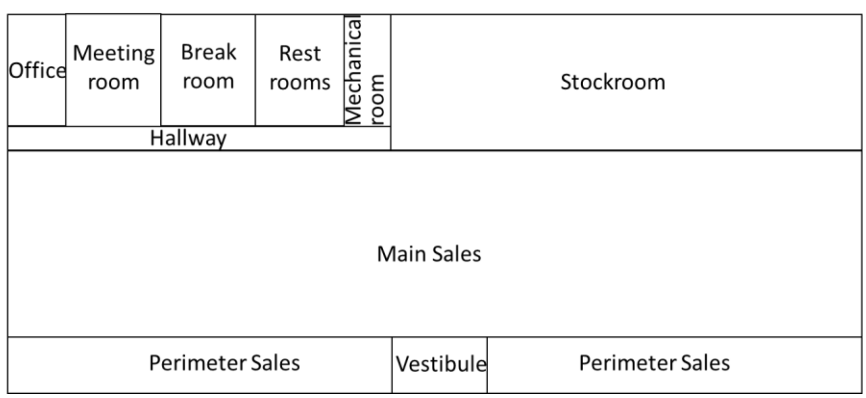

Figure 13 HVAC zoning for standalone retail building used in this study

- *Occupants, lighting and equipment* – Retail lighting can be general or accent [26]. General lighting provides uniform illuminance, while accent lighting provides additional illuminance to draw attention and emphasize specific items of merchandize [27]. Table 10 shows the occupant, lighting and plug load densities for different space types. The occupant density is measured in area (ft^2) per person. Lighting power density is measured in terms of power consumption of lighting load (Watt) per unit area (ft^2). Similarly, plug load density is measured in terms of power consumption of plug loads (such as cash registers, computers, monitors, printers, and copiers) per unit area (ft^2). This study considers fluorescent lamps, most commonly used for general illumination in retail establishments [28], for providing general lighting for the simulated retail building. As light-emitting diodes (LEDs) are increasingly being used to provide retail accent lighting [28], LED lamps are considered to provide accent lighting on the simulated retail building's sales floor.

Zone type	Zone Area (ft^2)	Peak occupant density (person/1000 ft^2)	Lighting power density (W/ft^2)	Plug load density (W/ft^2)
Sales floor	32,100	15	1.15 (general lighting) 0.75 (accent lighting)	0.40
Vestibule	300	15	0.45	0.00
Corridor	600	0.00	0.54	0.00
Restroom	750	15	0.86	0.10
Stock room	4,500	3.33	0.86	0.75
Office	450	5	0.81	0.75
Meeting room	750	50	0.81	0.75
Break room	750	70	0.45	2.60
Mechanical room	300	0.00	0.86	0.00

Table 10 Standalone retail building occupant, lighting and plug load densities

The parking area of the simulated retail building is 101,245ft^2, which is about 2.5 times larger than the building. The exterior lights in the parking area consume 15,188W and turn on and off with sunset and sunrise respectively. The simulated retail building has a 6.685ft^3 electric water heater storage tank to provide hot water to the sinks and lavatories. The water heater continuously cycles on and off to maintain a temperature set point of 60°C within the specified dead band of 2°C. Upon reaching the temperature set point the heater turns off.

3.5 Plug Load Models for Office Buildings

This Section describes selected dynamic plug load models with 1-minute intervals developed and simulated in EnergyPlus, including, beverage vending machine, fax machine, server computer, desktop computer, laptop computer, monitor, laser printer, copy machine, water cooler, coffee maker, refrigerator, portable fan and miscellaneous appliances. Office buildings have various types of plug loads, such as office equipment, refrigerators, coffee makers, beverage and vending machines. The developed typical weekday profiles of key plug loads were randomized to depict real-time occupant behavior. For modeling purposes some of the office equipment including coffee maker, laser printer, copy machine, refrigerator and portable HVAC were monitored and their power consumption measured by a power analyzer while other plug loads power consumption and usage data were obtained from existing research.

3.5.1 Beverage vending machines

A vending machine has a condenser section which comprises a compressor and a cooling fan. A circulation fan to circulate cold air throughout the machine, fluorescent lighting system, and electronics [220]. Two types of vending machine models were developed in EnergyPlus using data from [220]. First vending machine's compressor is on for 5 minutes consuming 761W. Compressor cycling time, i.e. time elapsed from one compressor energization to the next, is 7 minutes during which only the circulating fans and lights are on consuming 281W. Second vending machine's compressor runs for 8 minutes and consumes 776W. Compressor cycling time is 15 minutes during which the circulating fans and lights are on and consume 276W. Figures 14 and 15 show the power consumption profiles for the two types of vending machines generated in EnergyPlus.

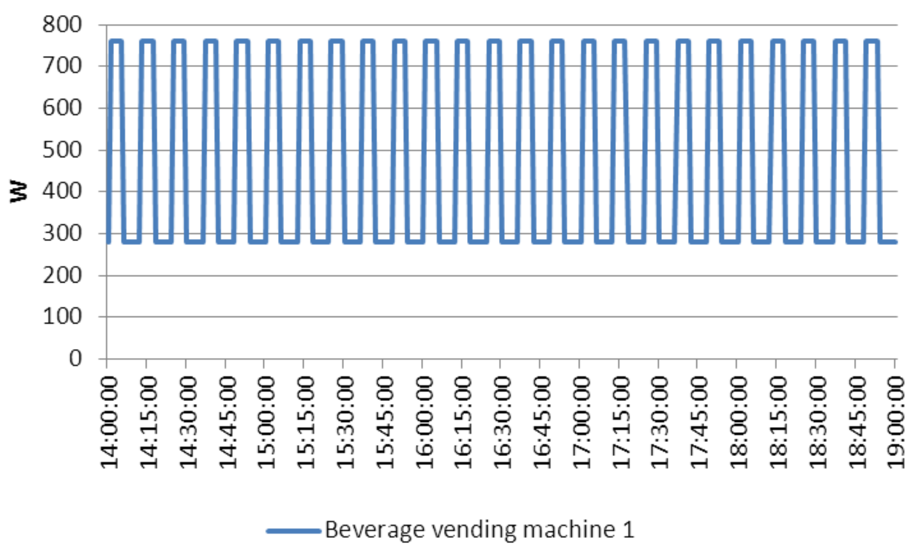

Figure 14 Beverage vending machine model 1 weekday power consumption profile used in this study

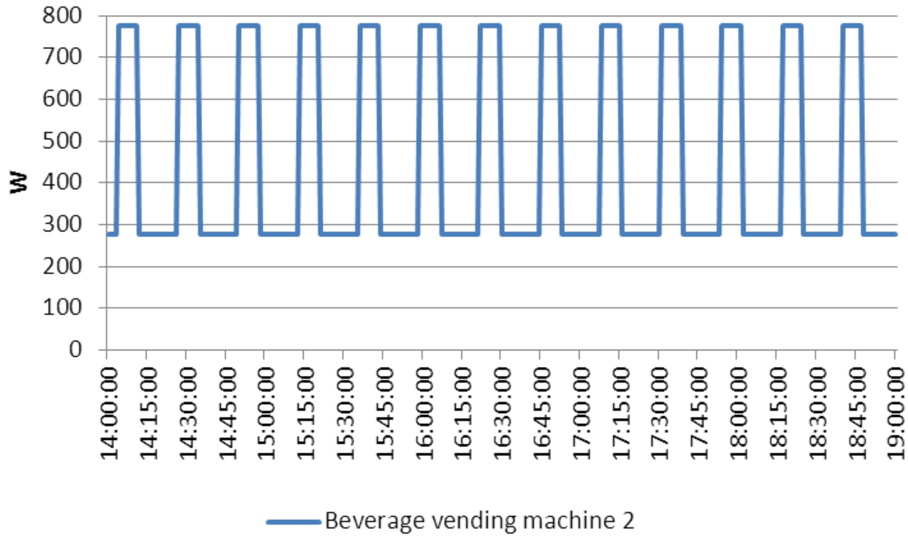

Figure 15 Beverage vending machine model 2 weekday power consumption profile used in this study

3.5.2 Fax machines

Fax machines are always operating either in active or standby mode [221]. During an active mode a fax machine is either transmitting or sending fax. In a stand-by mode a fax machine is ready to but not carrying out intended operation. Table 11 shows the modes of operation and power consumption for fax machines with data from [221]. Taking into account EnergyPlus's minimum resolution in minutes, it was assumed that minimum faxing activity takes no less than 1 minute to complete. Figure 16 shows an example of the power consumption profile of a single fax machine generated in EnergyPlus developed with data from Table 11. Fax usage profile is randomized to generate power consumption for other fax machines in the simulated office buildings.

Mode of Operation	Power Consumption (W)	Usage (minutes/day)
Active	30	10
Standby	15	1430

Table 11 Fax machines modes of operation used in this study

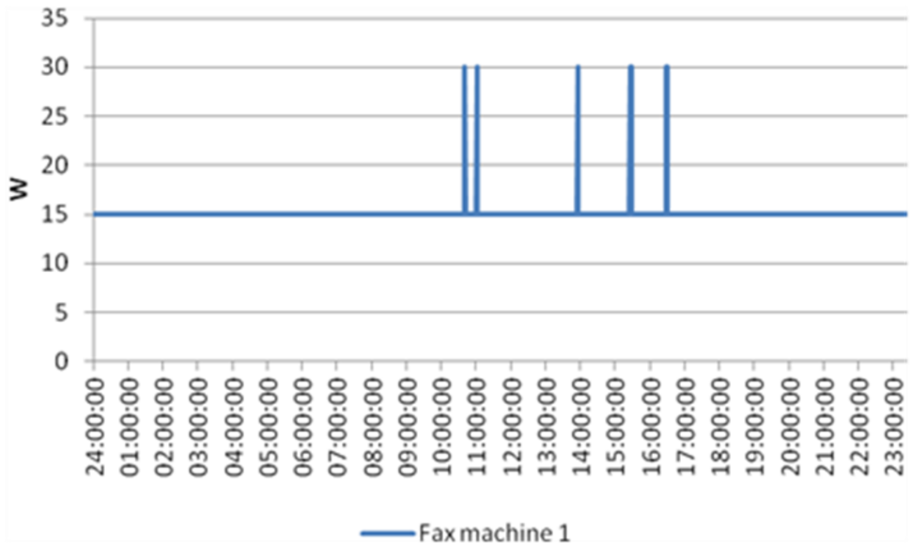

Figure 16 Fax machine weekday power consumption profile used in this study

3.5.3 Server computers

Server refers to a computer that is not directly associated with a specific human user and provides common functions to a group of users, or performs back-end processing invoked on a scheduled basis or by other computers. Server computers operate in active mode around the clock [221]. The actual power draw during the active mode is less than the nameplate power. Author in [222] found out the measured power draw is about 50% of nameplate power. Server's power range is between 50W to 270W. In this study, active mode power consumption was considered 75W from [223] .

3.5.4 Desktop computers

Desktop computers are either in active mode, low power or off mode. Table 12 shows the modes of operation and power consumption for desktop computers with data from [223]. Desktop computers are in the off mode during non-office hours. A desktop computer is maybe in a standby mode when an employee is unseated during lunch time or attending a meeting. Occupants are usually seated at their desks for less than one third of the average workday [224]. Desktop computers in offices usually do not enter low power mode when not in use [225]. Authors in [226] found in a survey about 94% of computers do not have power management feature and the turn off rate is 36%. A study by the Lawrence Berkeley National Laboratory (LBNL) reveals that 60% of office computers remain on overnight and during weekends, and only 6% use aggressive power-management settings [227]. Employees usually do not turn off computers or disable power settings—either because it's policy to leave equipment on overnight, they do not care about saving energy, or they believe the computer will go into sleep mode by itself. Some studies have evaluated that good power management and user behavior are necessary factors for efficient use of office equipment [226, 228]. Based on this occupant behavior information and with data from Table 12, typical weekday power consumptions of desktop computers were generated in EnergyPlus as shown in Figure 17.

Mode of Operation	Power Consumption (W)	Usage (hours/day)
Active	55	9
Low power	25	2
Off	1.5	13

Table 12 Desktop computers modes of operation used in this study

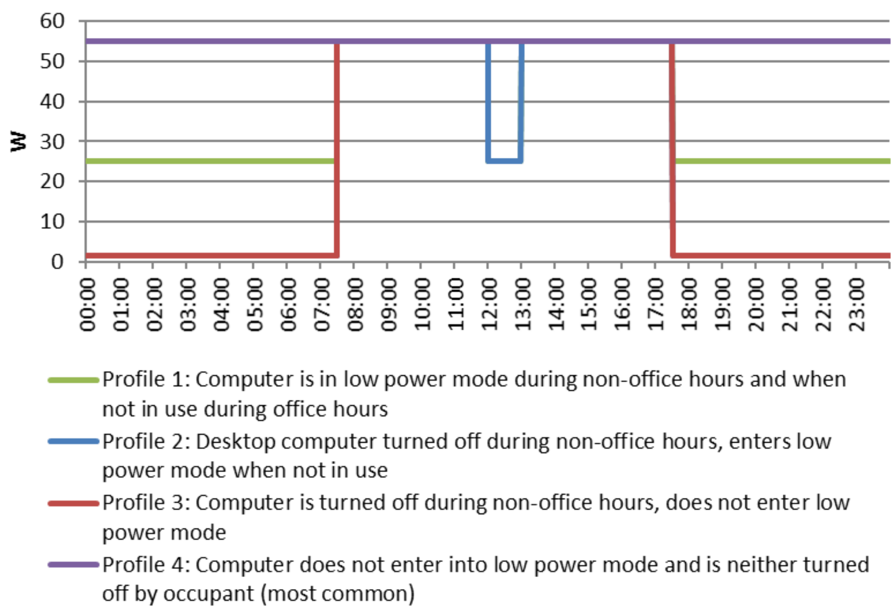

Figure 17 Desktop computer weekday power consumption profile used in this study

3.5.5 Laptop computers

Desktop computers are either in active mode, low power, off mode or unplugged. During non-office hours occupants usually unplug laptops to take them home. A power analyzer was used to measure a laptop's power consumption. Figure 18 shows the laptop's power consumption, depending upon processor activity, fluctuates around 37W, during idle mode the power consumption drops to 14W, after 2 minutes when the screen saver runs the power consumption increases to 18W. Findings from [223], shown in Table 13, represent that a laptop on a regular office weekday is active for only about 3 hours and is in low power mode for about 9 hours. Unlike desktop computers, laptop computers active mode duration is less due to power management feature. Figure 19 shows the typical weekday power consumption of a laptop computer generated in EnergyPlus using the measured power consumption data for different modes of operation from Figure 18 and usage information from Table 13. Profile 1 represents a laptop computer's power consumption with screen saver and profile 2 represents a laptop computer's power consumption without a screen saver.

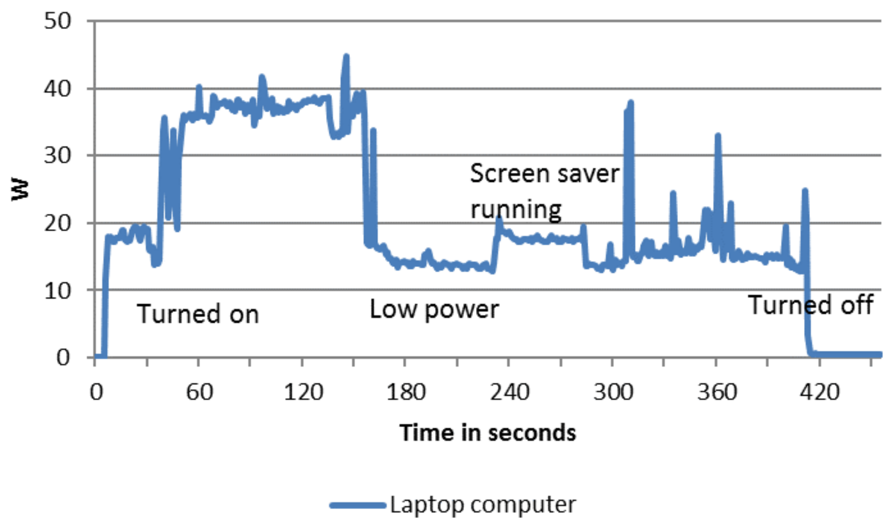

Figure 18 Laptop computer measured power consumption

Modes of Operation	Usage (hours/day)
Active	2.7
Low power	8.7
Off	0
Unplugged	12.5

Table 13 Laptop computers modes of operation used in this study

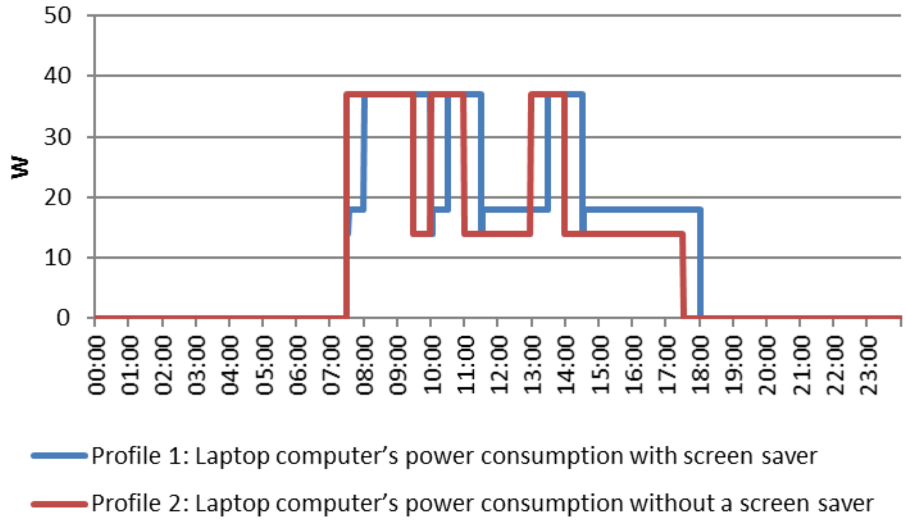

Figure 19 Laptop computer weekday power consumption profile used in this study

3.5.6 Liquid Crystal Display (LCD) monitors

Typical 17inch LCD monitors for office buildings have been modeled. The monitor can be in either active, low power or off mode. During the active mode, power draw is usually less than the nameplate power by a factor of 3 or more [222]. Low power mode is defined when the screen is powered down and off mode when the screen is switched off. Table 14 shows the modes of operation and power consumption for LCD monitors with data from [221] [223]. Survey conducted by [226] shows that the turn off rate for LCD monitors is about 18%. Based on this information and with data from Table 14, weekday power consumptions for monitors were generated in EnergyPlus as shown in Figure 20.

Modes of Operation	Power Consumption (W)	Usage (hours/day)
Active	16.7	6
Low power	4.8	5
Off	0.8	13

Table 14 Monitors modes of operation used in this study

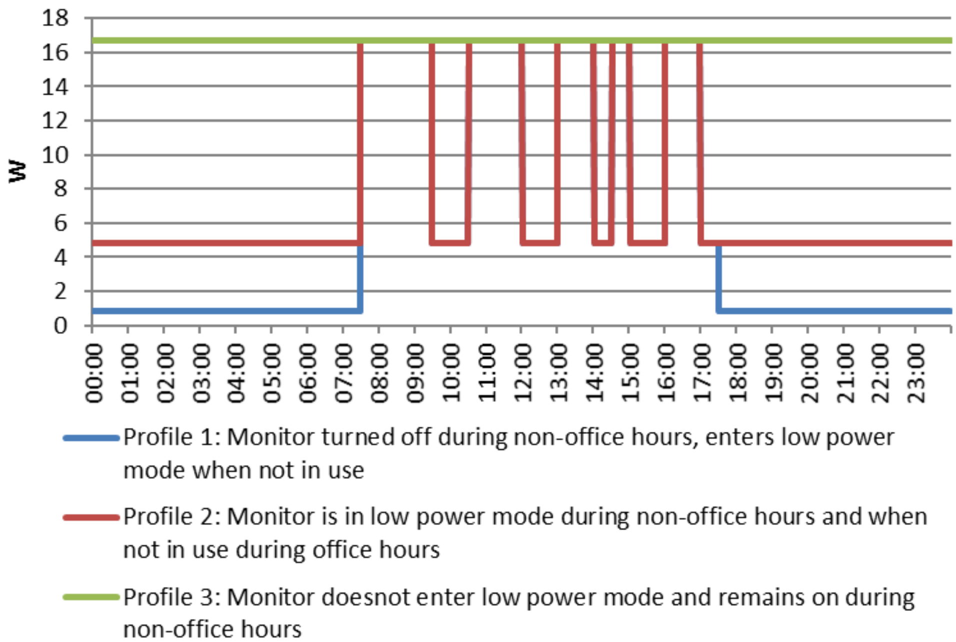

Figure 20 LCD monitors weekday power consumption profile used in this study

3.5.7 Laser printer

Laser printers have been considered for the simulated buildings. Laser printers are usually shared resources between several users in a computer network [221]. Shared equipment is usually left on indefinitely [224]. Two different copy machine's power consumptions were measured with a power analyzer, shown in Figure 21. Printer 1 consumes 800W while printing a page in about 10 seconds and 4.4W in standby mode. Printer 2 consumes 548W while printing a page in about 30 seconds and 10.9W in standby mode. Findings from [229, 230] show that laser printers are active i.e. perform printing operations for about 43 minutes in a day. Taking into account EnergyPlus's minimum resolution in minutes, it was assumed that printer 1 prints no less than 6 pages at a time and printer 2 prints no less than 2 pages at a time, and the minimum printing activity takes 1 minute to complete. Figure 22 shows the weekday power consumption for the two laser printers generated in EnergyPlus.

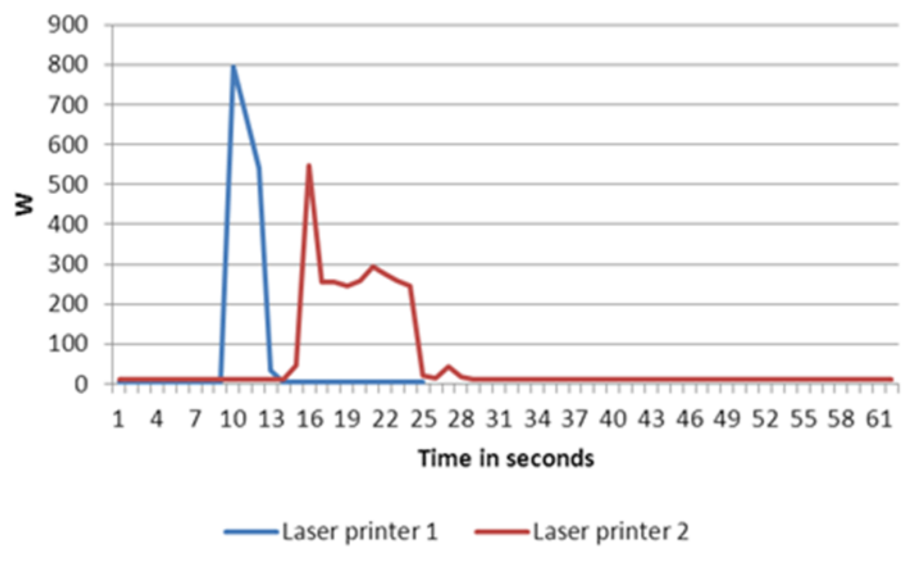

Figure 21 Laser printer measured power consumption

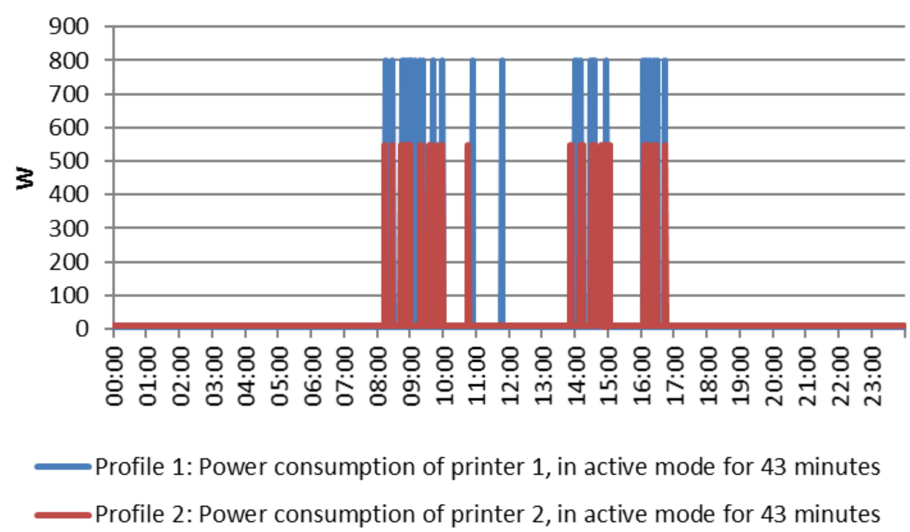

Figure 22 Laser printers weekday power consumption profile used in this study

3.5.8 Copy machine

Copy machines are shared resources and like printers are left on indefinitely. Two different copy machine's power consumptions were measured with a power analyzer, shown in Figure 23. Copy machine 1 consumes 900W while copying a page in about 10 seconds and 6.5W during standby. Copy machine 2 consumes 800W while copying a page in about 10 seconds and 4.4W during standby. Findings from [221, 229] show that copy machines are active i.e. performing copy operations typically for about 37 minutes on a weekday. Taking into account EnergyPlus's minimum resolution in minutes, it was assumed that the two copy machines copy no less than 6 pages at a time, and the minimum copying activity takes 1 minute to complete. Figure 24 shows the weekday power consumption for the two copy machines generated in EnergyPlus. Profile 1 and 2 represent power consumption for copy machines 1 and 2 respectively; both machines perform copying activity for 37 minutes.

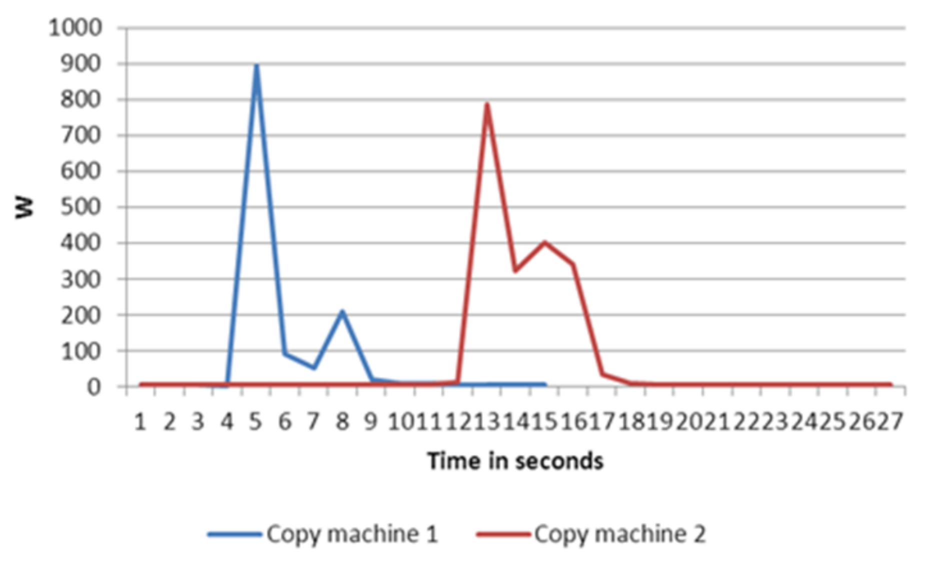

Figure 23 Copy machines measured power consumption profile

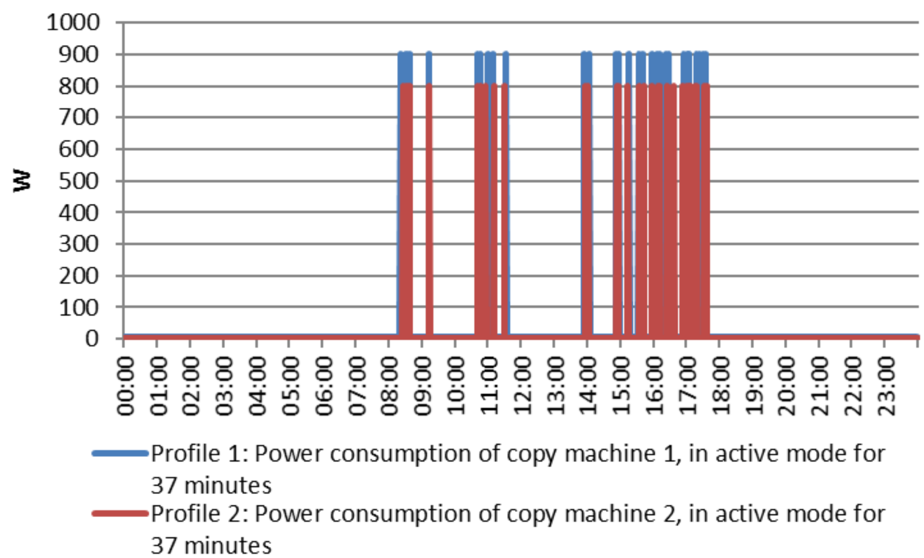

Figure 24 Copy machines weekday power consumption profile used in this study

3.5.9 Water cooler

Water coolers deliver water between 5°C to 10°C. When switched on, the unit cools the water at ambient temperature to the desired temperature. Once the specified temperature is reached the power input stops and when the temperature falls below a defined value again it is cooled to the desired temperature. When water is drawn off, fresh ambient temperature water flows in the storage vessel and is cooled to the desired temperature. The water coolers are typically switched on 24 hours. Pressurized water dispensers, also known as refrigerated water fountains, are typically installed in commercial buildings. They come in a number of configurations and dispense only cold water. These devices can typically provide 3-10 gallons of 10ºC water per hour. For the modeled water cooler, based on different manufactures datasheets, it was assumed that the compressor is on for 7 minutes and consumes 260W and is off for 5 minutes consuming no power. Figure 25 shows the power consumption for the modeled water cooler generated in EnergyPlus.

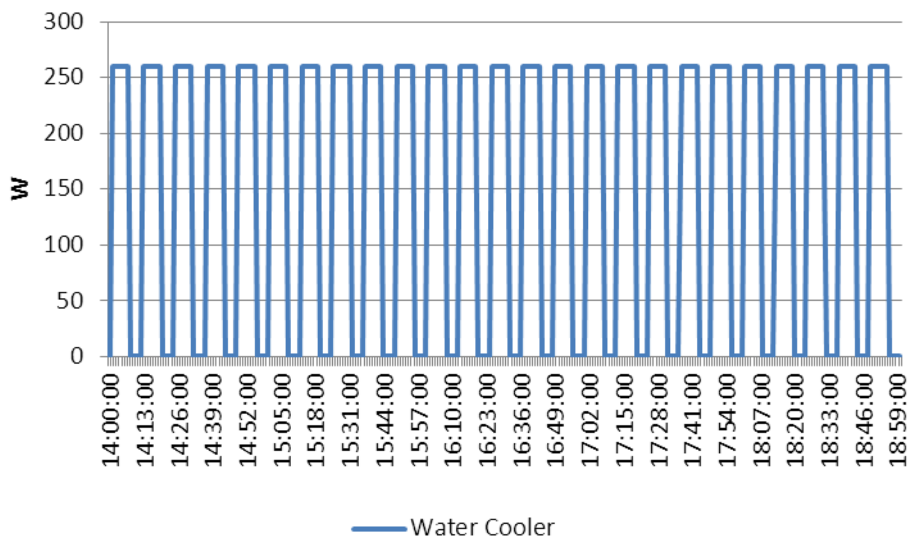

Figure 25 Water cooler weekday power consumption profile used in this study

3.5.10 Refrigerator

The refrigerator model used in this study was developed by measuring the power consumption of a refrigerator with a power analyzer. The refrigerator model used in this study is on for 8 minutes during which it consumes 135W. If the door is opened there is an additional 40W power draw due to the incandescent light bulb inside the refrigerator and duration of on time exceeds. The off mode duration is 15 minutes and during this time there is no power consumption. A defrost cycle happens every 30-40 hours and lasts for about 20 minutes consuming 365W. The defrost cycle is followed by a long refrigerator operating duration. Figure 26 shows the power consumption for the modeled refrigerator generated in EnergyPlus. Increased refrigerator door opening is observed during morning hours, lunch hours, and in the evening hours.

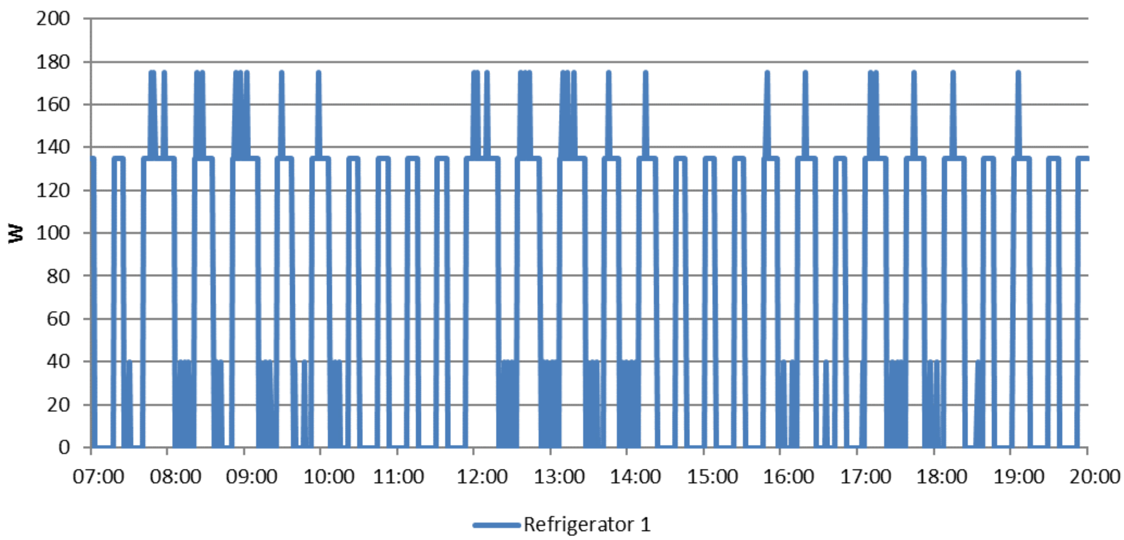

Figure 26 Refrigerator weekday power consumption profile used in this study

3.5.11 Coffee maker

Power consumption of a coffee machine was measured with a power analyzer, shown in Figure 27. It was observed that the machine is never unplugged by the occupants. However, if the machine is off but plugged in, it consumes around 8.3W. When not is use it consumes around 10.4W with brief power surges to keep the water hot. When hot water is drawn, fresh ambient temperature water enters the coffee maker and is heated to the desired temperature. While brewing 1316 W power is consumed. Taking into account EnergyPlus's minimum resolution in minutes, the brewing time was assumed to be no less than one minute.

Based on Figure 27, weekday power consumption profile for the modeled coffee maker was generated in EnergyPlus, shown in Figure 28. Increased use is observed during early morning hours and in late afternoon due to more people drinking coffee or using hot water.

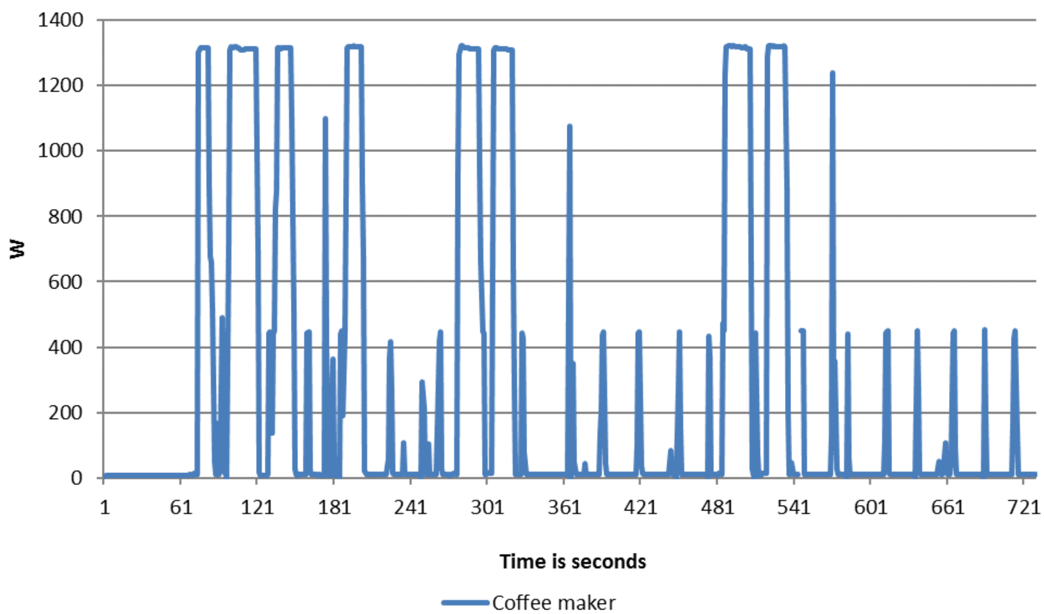

Figure 27 Coffee maker measured power consumption

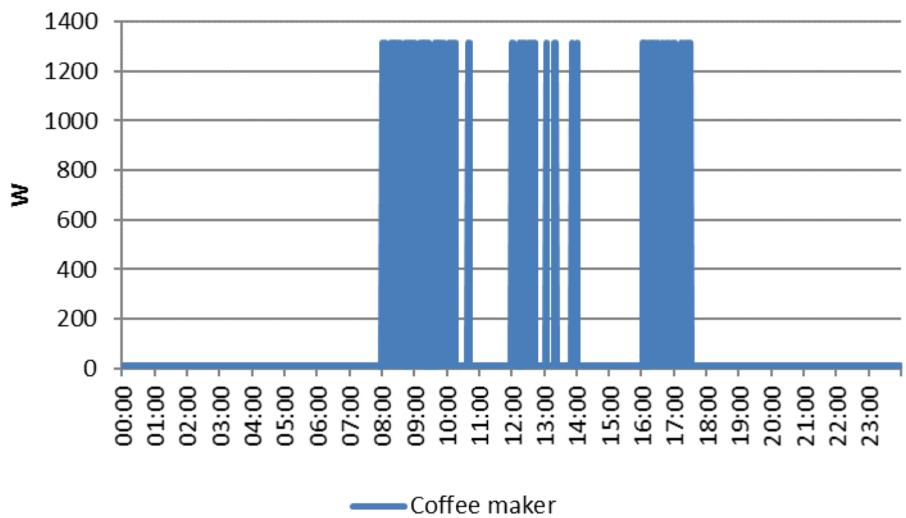

Figure 28 Coffee maker weekday power consumption profile used in this study

3.5.12 Portable fan

A portable fan consumes around 30W when operating [28]. Based on this data, random weekday power consumption profiles were generated in EnergyPlus to depict occupant behaviors.

3.5.13 Miscellaneous appliances

There is a wide range of miscellaneous equipment in office buildings like phone or iPad chargers, table radio, adding machine, battery charger, portable stereo, portable CD player, stapler and corded phone. These miscellaneous appliances consume around 4W power [213]. The miscellaneous appliances follow the schedule shown in Figure 29. From 8am to 5pm equipment usage is about 90%, reducing to 80% during lunch hours from 12pm to 1pm. After 5pm, as number of occupants decrease, gradually equipment usage reduces to 40% for unoccupied periods.

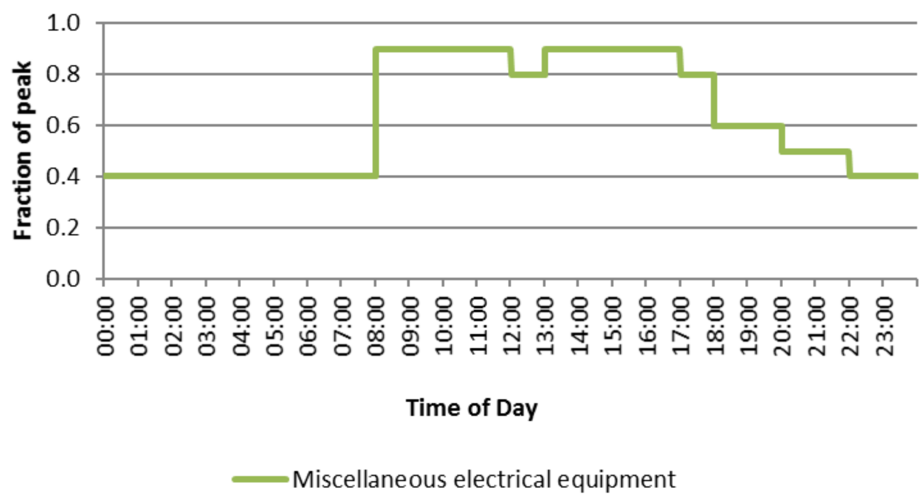

Figure 29 Miscellaneous equipment weekday schedule used in this study

3.6 Integrating the demand responsive commercial buildings to the distribution feeder

In this study, the modeled demand responsive commercial buildings were integrated into the modeled distribution feeder, discussed in Section 3.3, and thus their power consumption was scaled down to match with the existing load and distribution transformer ratings. See Figure 30, which shows the scaled down power consumption profiles of three types of simulated commercial buildings for a summer day.

In particular, the small- and medium-sized office buildings originally have an area of 5,500ft^2 and 53,628ft^2, respectively; and the retail building's original area is 40,500ft^2. In order to accommodate these buildings in the distribution feeder, their areas were scaled down by a factor of three, hence their power consumption was reduced accordingly.

With respect to building operation, both small- and medium-sized office buildings follow typical occupancy patterns, with peak occupancy between 8am to 5pm on weekdays. Occupancy is limited beginning at 6am and extended until midnight to include janitorial function and after-hours work. During peak occupancy, lights and equipment usage is also at its maximum with a decrease during lunch time, i.e., between 12pm to 1pm. These buildings have a scaled down peak load of 10kW (at 4pm) and 74kW (at 4:10pm) for small- and medium-sized offices, respectively. On the other hand, the retail building has the peak occupancy between 11am to 1pm and 5pm to 7pm on weekdays. Lighting and equipment usage is high from 9am to 9pm. The retail building has a scaled down peak load of 73kW at 7:50pm due to additional power consumption by the external lights along with high internal loads. Table 15 summarizes the simulated demand responsive buildings' peak loads.

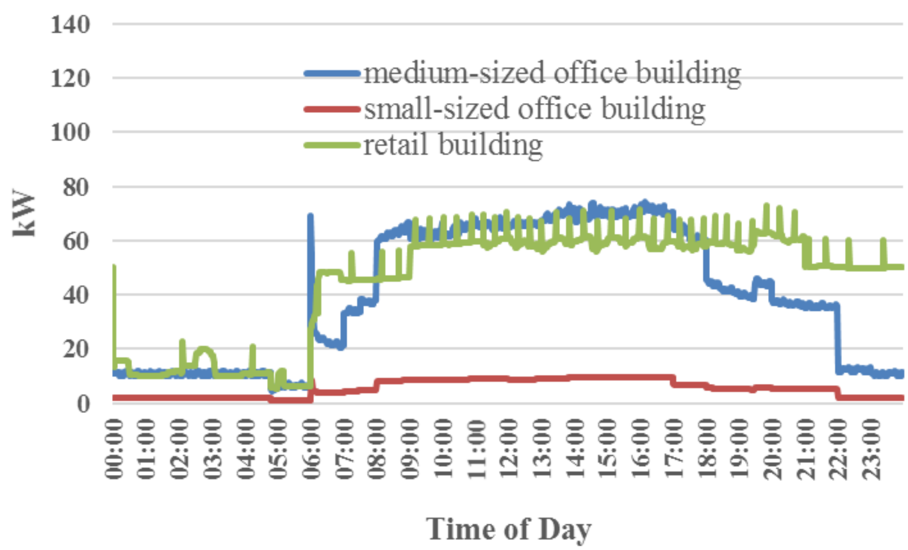

Figure 30 Scaled down power consumption profiles for the commercial buildings used in this study for a summer day

Buildings	Peak demand in kW	Occurrence of peak demand
Small-sized office	10	4:00pm
Medium-sized office	74	4:10pm
Standalone retail	73	7:50pm

Table 15 Demand Responsive Buildings Peak Demand

3.7 PV Models in EnergyPlus and DEW Software

This Section explains the PV models developed in EnergyPlus and DEW. PV models developed are grid-tied rooftop units.

PV modeling in EnergyPlus allows capturing the shading effects of PV modules on the building roof, which impacts the building HVAC load. Also in EnergyPlus, a PV system can be sized as per the available roof space (as a portion of the roof space is usually occupied by HVAC equipment) taking into account the inter-spacing requirement between rows of PV modules.

On the other hand, PV modeling in DEW allows capturing the impacts of grid-tied PV on secondary distribution transformers, hence any reverse power flow or voltage rise phenomena can be analyzed.

Based on these features when analyzing PV impacts on the building load alone, PV modeling was performed in EnergyPlus. This allowed the PVs to be properly sized and the PV shading effect on the building load profile to be analyzed. On the other hand, PV modeling was performed in DEW to analyze its impacts on the distribution feeder load profile.

3.7.1 PV model in EnergyPlus

EnergyPlus has PV performance computational models which are relevant for rooftop integrated PV. Incident solar radiation on the PV surface is calculated using the same algorithms used for all exterior surfaces. Based on the geometry of surface the direct beam, diffuse and reflected solar radiation is calculated. EnergyPlus takes into account shading of PV surface by trees or other buildings. The PV surface may reduce the incident radiation on the roof beneath it; this partial transmission through a semi-transparent shading surface is also calculated by EnergyPlus. Incident solar radiation data is obtained from hourly weather data and is made available for sub-hourly time steps by carefully distributing and interpolating data between the hours. PV modules in EnergyPlus produce power only if the incident solar radiation is greater than 0.3W.

The PV system has a solar PV panel which generates DC power by converting solar energy to electrical energy, an inverter which converts DC power to AC power and a battery to enable power storage. There are three types of PV simulation models in EnergyPlus including

Simple Model, Equivalent One-Diode Model and Sandia Model. The Equivalent One-Diode Model and has been used as rooftop PV for the modeled commercial buildings.

Equivalent One-Diode PV Model

This model is based on the equivalent circuit comprise a direct current source, diode and one or two resistors. When there is no light PV cell behaves like a diode. As the incident radiation increases current is generated by the PV cell. The model takes into account the effect of cell operating temperature on the current voltage characteristics by including temperature coefficients of the short circuit current and open circuit voltage, the hotter the module the lower is its electrical output. Current is determined as a function of load voltage. The mathematical description of the model is available at [231]. Following parameters need to be defined for the Equivalent One-Diode model: Cell type, number of cells in series, cell's active area, transmittance absorption product, semiconductor bandgap in eV, shunt resistance in ohms, short circuit current in A, open circuit voltage in V, reference temperature in °C, reference insolation in $\mathrm{W/m^2}$, module current at maximum power in A, module voltage at maximum power in V, temperature coefficient of short circuit current in A/K, temperature coefficient of open circuit voltage in V/K, nominal operating cell temperature test ambient temperature in °C, nominal operating cell temperature test cell temperature in °C, nominal operating cell temperature test insolation in $\mathrm{W/m^2}$, module heat loss coefficient in $\mathrm{W/m^2K}$ and total heat capacity in $\mathrm{J/m^2K}$.

Using the mathematical model and the assumption that the panels operate at maximum power point, it is direct calculation to determine the DC power output. The inverter efficiency is applied linearly to derate the energy production. The inverter capacity forms a limit for power production from a PV generator.

PV area

A building's available roof space limits the size of a PV along with the customer's budget. Reports [232-234] conclude that in the U.S. about 63% of all commercial roofs are flat and 60% to 65% of rooftop space is suitable for PV. Authors in [235] estimate that 5% of flat rooftop buildings are covered by HVAC equipment, shadowing about 35% of roof and allowing flat roofs to have 65% space available for PV. Authors in [236] suggest 70% of flat roof is available for PV installation. In view of these studies PV was assumed to cover about

65% to 70% of the simulated commercial building's roof area. Spacing between rows of PV modules can be calculated based on site's latitude, the desired solar window and the modules' height and tilt angle. If incorrectly spaced, tops of tilted row of PV modules can shade the bottom of behind row.

As an example, for a medium-sized office building, LG PV module, LG230M1C, parameters were utilized for modeling roof top PV. Each modeled PV module had an area of $17ft^2$. The modeled medium-sized office building is located at latitude 38.87°, longitude -77.03°, the PV module's height is 0.986m and the tilt angle is 15.14°. An inter-row spacing of 0.6m, calculated using [237], was sufficient to avoid shading on winter solstice, the day when the sun is lowest in the sky, for a solar window from around 10am to 2pm. This allowed the maximum of 450 PV modules (30 parallel strings of 15 modules in series) to be installed on the rooftop. The total PV area, along with inter-row spacing, was calculated as $11560ft^2$out of the entire building's roof area of $17876ft^2$, which is equivalent to about 65% of the building roof area. Installed PV panels maximum power output was about 104kWp. Figure 31 shows the axonometric view of the simulated medium-sized building with installed PV panels covering 65% of building roof area and casting shadows on the roof.

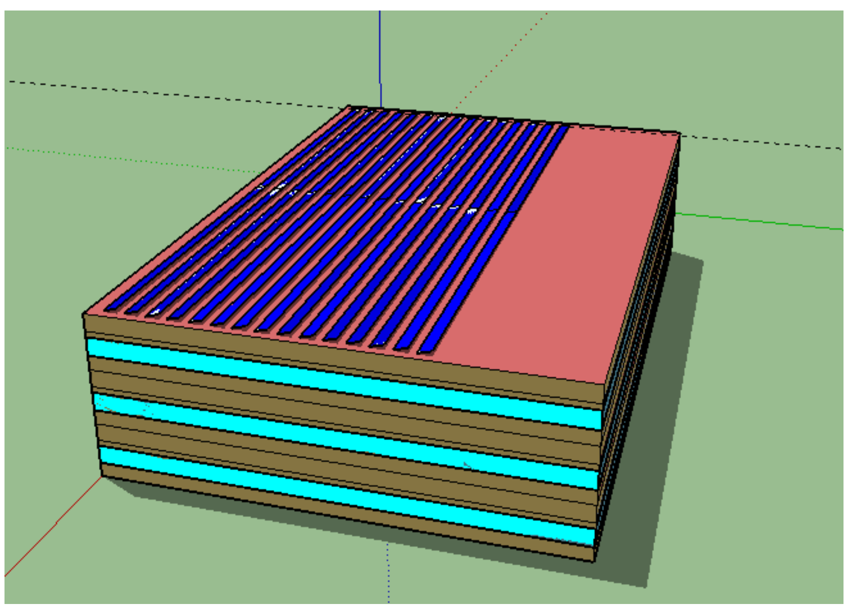

Figure 31 Axonometric view of the simulated medium-sized office building with installed PV panels

Inverters

The PV to inverter sizing ratio (R_s) defines the relationship between PV peak power generated at Standard Test Conditions (STC) (93W/ft^2 and 25°C) to the nominal AC power rating of the inverter as shown in Equation 3.7.1 [238]. If PV frequently operates at high ambient temperatures, i.e. does not frequently operates at maximum power or is installed at a low tilt angle, the DC-STC power rating of PV is considered higher than the AC output rating of the inverter; typical range of R_s is 0.80 to 1.30 [239]. An extremely undersized inverter will be clipping PV output most of the time and an oversized inverter will spend more time operating less efficiently. Inverters are usually undersized as the STC conditions at which PV is rated are less likely to occur in real world conditions [239]. PV output derates with time due to soiling and aging.

$$R_s = \frac{P_{DC(STC)}}{P_{AC(Nominal)}} \qquad \text{Equation 3.7.1}$$

Where R_s is the PV to inverter sizing ratio; $P_{DC(STC)}$ is the PV peak power at STC conditions; $P_{AC(Nominal)}$ is the nominal AC power rating of inverter.

For a medium-sized office building, for R_s of 1.09, $P_{DC(STC)}$ of 104kWp the inverter nominal AC power rating is 95kW from Equation 3.7.1. Inverter data, including make and model, available in [240] was used for modeling inverter in EnergyPlus. An inverter with rated maximum continuous power of 95kW (Solectria PVI 90kW-480Vac) [241] was selected. The inverter's nominal input voltage is 390V and the power consumed during standby is less than 1W. Inverter efficiencies at nominal input voltage and percentage of rated power are shown in Table 16.

Output Power at nominal voltage (% of rated)	**Efficiency (%)**
10	89.4
20	94.7
30	97.8
50	98.0
75	97.1
100	96.0

Table 16 Inverter efficiencies at nominal input voltage and percentage of rated power

Three models of inverters are available for converting DC electrical power to AC electrical power in EnergyPlus. The inverter converts the solar generated DC power to AC power using Equation 3.7.2.

$$P_{AC-OUT} = P_{DC-IN} * \epsilon_{INT} \quad \text{Equation 3.7.2}$$

If "Simple" inverter model is used than the efficiency is constant. For the "Look Up Table" model, inverter efficiency is calculated using linear interpolation. For the "Function of Power" model, efficiency is calculated using a single variable curve object.

Thermal losses are calculated by the difference between P_{AC-OUT} and P_{DC-IN}.

The inverter "Look Up Table" model was used in this study. The inverter efficiency is applied linearly to derate the energy production. The inverter capacity forms a limit for power production from a PV generator.

3.7.2 PV model in DEW

DEW was used to model grid-tied PVs with actual PV output profiles in one-minute resolution from the PV units installed at the Virginia Tech – Advanced Research Institute in Arlington, VA. In this study, the rating of rooftop PV is dependent upon the building's available roof space as explained in [242, 243]. As demand responsive buildings are located at various sites in the distribution feeder, PV output profiles of these buildings vary from location to location.

3.8 Ice Storage Model in EnergyPlus

This Section provides details for the ice storage models integrated with packaged air conditioning developed in EnergyPlus. Usually ice storage systems are integrated with chillers. Mostly small and medium-sized commercial buildings have packaged air conditioning units and if ice storage systems can be integrated with these, its deployment potential could be high. Ice storage system provides peak load shifting, i.e., changing the timing of energy consumption for space cooling. For an ice storage system integrated with packaged air condition unit, their charging and discharging involves circulating a heat transfer fluid between ice storage system's refrigeration cycle equipment and its storage section.

3.8.1 Ice storage model description

The main components of ice storage system integrated with packaged air conditioning are compressor, condenser, evaporator and ice storage tank. The model operates in six different modes of operations defined below.

Off mode - During the off mode the unit does not operate but the ice tank interacts with the ambient surrounding; therefore its state of charge has to be tracked.

Cooling only mode - During this mode the ice tank is neither being charged or discharged. The compressor alone meets the building cooling needs.

Cool and charge mode - In this mode the unit both cools the building and charges the ice tank.

Cool and discharge mode - In this mode building cooling needs are met both by the compressor and the storage discharge.

Charge only mode - In this mode the unit only charges the ice tank and there is no heat flow at the evaporator.

Discharge only mode - In this mode the unit only discharges storage, there is no heat flow at the condenser.

3.8.2 Ice storage system size

The ice storage system should be sized to meet the total integrated and peak hourly load [244]. An undersized system will not be able to recover when the load exceeds its capacity and an oversized system diminishes its benefits being unnecessarily expensive and inefficient. For sizing ice storage systems, hourly cooling load for the 24-hour design day is required along with the shape of the load profile. An operating strategy, which defines the logic that dictates when each operating mode is to be energized and what control strategy should be implemented in each mode is required to achieve the design intent. Ice storage systems are sized according to ASHRAE 0.4% (actual outdoor hourly temperatures being greater than the design temperatures 35 hours of all annual hours) design day conditions (Note: ASHRAE = American Society of Heating, Refrigerating, and Air-Conditioning Engineers). It is advisable to use conservative selection of design temperatures to recover if design loads are exceeded [245]. An ice storage system sized for full storage can operate under different operating strategies including partial mode of operation as full storage determines the maximum storage size required to completely eliminate DX unit operation.

As an example, the storage capacities for the bottom, middle and top floors of the medium-sized office building, discussed in Section 3.4.2, were calculated as 6.02GJ, 6.84GJ and 6.81GJ, respectively.

3.8.3 Ice storage system control

Ice storage operation during the day, i.e., when it should operate in charge-only mode or discharge mode or cool and charge mode is defined in the form of a schedule in which time durations are specified during which the system has to operate in a certain mode of operation. During a DR event the ice storage system can be made to operate in either discharge-only mode (full storage discharge) or cool and discharge mode (partial storage discharge) where both ice storage and packaged AC meet building cooling needs.

EMS can also be used to override the system's mode of operation. If for example the system is operating in cool and charge mode and the tank is gets 99% charged than EMS can force the system to operate in cool-only mode of operation since further tank charging is unnecessary. Similarly, if the system is operating in discharge-only mode and 1% ice remains than EMS can force the system to operate in cool-only mode so that it can continue to meet building cooling requirements.

3.9 EV Models in EnergyPlus

This Section describes the EV models developed in EnergyPlus as active building loads. In order to accurately determine the impacts of EVs on the distribution feeder, EV models indicating real world charging scenarios are needed. EV models used in many studies are based on assumptions ignoring either vehicle types, diversity of usage, multiple charging events over the day, dynamics of EV arrivals and departures in real time, or driving habits [47]. In this study, real-time EV slow and fast charge profiles monitored over a year at different charging stations (courtesy of Dominion Electric) were used. AC level 1 and 2 charging power consumptions of different EVs including, Nissan Leaf, Chevrolet Volt and Tesla Model S at various residential sites were monitored along with aggregate EV DC fast charge profiles for charging stations located at a retail site. The monitored data represents varying driving distance, vehicle class (sedan, small car, SUV etc.), driving cycle (city, highway, congested etc.) and the driver style (aggressive, passive etc.) for the residential and public EVs.

3.9.1 Measured EV charge profiles used for modeling EVs as active loads

In this study, workplace EVs were charged with AC level 2 chargers. These chargers use 208V or 240V and can deliver up to 19.2kW maximum power [246, 247]. Table 17 shows the type, number and rating of EV charge stations assumed to be available at each type of demand responsive buildings. It was assumed that the small-sized office building had 1 AC level 2 EV charging station, hence a single EV owner can charge at a time. The medium-sized office building was assumed to have 2 AC level 2 EV charge stations. The retail site had a 50kW DC fast charging station. EVs parked at workplace or retail site may be charged instantly upon arrival depending upon charger availability. The EV charge profiles were added to the buildings' existing electric service i.e., the buildings' existing power consumptions.

Buildings	Type of EV charge station	Number of EV charge station	Maximum power consumption during charging (kW)
Small-sized office	AC level 2	1	19.2
Medium-sized office	AC level 2	2	19.2
Standalone retail	DC fast charging	1	50

Table 17 EV Charge Stations for Demand Responsive Buildings

Figure 32, shows examples of power consumption profiles with EV for the modeled commercial buildings. These profiles were slightly varied for respective building types to depict diversity. A survey [248] shows that EV owners primarily recharged their vehicles upon arrival at work, and charging at public stations takes place throughout the day. Hence it was assumed that EV owners in office buildings plug-in their cars upon arrival in the morning and un-plug during lunch time to allow other EV owners to charge their EVs. Hence EV charging consumption is high from around 8am to 12pm and from around 1pm to 5pm. DC fast charging of EVs at retail sites mostly occurs in the afternoon and evening hours while owners do shopping. EV charging consumption is higher from around 11am to 1pm and 5pm to 7pm when retail building's occupancy is also high.

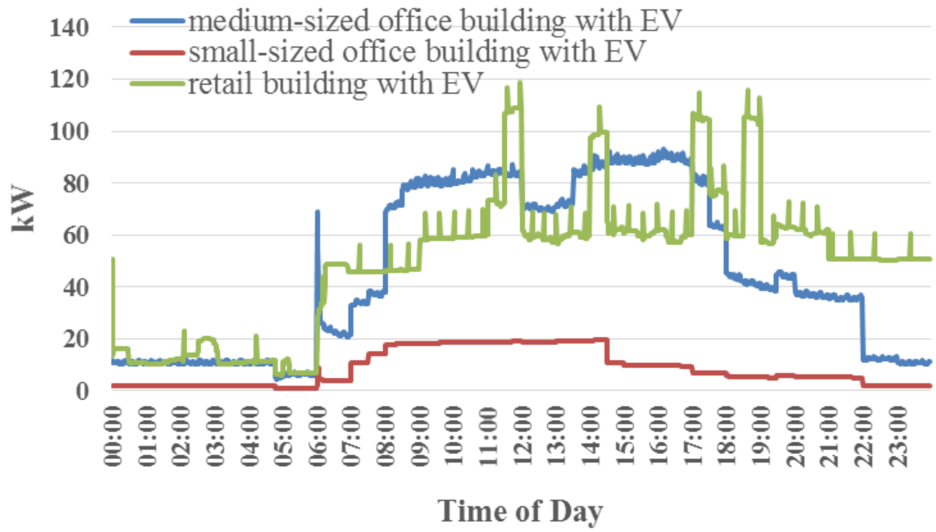

Figure 32 Scaled down building power consumption profiles with EV charging used in this study

Table 18 shows the demand responsive buildings peak demand with the selected EV charge profiles shown in Figure 32. Small and medium-sized office and retail buildings' peak demand increases by 100%, 26% and 63% respectively with EV penetration.

Buildings	Peak demand without EV in kW (Occurrence)	Peak demand with EV charging in kW (Occurrence)	Percentage increase
Small-sized office	10 (4:00pm)	20 (2:30pm)	100
Medium-sized office	74 (4:10pm)	93 (4:10pm)	26
Standalone retail	73 (7:50pm)	119 (11:58am)	63

Table 18 Demand Responsive Buildings Peak Demand with and without EV

3.9.2 Control of EV charging

In this study EV owners, arriving at the available charging stations, were given priority over building requirements to charge their vehicles instantly without any delay. The EV continues to charge till the EV owner unplugs the vehicle; if for example the owner is leaving the building. During charging, EVs act as active loads and increase building's existing power consumption. Building end-use loads were controlled instead of EVs to reduce building power consumption and absorb EV penetration.

4 Simulation Results and Discussions

This Section presents the simulation results for the load control strategy for the distribution feeder for absorbing EV penetration and the load control strategy at building level using medium-sized office building for experimentation. The simulations were performed for a hot summer day at a resolution of 1-minute intervals.

4.1 Case study: Distribution feeder load control strategy for EV absorption

This Section presents the simulation results for the distribution feeder with the designed strategy for absorbing EV penetration with load control, ice storage and PV systems. The simulations were performed for a summer day at a resolution of 1-minute intervals.

For the base case EVs are charged at all the demand responsive buildings representing 100% penetration. Figure 33 shows the 3-phase load profiles at the substation with and without EV penetration. Without EV penetration the distribution feeder has a peak load of 9.75MW at 3:59pm. With 100% EV penetration, the feeder's demand increases and gets quite high at times when EV charging is higher in the demand responsive buildings as described in Section 3.9. The distribution feeder has a new peak load of 11.01MW at 3:08pm, an increase of 13.4% than the original peak load.

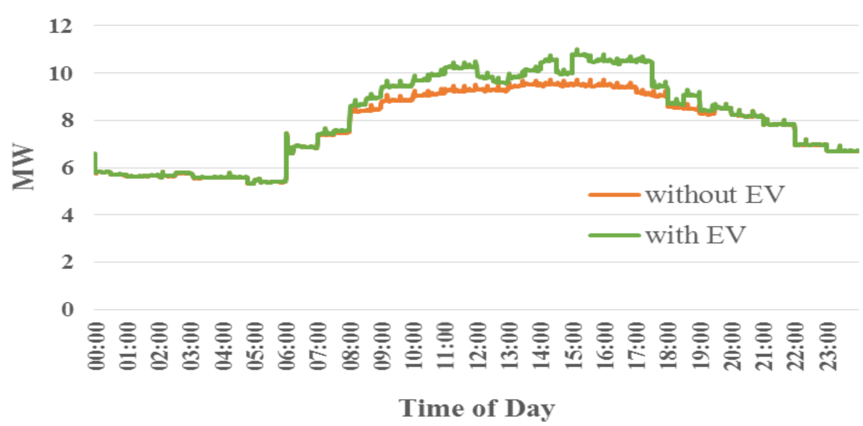

Figure 33 Distribution feeder's load profiles with and without EV penetration

Also EV penetration increases the losses and lowers the load factors as discussed in the Table 20. This problem can be overcome by introducing load control strategies, discussed in

Section 3.1, in demand responsive buildings to optimally control their end-use loads without sacrificing occupant comfort and perform ice storage control. If load control alone is unable to improve the feeder's profile and bring it back to the threshold value then rooftop PV units can be recommended.

For the base case (i.e., 100% EV penetration in all 21 demand responsive buildings), to evaluate the ability of the proposed load control strategy to absorb EV penetration, end-use building loads in all buildings were controlled, and ice storage units (if available) were discharged. Table 19 summarizes the participation by different types of demand-responsive buildings.

	Small-sized office building	**Medium-sized office building**	**Stand-alone retail store**
Load control participation duration: Maximum three (3) hours for each building	All six (6) small-sized office buildings control end-use loads from 3pm-6pm	One (1) building: end-use loads control from 9am-12pm One (1) building: full ice storage discharge from 10am-1pm One (1) building: end-use loads control from 1pm-4pm One (1) building: end-use loads control from 3pm-6pm Four (4) buildings: discharge partial ice storage plus end-use loads control from 3pm-6pm	One (1) building: end-use loads control from 11am-2pm Three (3) buildings: end-use loads control from 4pm-7pm Three (3) building: end-use loads control from 5:30pm-8:30pm

Table 19 Demand Responsive Buildings Participation

In this study, small-sized office buildings were made to participate together in the load control from 3pm to 6pm during their high demand period. Together, they could provide appreciable load control savings. Medium-sized office buildings and retail buildings were utilized in the late morning and afternoon hours to absorb EV penetration due to the nature of their building operation. Retail buildings were made to participate during the morning to late evening hours due to their longer operating hours and potential to provide load control savings during these periods. To avoid demand restrike, the next group of buildings about to participate in load control overlaps their end-use loads control with those already participating in load control.

Figure 34 shows the distribution feeder's load profiles without EV and with EV plus load control. With all 21 buildings participating in reducing the feeder peak demand, the distribution feeder's peak load with EV penetration is reduced from 11.01MW to 10.44MW, a decrease of 5.18%. Feeder demand in the evening, from around 5:30pm to 6pm, gets lower than the threshold value as occupancy in office buildings gets lowered and load control in these buildings provides more savings. Similarly, demand from 7pm to 9pm is also lower or close to the threshold value since the retail buildings occupancy lowers and load control in these buildings achieves more savings. The result indicates that load control alone is unable to bring the distribution feeder's demand to its threshold limit at all times. Also with load control off-peak electricity consumption increases from around midnight to 5:30am in the morning and from 9pm to 10pm, as shown in Figure 34, due to charging of full and partial ice storage systems.

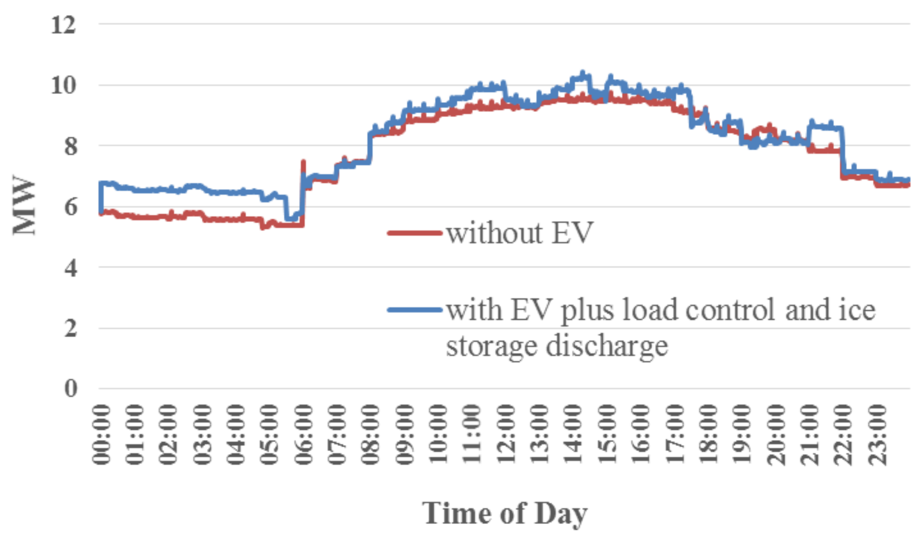

Figure 34 Distribution feeder's load profiles without EV and with EV plus load control and ice storage discharge

As load control alone is unable to bring the distribution feeder's demand to its threshold value hence, the proposed strategy recommends the deployment of 13 rooftop PVs, about 62% penetration, among the demand responsive buildings to bring the distribution feeder's load profile to its threshold value and improve the load factors and further reduce losses. Figure 35 shows example PV profiles with varying output for the each type of demand responsive building in the distribution feeder. As shown, peak PV output, for the small-sized office, medium-sized office and retail building are 3kW, 35kW and 41kW, respectively. The building size hence, the available roof space for PV has been scaled down when integrating the demand responsive buildings in the distribution feeder. Demand responsive buildings located elsewhere in the feeder have slightly different PV profiles.

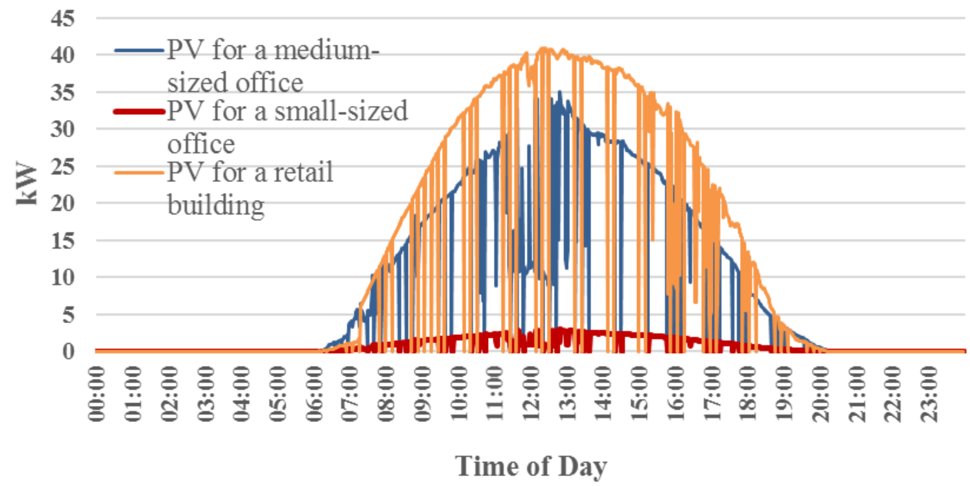

Figure 35 PV profiles for the demand responsive commercial buildings used in this study

Figure 36 shows the distribution feeder's load profiles without EV and with EV, load control and PV together. With load control and PV, the feeder has a peak demand of 9.53MW at 3:11pm, a decrease of 13.4% from the 11.01MW demand with EV penetration alone.

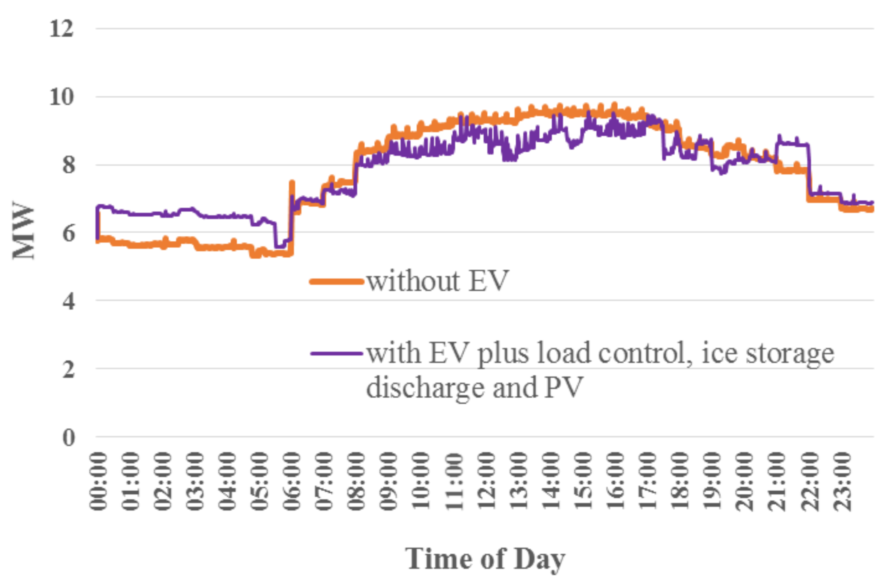

Figure 36 Distribution feeder's load profiles without EV, with EV, load control, ice storage discharge and PV

PV along with load control brings the distribution feeder's demand close to the threshold limit, in fact demand gets quite lower than the threshold value in the afternoon hours from around noon to 3pm due to high PV output. PV output is both variable and intermittent due to weather changes and therefore varies on a daily basis. Hence, the peak load will vary due to PV output changes. Table 20 summarizes the peak loads, load factors and power losses for the distribution feeder under study without EV and with EV, load control and PV.

	Without EV	**With EV**	**With EV+ Load control**	**With EV+ Load control and PV**
Peak load	9.75 MW	11.01 MW	10.44 MW	9.53 MW
Load factor	79.7%	73.6%	78.2%	81.6%
Feeder losses	317 kW	362 kW	339 kW	320 kW

Table 20 Summary of distribution feeder's peak loads, load factors and losses without EV, with EV, load control and PV

- Quantifying peak demand reduction potential with the proposed load control strategy

  For the base case, 100% EV penetration among demand responsive buildings increases the distribution feeder's peak load from 9.75MW to 11.01MW, or 12.9%. Implementing load control in all demand responsive buildings and PV are able to reduce the peak load with EV penetration from 11.01MW to 9.53MW, representing a 13.4% improvement. This new peak demand is lower than the original demand without EV penetration by 2.26%.
- Impact of the proposed strategy on distribution system load factor

  Load factor is defined as the ratio of the average load to the peak load. The original load factor without EV is 79.7%. With 100% EV penetration, the original load factor decreases to 73.6%. With the introduction of load control and PV together, the load factor is improved to 81.6%, representing a 10.9% improvement. In fact, the load factors are slightly higher than the original load factor without EV penetration.
- Impact of the proposed strategy on distribution system losses

  100% EV penetration increases the feeder losses from 317kW to 362kW, or 14.20%. When load control and PV are introduced, feeder losses with EV at 362kW are reduced to 320kW, representing an 11.6% loss reduction.

4.2 Case study: Building level load control (DR) strategy

This Section presents results for building level load control strategy implementation. A medium-sized office building model was used for analysis purposes. The simulations were performed for a summer day at a resolution of 1-minute intervals. DR event considered is from 2pm to 5pm during which end-use loads along with ice storage discharge were controlled to reduce building demand. PV system was sized as explained in Section 3.7.1. The ice storage system was sized as explained in Section 3.8.2.

PV output is available all day. For the ice storage system two control strategies have been analyzed, full storage and partial storage. In a full ice storage system, DX unit operation is eliminated completely during a DR event and the building cooling load is met by storage discharge only, i.e., the ice storage system is in the discharge-only mode during the DR event. Before the start of the DR event, from 12 noon to 2pm, the ice storage unit operated in the cooling-only mode where the building cooling demand was met by DX cooling only, no storage discharge. During the DR event, 2pm to 5pm, the system was in the discharge-only mode, i.e., cooling was provided by storage discharge only. If the ice tank was depleted before 5pm and cooling load remained, the system switched to DX cooling. After the end of the DR event, the system again switched to the cooling-only mode until 8pm. From 8pm to 12 noon, the system was in the cool-and-charge mode, where the building was cooled with DX along with charging of the ice tank. While operating in the cool-and-charge mode if the tank charged up to 99% before 12 noon, the system switched to the cooling-only mode.

In a partial ice storage system, the DX unit along with storage discharge met the building's cooling load. Before the start of the DR event, from 12 noon to 2pm, the ice storage unit operated in the cooling-only mode. During the DR event, 2pm to 5pm, the system was in the cool-and-discharge mode where cooling was provided by the DX unit and storage discharge. If the ice tank was depleted before 5pm and cooling load remained, the system switched to DX cooling. After the end of the DR event, the system again switched to the cooling-only mode until 8pm. From 8pm to 12 noon, the system was in the cool-and-charge mode. While operating in the cool-and-charge mode the tank was allowed to charge up to 55% to avoid excessive energy consumption to charge a large storage. If the tank was charged up to 55% before 12 noon, the system switched to the cooling-only mode.

4.2.1 Building end-use loads profile

Figure 37 shows the power consumption of major end-use loads in the simulated medium-sized office building with a conventional DX unit and the outdoor air temperature profile for a typical summer day used in this study. From 12 noon to about 6pm outside air temperatures are higher than 30°C. This increase in outside dry bulb temperature increases building cooling load in the afternoon. The power consumption profile follows occupancy data along with HVAC and lighting load usage depicted in Section 3.4.2 for a medium-sized office building. There is a power surge at 6am as the HVAC system starts to operate and there is an immediate cooling demand as the cooling set points of all zones are reduced from 26.7°C to 24°C. Building and HVAC peak loads of 223.40kW and 107.34kW, respectively occur at 4:10pm.

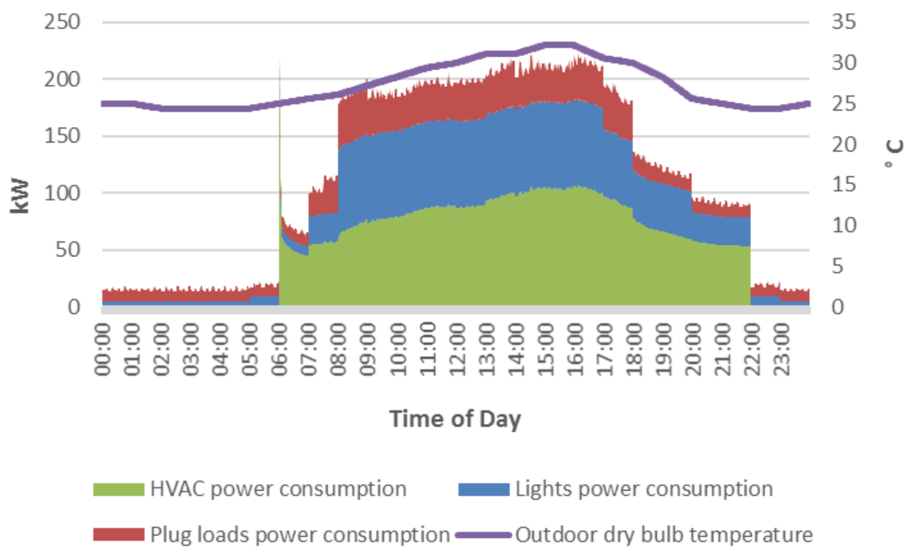

Figure 37 Power consumption of major end-use loads for the simulated medium-sized office building for the simulation day

4.2.2 Rooftop PV system potential

Figure 38 shows the power output for PV sized to cover 65% of the building roof area in response to the sky clearness factor, which describes attenuation of solar radiation due to clouds. It indicates an overcast sky when close to 1 and a clear sky when greater than 6. The sky clearness factor for the simulated day is at its maximum, about 3.2, at 11:30am. It is at this time that the PV generates maximum output, about 82kW, which does not coincide with the building peak demand. During late afternoon hours building demand is higher but PV output gets lower. After 11:30am PV output starts to decrease but from around 2pm to

2:30pm starts to increase again, going up to 56.41kW as the sky clearness factor increases to 2. For the simulated day the building's total electricity consumption is 2786kWh and PV production is 550kWh.

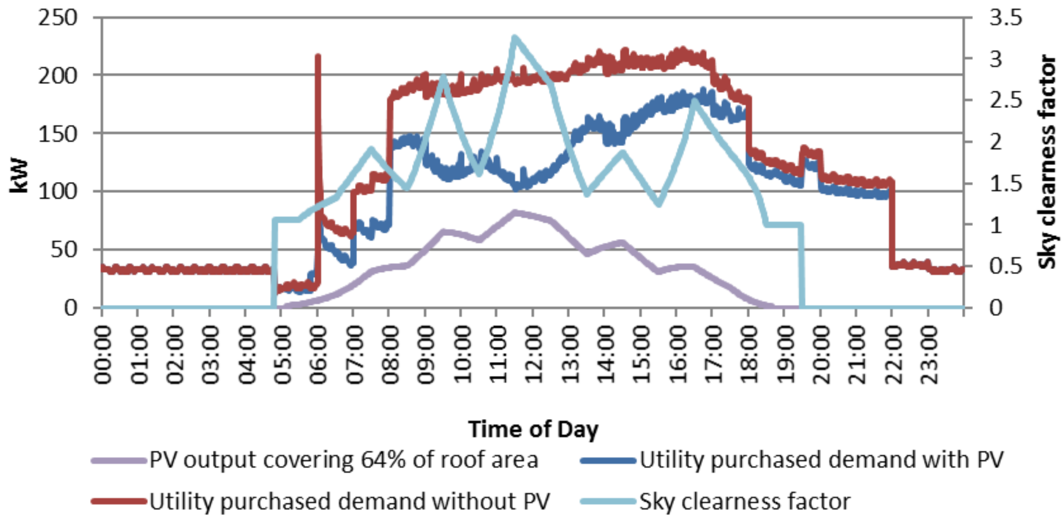

Figure 38 Power generated by PV and purchased from utility for the simulated building for the simulation day

The PV unit - covering 65% of building roof area - produces 35.52kW at 4:10pm, reducing utility purchased peak demand from 223.40kW to 185.91kW, a decrease of 17%.

4.2.3 Ice storage system potential

Two control strategies of an ice storage system during DR are investigated including full storage and partial storage. Figures 39 and 40 show the building and HVAC power consumption profiles with full and partial ice storage systems, respectively. There is a power surge at 6am as cooling set points of all zones reduce to 24°C. As shown in Figure 40, the full ice storage system almost completely eliminates DX unit operation during load control by discharging storage, whereas the partial ice storage partially reduces DX unit operation during load control. After participation in DR there is an increase in power consumption as the ice storage switches to the cooling-only mode and compressors operates at full load to provide DX cooling.

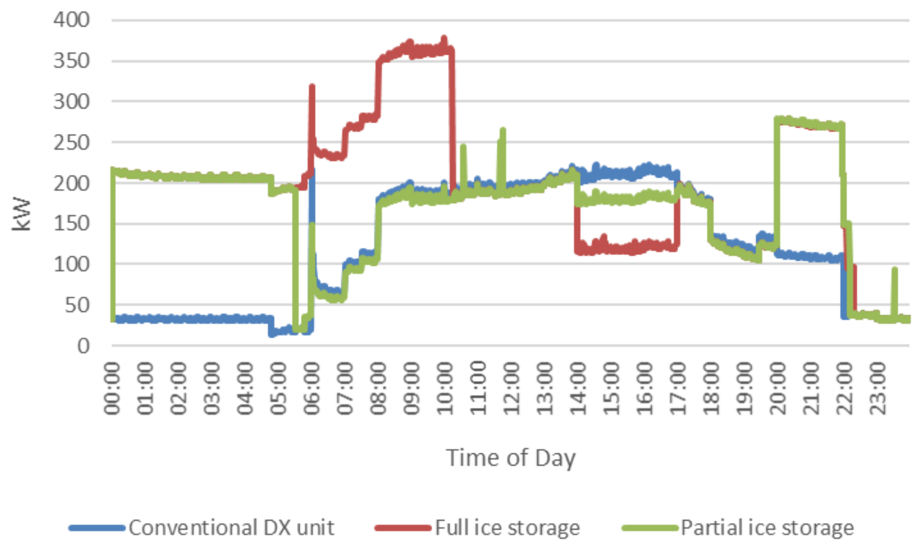

Figure 39 Simulated building power consumption profiles with and without ice storage for the simulation day

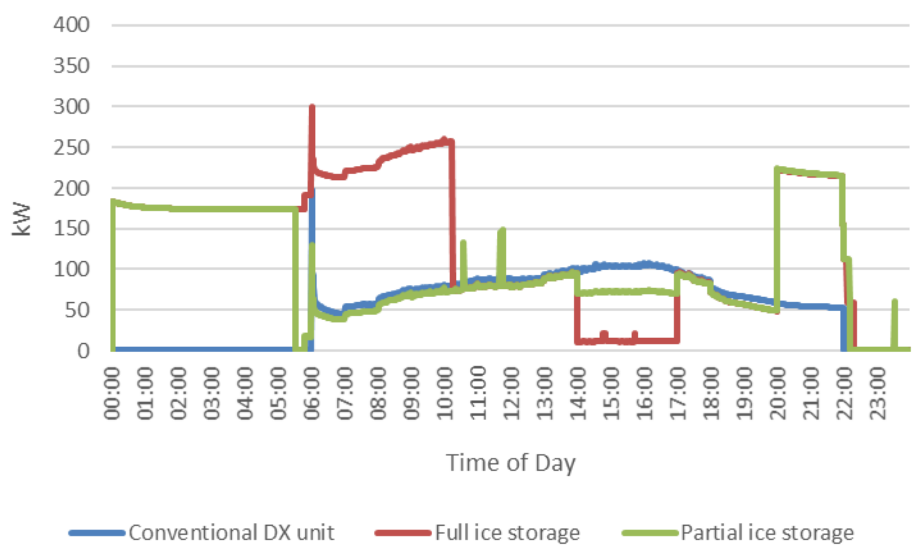

Figure 40 Simulated building's HVAC power consumption profiles with and without ice storage for the simulation day

Table 21 shows the peak load savings during DR for the two ice storage systems. The full ice storage unit reduces the building peak load at 4:10pm by 42.54% whereas the partial storage unit reduces it by 14.85%. Both systems however increase the buildings' overall energy consumption for the simulation day as ice is charged during unoccupied periods at lower temperatures hence the Coefficient of Performance (COP) reduces [165].

	Peak load at 4:10pm (kW)		Energy consumption for the simulation day (GJ)	
	Building	HVAC	Building	HVAC
without ice storage (conventional DX unit)	223.40	107.34	10.42	4.52
with full ice storage	128.37	12.31	16.88	10.98
with partial ice storage	190.22	74.15	14.52	8.63

Table 21 Peak load savings and energy consumption with full and partial ice storage

4.2.4 End-use loads control (DR) potential

Based on a demand reduction signal from a utility, end-use load control can be prioritized by zone based on their peak load reduction opportunity and impact on occupant comfort. For example, cooling set points for the bottom floor and core zones on all floors, which are cooler due to less solar heat gain than other floors, can be raised to meet the peak load reduction requirement. Similarly, on an extreme sunny day, based on a demand reduction signal, only lights in perimeter zones can be controlled to meet peak load savings. In this study, all zones lights, cooling set points and plug loads are controlled to achieve maximum savings possible while maintaining occupant comfort needs. Figures 41 and 42 show building and HVAC power consumption profiles with EMS for the simulated building, respectively.

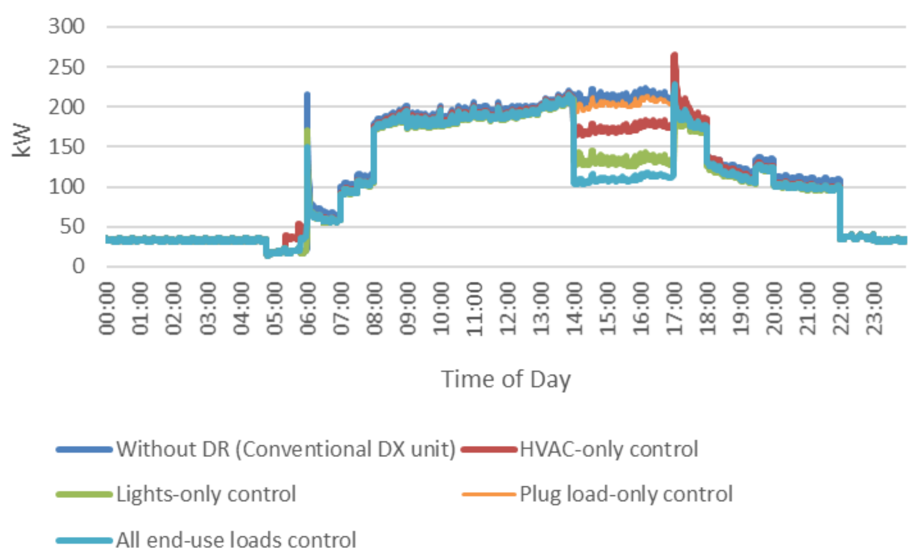

Figure 41 Simulated building power consumption profiles with and without end-use loads control by EMS for the simulation day

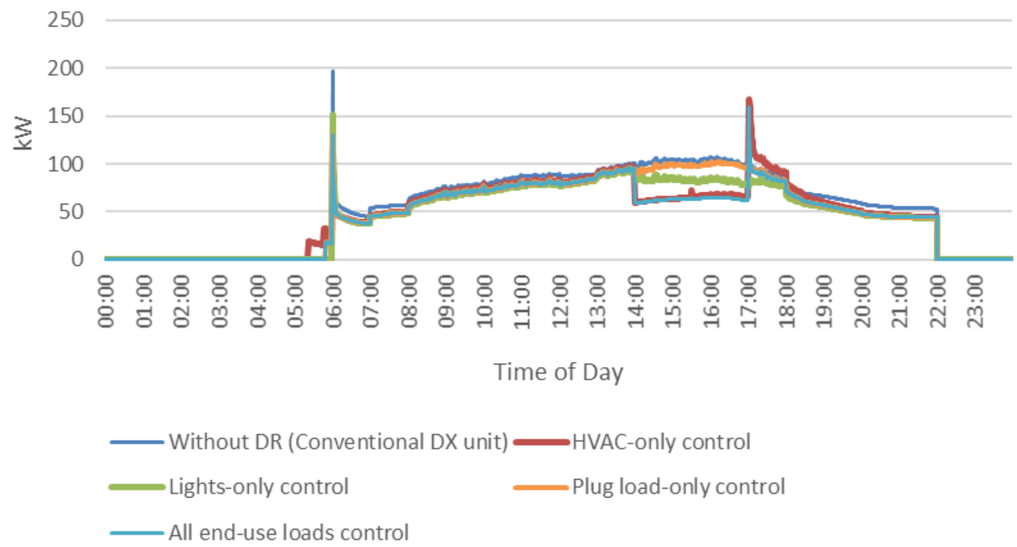

Figure 42 Simulated building's HVAC power consumption profiles with and without end-use loads control by EMS for the simulation day

The developed DR approach reduces the building peak load at 4:10pm from 223.40kW to 116.41kW, representing a 48% decrease. The HVAC peak load at 4:10pm is reduced from 107.34kW to 64.66kW, representing a 39.76% decrease. From Figure 42 it is observed that the HVAC load has a spike when DR ends at 5pm, which causes the HVAC load to increase from 61.65kW to 159.17kW, representing an increase of 158%. This demand rebound is due to the simultaneous HVAC operation after load control has ended, and can be reduced by slowly bringing back all zones' temperature set points to their nominal values or extending the load control duration to later hours, e.g. 7pm instead of 5pm. Extending a DR duration will allow the previously deferred loads to be partially operated after working hours (e.g., between 5pm and 7pm), when building occupancy has reduced and outside temperatures already get lowered [123]. As a result, less load compensation will be needed after DR ends at 7pm.

Table 22 summarizes the peak load and energy savings with end-use loads control during DR. It can be observed that light control achieves maximum peak load and energy savings followed by cooling set point control. In particular, about 35.59% of the building peak load can be reduced with lights-only control; about 17.54% of the building load can be reduced with HVAC-only control; and about 4.99% of the building peak load can be reduced with plug load-only control. Controlling all end-use loads results in an overall 48% peak load reduction in the building. This also results in the decrease of the overall building energy consumption by 13.82% for the simulation day.

It is also interesting to see that dimming lights and shutting down selected plug loads reduce HVAC power consumption due to the decrease in cooling loads. Specifically, lights-only control contributes to about 19.46% reduction in HVAC peak load; and plug load-only control contributes to about 5.08% reduction in HVAC peak load.

	Peak load at 4:10pm (kW)				**Energy consumption for the simulation day (GJ)**			
	Building	**HVAC**	**Lights**	**Plug loads**	**Building**	**HVAC**	**Lights**	**Plug loads**
Without DR (Conventional DX unit)	223.40	107.34	75.73	40.33	10.42	4.52	3.42	1.88
HVAC-only control	184.21	68.15	75.73	40.33	9.83	3.93	3.42	1.88
Lights-only control	143.89	86.45	17.11	40.33	9.13	3.87	2.79	1.88
Plug load-only control	212.26	101.89	75.73	34.64	9.99	4.12	3.42	1.85
All end-use load control	116.41	64.66	17.11	34.64	8.98	3.74	2.79	1.85

Table 22 Peak load and energy savings for simulated building with and without end-use loads control by EMS for the simulation day

4.2.5 PV, ice storage and DR potential

Coordinated control of DR strategy, PV and ice storage systems is implemented in the simulated medium-sized office building and presented in this Section. Figures 43 and 45 show the building and HVAC power consumption profiles by implementing various combinations of DR, PV and full ice storage systems, respectively. Figures 46 and 47 show the building and HVAC power consumption profiles by implementing various combinations of DR, PV and partial ice storage systems, respectively.

In all scenarios, at the end of DR, at 5pm, the system is immediately brought back to its normal operation, i.e., cooling set points are reduced to 24°C and in case of ice storage operation, the cooling system switches to DX cooling only. In case of full storage, the compressor has to start up to provide DX cooling by cycling the refrigerant to cool the building air. In case of partial storage, the compressor is already operating during DR and partly meets the cooling load along with storage discharge. At the end of DR, the DX unit alone has to meet the cooling load. It is interesting to note that for the full storage, end-use DR and PV combination (Case 5a), from 2pm to around 2:40pm building power consumption is zero and there is some surplus PV generation available shown in Figure 44. Surplus power reaches a maximum of 6kW at around 2:30pm and decreases afterwards. This is due to the decrease in building load as a result of the operation of DR and ice storage, as well as due to the increase in PV generation during this time as seen in Figure 38 going up to 56.41kW and then decreasing again. The building acts as an energy generating unit or a positive energy building. From Figure 45, DR and PV combination (Case 2) and DR, PV and partial ice storage combination (Case 5b) produce almost similar load shapes during DR. This can be explained as follows, for Case 5b, the DX unit is operating along with partial storage discharge to meet the cooling load which has been reduced by employing DR strategy. Due to the reduced cooling load impact of partial storage is not significant. It is also observed from Figures 43, 45 to 47 - that for Case 4a and 4b - more ice is discharged during DR than other cases which have end-use DR strategy deployed, reducing the building cooling load, as a result the ice tank is charged for a longer time duration, until around 10pm, to get completely charged up.

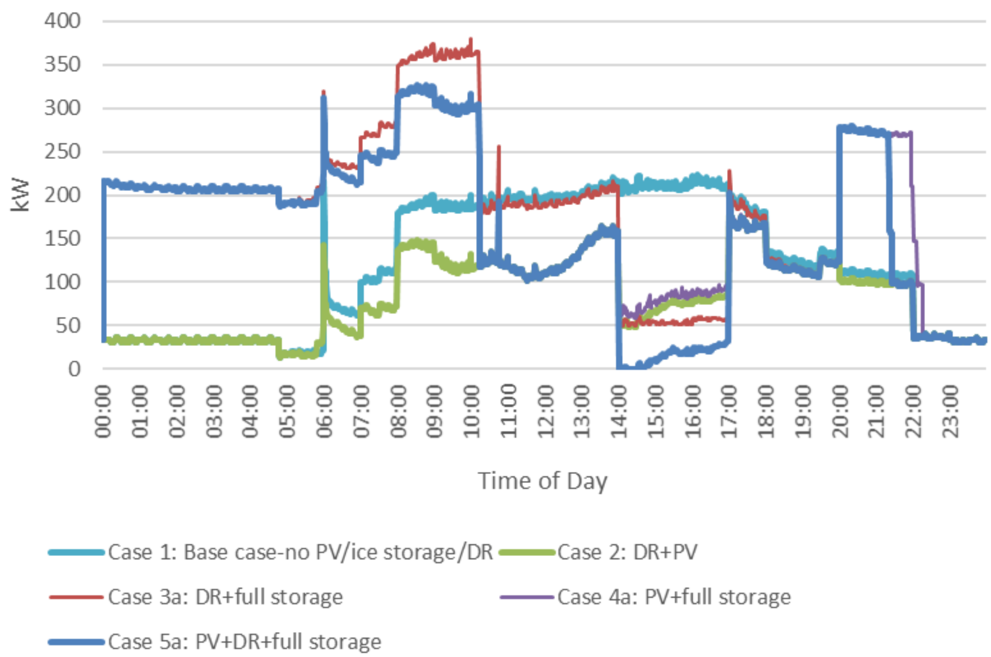

Figure 43 Simulated building power consumption profiles with combinations of PV, full ice storage and DR for the simulation day

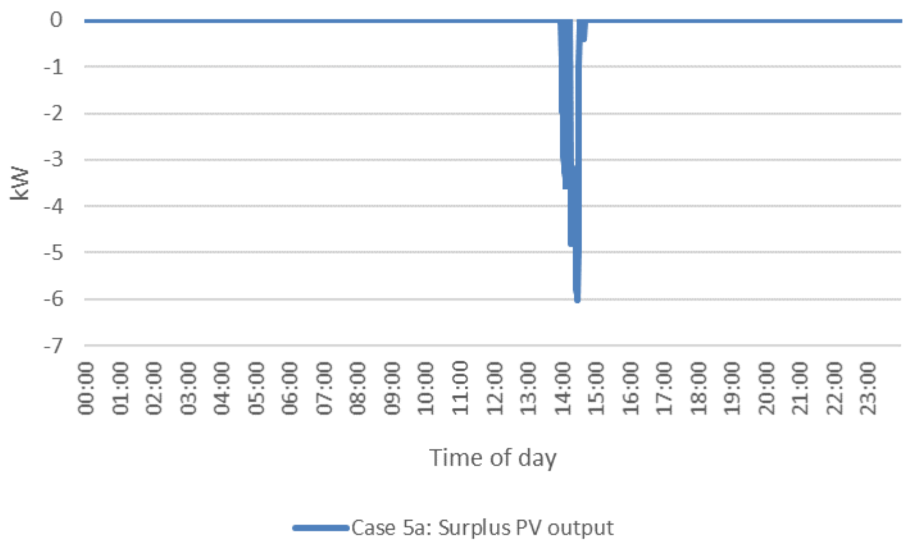

Figure 44 Simulated building surplus PV power generation for Case 5a for the simulation day

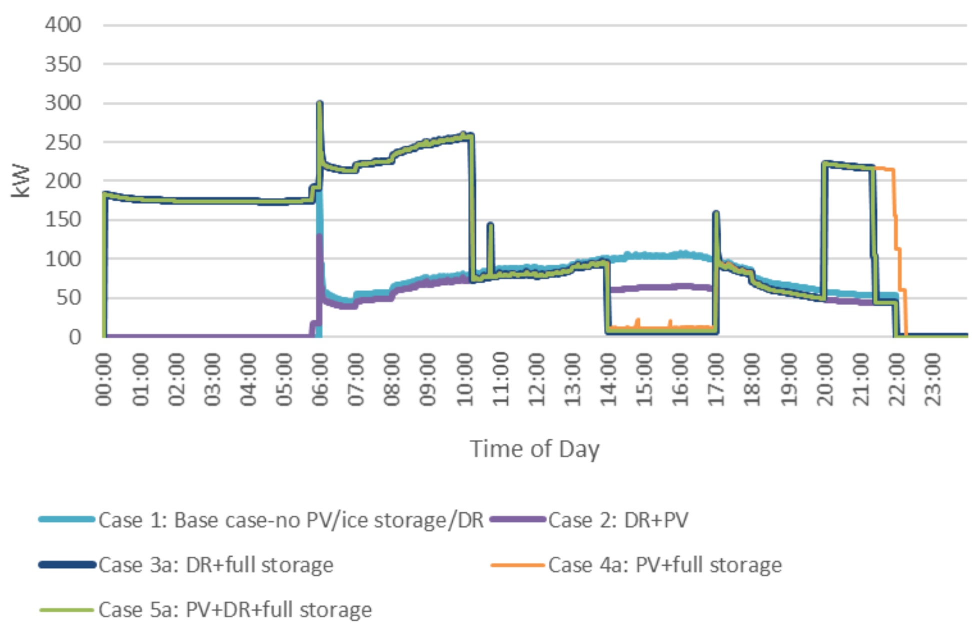

Figure 45 Simulated building's HVAC power consumption profiles with combinations of PV, full ice storage and DR for the simulation day

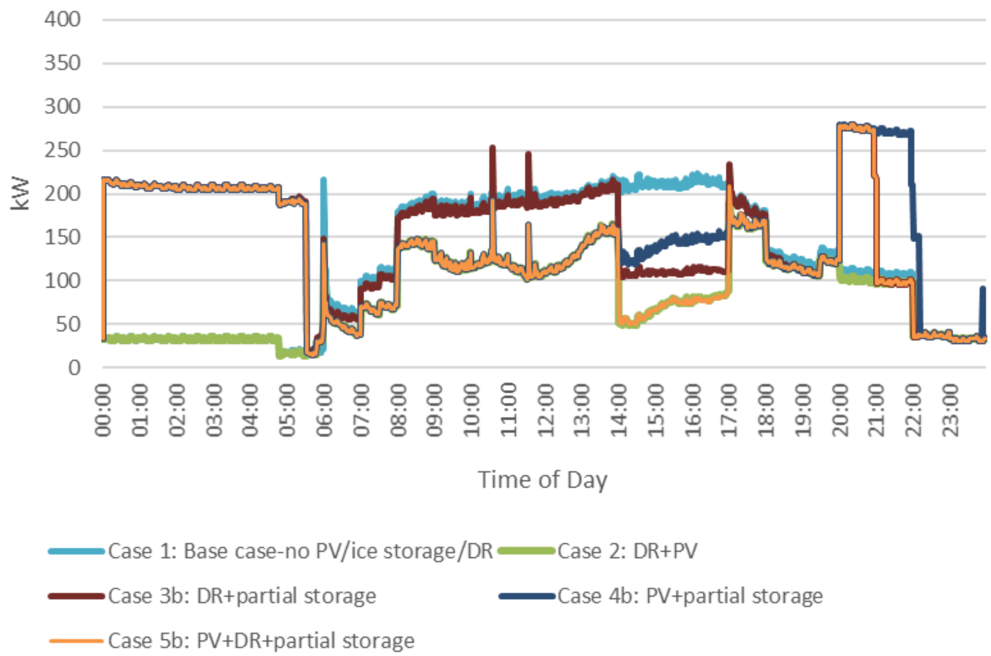

Figure 46 Simulated building power consumption profiles with combinations of PV, partial ice storage and DR for the simulation day

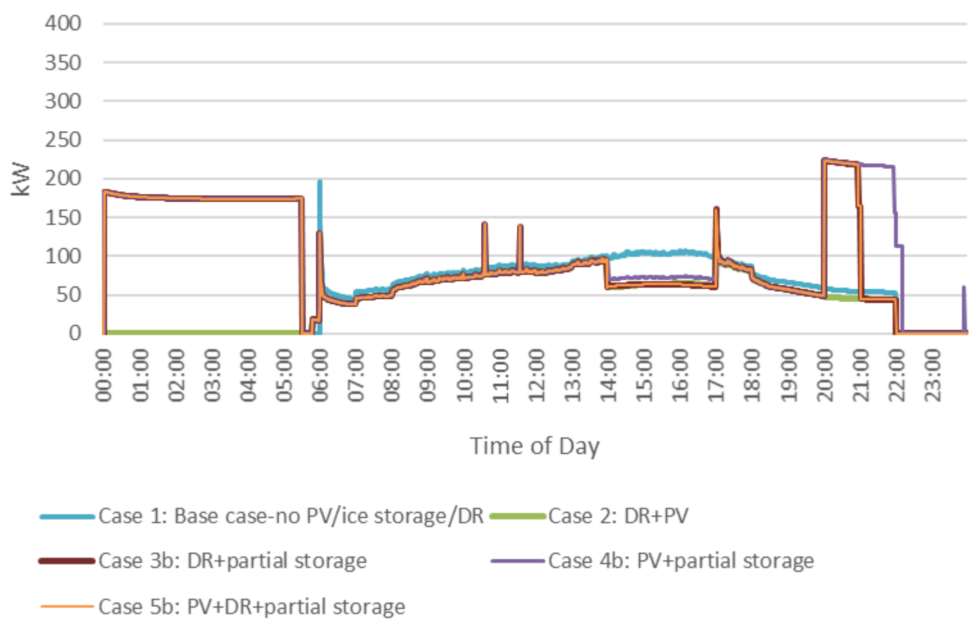

Figure 47 Simulated building's HVAC power consumption profiles with and without PV, partial ice storage and DR for the simulation day

Table 23 summarizes the peak load and energy consumption of the simulated building when various combinations of DR, PV and ice storage are deployed.

Notice that while the building peak demand can be drastically decreased in all scenarios with ice storage, implementing ice storage (either full or partial) will result in an increase in overall building and HVAC energy consumption as there is a need to charge the storage at night. On the other hand, scenarios without ice storage in Case 2 (combination of PV and DR), Case 6 (PV-only) and Case 7 (DR-only) reduce not only the peak load but also the overall energy consumption of the building.

Full ice storage together with DR and PV (Case 5a) achieves the highest peak load savings, i.e., about 89.51% reduction in the building peak load. Implementing full storage alone (Case 8a) results in a peak load saving of about 42.54% and the highest building energy consumption, an increase of about 62% from the base case with no PV, DR or ice storage, as there is no PV to provide excess generation or DR strategy to reduce end-use loads during DR. DR-only (Case 7) and DR and PV together (Case 2) achieve more building peak load savings than full storage alone (Case 8a) and at lower building energy consumption. DR-only is able to achieve more peak load savings than full storage alone as DR raises the cooling set points lowering HVAC consumption and also shuts down lights (which achieves maximum peak load savings) and plug loads which further reduce HVAC consumption.

Partial ice storage together with DR and PV (Case 5b) achieves higher building peak load savings than full ice storage with PV (Case 4a) but with lesser energy consumption. Partial storage alone (Case 8b) achieves the lowest building peak load savings of about 14.85% and the increase in building energy consumption is about 39.35%. However, if partial storage is implemented with DR (Case 3b) building peak load reduces by 48.67% and the increase in building energy consumption is about 25.53%. It is interesting to note that DR and PV combination (Case 2) produces peak load savings comparable to PV, DR and partial storage operating together (Case 5b) as the DX unit is operating along with storage discharge to meet the cooling load which has been reduced by DR.

	PV	DR	Ice storage	Peak load at 4:10pm (kW)		Energy consumption for the simulated day (GJ)	
				Building	HVAC	Building	HVAC
Case 1 (Base case)	-	-	-	223.4	107.34	10.42	4.52
Case 2	•	•	-	80.87	64.66	7.00	3.74
Case 3a	-	•	Full	58.95	7.20	15.73	10.49
Case 3b	-	•	Partial	114.67	62.92	13.08	7.85
Case 4a	•	-	Full	92.85	12.31	14.90	10.98
Case 4b	•	-	Partial	154.75	74.21	12.55	8.63
Case 5a	•	•	Full	23.43	7.20	13.75	10.49
Case 5b	•	•	Partial	79.15	62.92	11.10	7.85
Case 6	•	-	-	185.91	105.37	8.05	4.14
Case 7	-	•	-	116.41	64.66	8.98	3.74
Case 8a	-	-	Full	128.37	12.31	16.88	10.98
Case 8b	-	-	Partial	190.22	74.15	14.52	8.63

Table 23 Peak load savings and energy consumption with various combinations of DR, PV and ice storage

The above analysis provides building owners and electric utilities an insight into what load shapes and energy savings can be achieved by deploying various technologies. Results show that in addition to DR and ice storage, PV helps to further reduce the demand during high tariffs. Ice storage can shift the cooling demand to low night time tariffs. Reduced demand during high tariffs and spreading building demand over a day provide benefits to both building owners and utilities. Utilizing ice storage or DR with PV avoids the need of a very large on-site PV system as both ice storage and DR reduce building electric load. By operating PV with a full ice storage system and deploying DR, a commercial building can act as a generating unit with surplus PV energy that can be sent back to the grid. While the initial cost would be high due to the installation of PV and ice storage, the building's operational costs would be lower due to the use of DR, renewable energy and ice storage. This shows a stepping stone towards net-zero energy buildings.

4.3 Sensitivity Analysis

In this Section, sensitivity analysis is performed to analyze how the proposed load control strategy can contribute to reducing distribution feeder peak load with EVs, thereby making the EV penetration transparent to the grid. This study was carried out by varying the number of buildings with EV from the base case, considering mixed type of buildings and EV charge stations, where all 21 demand responsive buildings (100%) have EVs to 15% where only 3 buildings have EVs.

For the base case, all 21 demand responsive buildings are needed to participate in load control, i.e. 100% load control, along with 13 buildings recommended to install rooftop PVs, i.e. 62% PV penetration, to absorb EV penetration. Table 24 summarizes the number of buildings needed to perform load control and to have PV in order to absorb different EV penetration levels. As shown, load control alone is able to bring the feeder demand to its threshold value for EV penetrations above 15% and up to 50%. 75% EV penetration needs around 9 demand responsive buildings with PVs to help absorb EV penetration along with load control. The distribution feeder is able to absorb EV penetration of up to 15% without load control and PV.

% of buildings with EV charge stations (No. of Buildings with EV charge stations)	No. of Buildings needed to participate in DR event in order to absorb EVs	No. of buildings with PVs needed to absorb EVs
Base Case 100% (21)	21	13
75% (16)	21	9
50% (10)	21	0
35% (7)	18	0
25% (5)	7	0
15% (3)	0	0

Table 24 Sensitivity Analysis considering Different Percent of Buildings with EV Charge Stations

5 Conclusions and Future Work

The analysis presented in this study shows that random and large-scale electric vehicle (EV) penetration in a distribution feeder results in the increase in system losses and reduction in load factors. In this study, a coordinated load control strategy, among participating commercial buildings in a distribution feeder, to optimally control buildings' end-use loads including ice storage, along with strategically deployed photovoltaic (PV) was developed to absorb EV penetration. This was done without sacrificing occupant comfort.

Results indicate that the developed approach can absorb 100% EV penetration, and result in 13.4% decrease in the peak load; 10.9% improvement in the load factor; and 11.6% reduction in feeder losses. Sensitivity analysis shows that both load control and PV are needed to absorb EV penetration above 50%. It should be noted that PV output variability will affect the outcomes of the proposed strategy. Research findings also indicate that PV-only, end-use load control-only, and their combination reduce both building peak load and energy consumption. Introducing ice storage increases overall building energy consumption but can provide significant peak load savings. Combining full storage together with end-use load control and PV can achieve maximum peak load savings at the expense of increased energy consumption. However, end-use load control and PV together can also achieve significant building peak load savings at reduced energy consumption. Operating partial storage with PV and end-use load control achieves similar peak load savings as end-use load control and PV operating together. Integrated automation of end-use load control, PV and full ice storage enable buildings to operate as generating units with excess renewable generation. It should be noted that, a hot summer day has been analyzed in this paper as an extreme case to demonstrate the applicability of the proposed automation tool. This guarantees the tool's applicability for other days of the year as well. Since there is always day-to-day variability in weather patterns, there will be variations in peak reduction and energy savings potentials for a given building throughout the year.

Overall, this research presents a methodology to improve a particular distribution feeder's load factors and losses due to EV penetration through control of major loads and ice storage discharge, along with rooftop PV systems in demand responsive commercial buildings. PV output is both variable and intermittent due to weather changes and therefore varies on a daily basis. Hence, the peak load will vary as PV output changes. On cloudy/rainy days with low or no PV output, more stringent load control strategies need to be implemented, which may compromise occupant comfort to provide more demand savings, as needed. More rooftop PVs and ice storage systems can be installed to compensate for PV output variability. It offers an improved understanding of building's peak demand reduction potential as a result of performing load control to maximize building's economic benefits while maintaining occupant thermal and lighting needs. This translates to improving the grid's reliability and efficiency. This research is expected to benefit building owners/operators by providing an improved understanding of building's load shapes as a result of performing end-use load control, install PV and ice storage systems to maximize their building's economic benefits while being sensitive to occupant thermal and visual comfort. The knowledge gained through this research will help researchers develop new and improved controls for reducing building and distribution feeder's peak load.

There are extensions of this research that deserve further consideration. The integrated control algorithm for HVAC adjusts the temperature set points during load control, however other HVAC load control strategies presented in the literature review (e.g. systemic adjustments to the air distribution and cooling systems) could also be implemented and their impacts on occupant thermal comfort analyzed. Load control strategies could be designed and implemented in other types of commercial buildings, including apartment buildings, restaurants and strip malls, which could then be integrated into the distribution feeder model. Load control strategy for the demand responsive commercial buildings could also be extended to residential dwellings which provide evening and night EV charging. A dynamic approach to distribution feeder's load control strategy implementation can overcome the limitations of the static approach presented in the research.

A summer peaking utility has been considered in this study. However, winter peaking utilities can also be analyzed where buildings have electric heating during winters. Battery storage can also be considered to cover PV variability. The distribution feeder can be expanded to include larger numbers, types and sizes of commercial buildings. This would affect the outcomes of sensitivity analysis.

6 References

1. Papadopoulos, P., et al. *Distribution networks with Electric Vehicles* in *Proceedings of the 44th International Universities Power Engineering Conference (UPEC)*. 2009. Glasgow: IEEE.
2. Yilmaz, M. and P.T. Krein, *Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles.* IEEE Transactions on Power Electronics, 2013. **28**(5).
3. *Developing Infrastructure to Charge Plug-In Electric Vehicles*. 2016; Available from: http://www.afdc.energy.gov/fuels/electricity_infrastructure.html.
4. *Initiative on Plug-in Electric Vehicles*. 2012, Illinois Commerce Commission.
5. Yong, J.Y., et al., *A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects.* Renewable and Sustainable Energy Reviews, 2015. **49**: p. 365-385.
6. Clement-Nyns, K., E. Haesen, and J. Driesen, *The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid.* IEEE Transactions on Power Systems, 2010. **25**(1): p. 371-380.
7. Singh, M., I. Kar, and P. Kumar. *Influence of EV on grid power quality and optimizing the charging schedule to mitigate voltage imbalance and reduce power loss*. in *Power Electronics and Motion Control Conference (EPE/PEMC), 2010 14th International*. 2010.
8. Richard Cowart, C., *Electric Vehicle Deployment: Policy Questions and Impacts to the U.S. Electric Grid* 2011, DOE Electricity Advisory Committee
9. Jin, C., J. Tang, and P. Ghosh, *Optimizing Electric Vehicle Charging: A Customer's Perspective.* IEEE Transactions on Vehicular Technology, 2013. **62**(7): p. 2919-2927.
10. Weiller, C. and A. Neely, *Using electric vehicles for energy services: Industry perspectives.* Energy, 2014. **77**: p. 194-200.
11. Wang, J., M.A. Biviji, and W.M. Wang, *Lessons learned from smart grid enabled pricing programs*, in *Power and Energy Conference (PECI)*. 2011: Illinois. p. 1-7.
12. FERC, *2010 Assessment of Demand Response and Advanced Metering*. 2011, Federal Energy Regulatory Commission.
13. Kreuder, L. and C. Spataru, *Assessing demand response with heat pumps for efficient grid operation in smart grids.* Sustainable Cities and Society, 2015. **19**: p. 136-143.
14. Smith, A.M. and M.A. Brown, *Demand response: A carbon-neutral resource?* Energy, 2015. **85**: p. 10-22.
15. Gils, H.C., *Assessment of the theoretical demand response potential in Europe.* Energy, 2014. **67**: p. 1-18.
16. Yan, C., et al., *A novel air-conditioning system for proactive power demand response to smart grid.* Energy Conversion and Management, 2015. **102**: p. 239-246.
17. Gelazanskas, L. and K.A.A. Gamage, *Demand side management in smart grid: A review and proposals for future direction.* Sustainable Cities and Society, 2014. **11**: p. 22-30.
18. Katipamula, S. et al., *Small- and Medium-Sized Commercial Building Monitoring and Controls Needs: A Scoping Study*. Oct 2012, PNNL-22169.
19. *California Statewide Pricing Pilot Commercial and Industrial Analysis Update* June 2006, CRA International.
20. Katipamula, S., et al., *Small- and Medium-Sized Commercial Building Monitoring and Controls Needs: A Scoping Study*. 2012, PNNL-22169.
21. Goldstein, N. and E. Bloom, *Energy Management for Small and Medium Buildings* 2014, Navigant Research.
22. U.S Energy Information Administration (EIA). *Commercial Buildings Energy Consumption (CBECS) Survey Data*. 2012; Available from: http://www.eia.gov/consumption/commercial/data/2012/.
23. Mathieu, J.L., et al., *Quantifying Changes in Building Electricity Use, With Application to Demand Response.* IEEE Transactions on Smart Grid, Sept 2011. **2**(3): p. 507-518.

24. FERC, *National Action Plan on Demand Response*. June 2010, The Brattle Group,GMMB,Customer Performance Group Definitive Insights,Eastern Research Group
25. *Benefits of Demand Response in Electricity Markets and Recommendations for Achieving them* February 2006, U.S. Department of Energy.
26. Aduda, K.O., et al., *Demand side flexibility: Potentials and building performance implications.* Sustainable Cities and Society, 2016. **22**: p. 146-163.
27. Kamilaris, A., et al., *A literature survey on measuring energy usage for miscellaneous electric loads in offices and commercial buildings.* Renewable and Sustainable Energy Reviews, 2014. **34**(0): p. 536-550.
28. Weng, T., et al. *Managing Plug-Loads for Demand Response within Buildings*. in *Proceedings of the ACM Workshop on Embedded Sensing Systems For Energy-Efficiency*. 2011. Seattle.
29. Acker, B., C. Duarte, and K. Van Den Wymelenberg. *Office Space Plug Load Profiles and Energy Saving Interventions*. in *Proceedings of the 2012 ACEEE summer study on energy efficiency in buildings*. 2012. Pacific Grove, CA.
30. *U.S. Department of Energy Commercial Reference Buildings*. 2016; Available from: http://energy.gov/eere/buildings/commercial-reference-buildings.
31. *Energy Models for Medium to Big Box Retail Buildings from the Advanced Energy Design Guide (AEDG)*. 2016; Available from: https://bcl.nrel.gov/search/site/aedg?f%5b0%5d=bundle%3Anrel_component&f%5b1%5d=im_field_component_tags%3A1347
32. Bonnema, E., M. Leach, and S. Pless, *Technical Support Document: Development of the Advanced Energy Design Guide for Medium to Big Box Retail Buildings – 50% Energy Savings* 2013, National Renewable Energy Laboratory (NREL).
33. Deru, M., et al., *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock* 2011, National Renewable Energy Laboratory (NREL).
34. Page, J., et al., *Automated Demand Response Technology Demonstration for Small and Medium Commercial Buildings* July 2011, Lawrence Berkeley National Laboratory.
35. *Overcoming Barriers to Electric-Vehicle Deployment: Interim Report* 2013, National Academy of Sciences.
36. Boulanger, A.G., et al., *Vehicle Electrification: Status and Issues.* Proceedings of the IEEE, 2011. **99**(6): p. 1116-1138.
37. *EV Everywhere: Electric Vehicle Basics*. [cited 2016; Available from: http://energy.gov/eere/eveverywhere/ev-everywhere-electric-vehicle-basics.
38. *SAE Charging Configurations and Ratings Terminology (SAE J1772)*. 2011; Available from: http://www.sae.org/smartgrid/chargingspeeds.pdf.
39. Rubinstein, F., *Automatic Lighting Controls Demonstration: Long-term Results*. July 1991, Lawrence Berkeley National Laboratory (LBNL).
40. *2017 Mitsubishi i-MiEV*. 2016; Available from: http://www.mitsubishicars.com/imiev#trims.
41. *2017 Volt*. 2016; Available from: http://www.chevrolet.com/volt-electric-car.html?ppc=GOOGLE_700000001291955_71700000013736255_58700001139978712_p10148611530&gclid=CMWb74CW5c8CFVBZhgodyi8KEg&gclsrc=aw.ds#content_chevrolet_northamerica_usa_nscwebsite_en_index_all-vehicles-nav_cars_2017-volt_overview_jcr-content_cnt_legalpage_c1_disclaimers_disclaimer_c1_0.
42. *Electric Vehicle Wiki* 2016; Available from: http://www.electricvehiclewiki.com/Nissan_Leaf.
43. *Tesla Model S*. 2016; Available from: https://www.tesla.com/models.
44. *Traffic data program*. 2009, British Columbia Ministry of Transportation.
45. Herron, D. *EV DC Fast Charging standards – CHAdeMO, CCS, SAE Combo, Tesla Supercharger, etc*. 2015; Available from: http://longtailpipe.com/ebooks/green-transportation-guide-buying-owning-charging-plug-in-vehicles-of-all-kinds/electric-car-charging-advice-systems/ev-dc-fast-charging-standards-chademo-ccs-sae-combo-tesla-supercharger-etc/.

46. *Electric Car Charging Guide*. 2016; Available from: https://chargehub.com/en/electric-car-charging-guide.html.
47. Shaaban, M.F., Y.M. Atwa, and E.F. El-Saadany, *PEVs modeling and impacts mitigation in distribution networks.* IEEE Transactions on Power Systems, 2013. **28**(2): p. 1122-1131.
48. ElNozahy, M.S. and M.M.A. Salama, *A Comprehensive Study of the Impacts of PHEVs on Residential Distribution networks*, in *IEEE Transactions on Sustainable Energy*. Jan 2014. p. 332-342.
49. DeForest, N., et al, *Impact of Widespread Electric Vehicle Adoption on the Electrical Utility Business – Threats and Opportunities*. August 2009, Center for Etrepreneurship & Technology, University of California – Berkeley.
50. Denholm, P. and W. Short, *An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles*. October 2006, National Renewable Energy Laboratory.
51. Pieltain, F.L., et al., *Assessment of the impact of plug-in electric vehicles on distribution networks.* IEEE Transactions on Power System, October 2006. **26**(1): p. 206-213.
52. Shao, S., M. Pipattanasomporn, and S. Rahman, *Challenges of PHEV penetration to the residential distribution network*. in *Proc. IEEE Power & Energy Society General Meeting, (PES)*. 2009.
53. Darabi, Z. and M. Ferdowsi. *Plug-in hybrid electric vehicles: Charging load profile extraction based on transportation dat*. in *Proc. IEEE Power and Energy Society General Meeting*. 2011. Detroit, MI, USA.
54. Darabi, Z. and M. Ferdowsi, *Aggregated impact of plug-in hybrid electric vehicles on electricity demand profile*, in *IEEE Trans. Sustain. Energy*. October 2011. p. 501-508.
55. Lopes, J.P., et al. *Smart charging strategies ffor elctric vehicles: Enhancing grid performance and maximizing the use of variable energy resources*. in *Proc. EVS24 Int. Battery, Hybrid and Fuel Cell Electric Vehicle Symp*. 2009. Norveska.
56. Papadopoulos, P., et al. *Predicting electric vehicle impacts on residential distribution networks with distributed generation*. in *Proc. IEEE Vehicle Power and Propulsion Conf. (VPPC)*. 2010. Lille, France.
57. Kelly, L., A.Rowe and P. Wild, *Analyzing the impacts of plug-in electric vehicles on distribution networks in British Columbia*, in *IEEE Electrical Power and Energy Conference (EPEC)*. 2009. p. 1-6.
58. *1995 national personal transportation survey databook*. October 2001, Oak Ridge National Laboratory.
59. Bhat, C.R. and S.K. Singh, *A comprehensive daily activity-travel generation model system for workers.* Transportation Research Part A: Policy and Practice, 2000. **34**(1): p. 1-22.
60. Clement-Nyns, K., E. Haesen, and J. Driesen, *The impact of charging plug-in hybrid electric vehicles on residential distribution grid.* IEEE Transactions on Power Systems, February 2010. **25**(1): p. 371-380.
61. Clement, K., E. Haesen, and J. Driesen, *Coordinated charging of multiple plug-in hybrid electric vehicles in residential distribution grid*, in *Proc.IEEE/PES Power Systems Conf. Exposition (PSCE)*. 2009: Seattle, WA. p. 1-7.
62. Richardson, D.B., *Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration.* Renewable and Sustainable Energy Reviews, 2013. **19**: p. 247-254.
63. Ralston, M. and N. Nigro, *PLUG-IN ELECTRIC VEHICLES: LITERATURE REVIEW*. July 2011, Center for Climate and Energy Solutions.
64. Parks, K., P. Denholm, and T. Markel, *Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory* May 2007, National Renewable Energy Laboratory.
65. Weiller, C., *Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States.* Energy Policy, 2011. **39**(6): p. 3766-3778.

66. Mallette, M. and G. Venkataramanan, *The role of plug-in hybrid electric vehicles in demand response and beyond*, in *IEEE PES Transmission and Distribution Conference and Exposition*. April 2010: New Orleans, LA, USA. p. 1-7.
67. *Plug-in Electric Vehicle and Infrastructure Analysis*. 2015, Idaho National Laboratory (INL).
68. Chang, D., et al., *Financial Viability Of Non-Residential Electric Vehicle Charging Stations*. 2012, UCLA Anderson School of Management.
69. *Plug-In Electric Vehicle Handbook for Public Charging Station Hosts*. 2012, National Renewable Energy Laboratory (NREL).
70. Arnold, D., M. Sankur, and D. Auslander, *Optimal Control of Office Plug-Loads for Commercial Building Demand Response*, in *6th Annual Dynamic Systems and Control Conference*. October 2013: Palo Alto, CA.
71. Benecchi, et al., *Electric Vehicles in America: The question is no longer "whether" they will come, but "how fast" and "where first*. 2010, Benecchi, Antonio, Matt Mattila, Nauman Syed, and Shamsuddin.
72. *Report On Electric Vehicle Charging*. December 2012, Florida Public Service Commission.
73. Di, W., D.C. Aliprantis, and K. Gkritza, *Electric Energy and Power Consumption by Light-Duty Plug-In Electric Vehicles.* Power Systems, IEEE Transactions on, 2011. **26**(2): p. 738-746.
74. Schneider, K., et al. *Impact assessment of plug-in hybrid vehicles on pacific northwest distribution systems*. in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*. 2008.
75. Loeiyud, K., N. Charbkaew, and T. Bunyagul. *Distribution transformer load management with adaptive EVs charging*. in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2012 9th International Conference on*. 2012.
76. Mets, K., et al. *Optimizing smart energy control strategies for plug-in hybrid electric vehicle charging*. in *Network Operations and Management Symposium Workshops (NOMS Wksps), 2010 IEEE/IFIP*. 2010.
77. Pillai, J.R. and B. Bak-Jensen. *Impacts of electric vehicle loads on power distribution systems*. in *Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE*. 2010.
78. Lopes, J.A.P., F.J. Soares, and P.M.R. Almeida, *Integration of Electric Vehicles in the Electric Power System.* Proceedings of the IEEE, 2011. **99**(1): p. 168-183.
79. Masoum, A.S., et al., *Smart load management of plug-in electric vehicles in distribution and residential networks with charging stations for peak shaving and loss minimisation considering voltage regulation.* IET Generation, Transmission & Distribution, 2011. **5**(8): p. 877-888.
80. Sortomme, E., et al., *Coordinated Charging of Plug-In Hybrid Electric Vehicles to Minimize Distribution System Losses.* IEEE Transactions on Smart Grid, 2011. **2**(1): p. 198-205.
81. Richardson, P., D. Flynn, and A. Keane, *Optimal Charging of Electric Vehicles in Low-Voltage Distribution Systems.* IEEE Transactions on Power Systems, 2012. **27**(1): p. 268-279.
82. Momber, I., T.Gomez, and M. Rivier, *Electric Vehicle Integration into Modern Power Networks*, in *Springer*. 2013. p. 251-271.
83. De Marco, M., et al., *Technical impacts of electric vehicles charging on an Italian distribution network*. 2014, CIRED Workshop.
84. Papadopoulos, P., S. Skarvelis-Kazakos, I. Grau, L. M. Cipcigan and N. Jenkins, *Electric vehicles' impact on British distribution networks.* IET Electrical Systems in Transportation, 2012. **2**(3): p. 91-102.
85. Duvall, M. and E. Knipping, *Environmental assessment of plug-in hybrid electric vehicles, Volume 1: National wide greenhouse gas emissions*. July 2007, EPRI: Palo Alto, CA.
86. Kintner-Meyer, M., Kevin,S., and Y. Zhu, *Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids; Part 1: Technical Analysis*, in *Electric Utilities Environmental Conference*. 2007.
87. Hadley, S.W. and A.A. Tsvetkova, *Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation.* The Electricity Journal, 2009. **22**(10): p. 56-68.

88. Falahati, B., et al. *Generation capacity extension in the power system with large-scale PHEV integration*. in *Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES*. 2012.
89. Roe, C., et al. *Power System Level Impacts of PHEVs*. in *System Sciences, 2009. HICSS '09. 42nd Hawaii International Conference on*. 2009.
90. Pieltain, F., et al., *Assessment of the Impact of Plug-in Electric Vehicles on Distribution Networks.* Power Systems, IEEE Transactions on, 2011. **26**(1): p. 206-213.
91. Maitra, A., et al. *Integrating plug-in- electric vehicles with the distribution system*. in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*. 2009.
92. Wood, T., et al., *eQUEST Training Module 1 Basic Energy Modeling and Comparative Runs*. 2011, Integrated Design Lab, Bozeman.
93. Gomez, J.C. and M.M. Morcos, *Impact of EV battery chargers on the power quality of distribution systems.* Power Delivery, IEEE Transactions on, 2003. **18**(3): p. 975-981.
94. Clement, K., E. Haesen, and J. Driesen. *Coordinated charging of multiple plug-in hybrid electric vehicles in residential distribution grids*. in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*. 2009.
95. Lopes, J.A.P., et al. *Quantification of technical impacts and environmental benefits of electric vehicles integration on electricity grids*. in *Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium on*. 2009.
96. Lopes, J.A.P., F.J. Soares, and P.M.R. Almeida. *Identifying management procedures to deal with connection of Electric Vehicles in the grid*. in *PowerTech, 2009 IEEE Bucharest*. 2009.
97. Putrus, G.A., et al. *Impact of electric vehicles on power distribution networks*. in *2009 IEEE Vehicle Power and Propulsion Conference*. 2009.
98. Papadopoulos, P., et al. *Distribution networks with Electric Vehicles*. in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*. 2009.
99. Rahman, S. and G.B. Shrestha, *An investigation into the impact of electric vehicle load on the electric utility distribution system.* IEEE Transactions on Power Delivery, April 1993. **8**(2): p. 591-597.
100. Shengnan, S., M. Pipattanasomporn, and S. Rahman, *Grid Integration of Electric Vehicles and Demand Response With Customer Choice.* Smart Grid, IEEE Transactions on, 2012. **3**(1): p. 543-550.
101. Qiuming, G., et al., *Study of PEV Charging on Residential Distribution Transformer Life.* Smart Grid, IEEE Transactions on, 2012. **3**(1): p. 404-412.
102. Rutherford, M.J. and V. Yousefzadeh. *The impact of Electric Vehicle battery charging on distribution transformers*. in *Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE*. 2011.
103. Sexauer, J.M., K.D. McBee, and K.A. Bloch. *Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers*. in *Electrical Power and Energy Conference (EPEC), 2011 IEEE*. 2011.
104. Michael Kuss, T.M., and William Kramer *Application of Distribution Transformer Thermal Life Models to Electrified Vehicle Charging Loads Using Monte-Carlo Method*, in *25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*. November 5 - 9, 2010: Shenzhen, China.
105. Babaei, S., et al. *Effects of Plug-in Electric Vehicles on distribution systems: A real case of Gothenburg*. in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES*. 2010.
106. Kejun, Q., et al., *Modeling of Load Demand Due to EV Battery Charging in Distribution Systems.* IEEE Transactions on Power Systems, 2011. **26**(2): p. 802-810.
107. *Assessment of Demand Response and Advanced Metering*. December 2012, Federal Energy Regulatory Commission (FERC).

108. Venkatesan, N., *Modeling and Integration of Demand Response and Demand Side Resources for Smart Grid Application in Distribution Systems* in *Electrical Engineering*. West Virginia University
109. *Statement of Principles for Demand Response*. 2007, Organization of MISO States.
110. Shao, S., M. Pipattanasomporn, and S. Rahman, *Grid Integration of Electric Vehicles and Demand Response With Customer Choice.* IEEE Transactions on Smart Grid, 2012. **3**(1): p. 543-550.
111. Shao, S., M. Pipattanasomporn, and S. Rahman, *Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles.* IEEE Transactions on Smart Grid, 2011. **2**(4): p. 624-631.
112. Motegi, N., et al., *Introduction to Commercial Building Control Strategies and Techniques for Demand Response*. May 2007, LBNL 59975.
113. Watson, D., Sila, K., N. Motegi, and M. Piette, *Strategies for demand response in commercial buildings.* Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, August 2006.
114. Piette, M.A., S. Kiliccote, and J.H. Dudley, *Field Demonstration of Automated Demand Response for Both Winter and Summer Events in Large Buildings in the Pacific Northwest*. December 2012, Lawrence Berkeley National Laboratory (LBNL).
115. Derrible, S. and M. Reeder, *The cost of over-cooling commercial buildings in the United States.* Energy and Buildings, 2015. **108**: p. 304–306.
116. Piette, M.A., et al., *Development and Evaluation of Fully Automated Demand Response in Large Facilities*. January 2005, Lawrence Berkeley National Laboratory (LBNL).
117. Piette, M.A., D.S. Watson, N. Motegi, and N. Bourassa, *Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities*. September 2005, Lawrence Berkeley Laboratory.
118. Piette, M.A., et al., *Automated Critical Peak Pricing Field Tests: Program Description and Results*. April 2006, Lawrence Berkeley National Laboratory (LBNL).
119. Tzivanidis, C., K.A. Antonopoulos, and F. Gioti, *Numerical simulation of cooling energy consumption in connection with thermostat operation mode and comfort requirements for the Athens buildings.* Applied Energy, 2011. **88**: p. 2871–2884.
120. Yanga, L., H. Yana, and J.C. Lam, *Thermal comfort and building energy consumption implications – A review.* Applied Energy, 2014. **115**: p. 164–173.
121. Plat,G., J.K.Ward, and J. Wall, *Optimal Supervisory HVAC Control: Experiences in Australia.* HVAC&R Research, 2011. **17**(3): p. 297-308.
122. Al-Mulla, A. and A. ElSherbini, *Demand management through centralized control system using power line communication for existing buildings.* Energy Conversion and Management, 2014. **79**: p. 477-486.
123. Sehar, F., M. Pipattanasomporn, and S. Rahman, *A peak-load reduction computing tool sensitive to commercial building environmental preferences.* Applied Energy, 2016. **161**: p. 279-289.
124. Sezgen, O., and Jonathan, G.K., *Interactions between Lighting and Space Conditioning Energy Use in U.S. Commercial Buildings* . 1998, Lawrence Berkeley National Laboratory (LBNL).
125. Alhafi, Z., *Calibrated energysimulations of potential energy savings in actual retail buildings*, in *Department of Architectural Engineering*. 2014, The Pennsylvania State University.
126. Haves, P., B. Coffey, and S. Williams, *Benchmarking and Equipment and Controls Assessment for a "Big Box" Retail Chain*, in *ACEEE Summer Study on Energy Efficiency in Buildings*. 2008.
127. *Field Implementation for Demand Response Strategies for Big Box Retail Stores* 2008, Southern California Edison
128. Dubois, M.-C. and Å. Blomsterberg, *Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review.* Energy and Buildings, 2011. **43**(10): p. 2572-2582.

129. Galasiu, A.D., M.R Atif, and R.A. MacDonald, *Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls.* Solar Energy, 2004. **76**(5): p. 523-544.
130. Newsham, G.R., et al., *Individual control of electric lighting in a daylit space.* Lighting Research and Technology, 2008. **40**(1): p. 25-41.
131. Shen, E., J. Hu, and M. Patel, *Energy and visual comfort analysis of lighting and daylight control strategies.* Building and Environment, 2014. **78**: p. 155–170.
132. Park, S., et al., *A Framework for Baseline Load Estimation in Demand Response: Data Mining Approach*, in *IEEE International Conference on Smart Grid Communications*. 2014.
133. Al-Mulla, A., et al., *Enhancement of building operations: A successful approach towards national electrical demand management.* Energy Conversion and Management, 2013. **76**: p. 781-793.
134. Galasiu, A. and J.A. Veitch, *Occupant preferences and satisfaction with the luminous environment and control systems in daylight offices: a literature review.* Energy and Buildings, 2007. **38**(7): p. 728–742.
135. Boyce,P.R., et al., *Occupant use of switching and dimming controls in offices.* Lighting Research and Technology, 2006. **38**(4): p. 358–378.
136. Moore, T., D.J.Carter, and A.I. Slater, *User attitude toward occupant controlled office lighting.* Lighting Research and Technology, 2002. **34**(3): p. 207–219.
137. Veitch,J.A., and G.R. Newsham, *Preferred luminous conditions in open-plan offices: research and practice recommendations.* Lighting Research and Technology, 2002. **32**: p. 199–212.
138. Moore, T., D.J. Carter, and A.I. Slater, *Long-term patterns of use of occupant controlled office lighting.* Lighting Research and Technology, 2003. **35**(1): p. 43-57.
139. Love, J.A., *Manual switching patterns in private offices.* Lighting Research and Technology, 1998. **30**(1): p. 45-50.
140. Ashley, R. and J.S. Reynolds, *Overall and zonal energy end use in an energy conscious office building.* Solar Energy, 1994. **52**(1): p. 75-83.
141. Gentile, N., T. Laike, and M.-C. Dubois, *Lighting control systems in peripheral offices rooms at high latitude: measurements of electricity savings and users preferences.* Energy Procedia, 2014. **57**: p. 1987-1996.
142. Begemann, S.H.A., G.J.ven den Beld, and A.D. Tenner, *Daylight, artificial light and people in an office environment, overview of visual and biological responses.* International Journal of Industrial Ergonomics, 1997: p. 231-239.
143. Rubinstein, F., and Sila, K., *Demand Responsive Lighting: A Scoping Study*. January 2007, Lawrence Berkeley Laboratory (LBNL).
144. *Project 3.2 Energy Efficient Load-Shedding Lighting Technology Final Report*. October 2005, California Energy Commission Public Interest Energy Research Program.
145. Husen, S.A., et al., *Lighting Systems Control for Demand Response*, in *Proceedings of IEEE Conference on Innovative Smart Grid Technologies*. January 2012: Washington, DC.
146. Raziei, S.A. and H. Mohsenian-Rad, *Optimal Demand Response Capacity of Automatic Lighting Control*, in *Innovative Smart Grid Technologies (ISGT), IEEE PES* February 2013. p. 1-6.
147. Kaneda, D., Brad J., and P. Rumsey, *Plug Load Reduction: The Next Big Hurdle for Net Zero Energy Building Design.* ACEEE Summer Study on Energy Efficient Buildings, 2010. **9**: p. 120-130.
148. Roberson, J.A., et al., *After Hours Power Status of Office Equipment and Energy Use of Miscellaneous Plug Load Equipment*. 2004.
149. Moorefield, L., B. Frazer and P. Bendt, *Office Plug Load Field Monitoring Report*. 2011, California Energy Commission, PIER Energy-Related Environmental Research Program.
150. Lobato, C., et al., *Reducing plug and process loads for a large scale, low energy office building: NREL's research support facility*, in *ASHRAE Winter Conference* February 2011: Las Vegas, Nevada.

151. Poll, S., and C.Teunert, *Pilot Study of a Plug Load Management System: Preparing for Sustainability Base*, in *IEEE Green Technologies Conference*. April 2012, IEEE: Tulsa, OK. p. 1-6.
152. Kawamoto, K., et al., *Energy Saving Potential of Office Equipment Power Management.* Energy and Buildings, 2004. **36**(9): p. 915-923.
153. Nordman, B., et al. *PC and monitor night status: Power management enabling and manual turn-off*. in *Proceedings ACEEE Summer Study on Energy Efficiency in Buildings*. 2000. Pacific Grove, CA (US).
154. Acker, B., C. Duarte, and K.V.D. Wymelenberg, *Office Space Plug Load Profiles and Energy Saving Interventions.* ACEEE Summer Study on Energy Efficiency in Buildings, 2012.
155. Metzger, I., et al., *Plug-Load Control and Behavioral Change Research in GSA Office Buildings*. June 2012, National Renewable Energy Laboratory (NREL).
156. Arnold, D., Shankar, M., and D.M. Auslander, *An architecture for enabling distributed plug load control for commercial building demand response.* Innovative Smart Grid Technologies (ISGT), IEEE PES 2013: p. 1-6.
157. Weng, T., et al. *Managing Plug-Loads for Demand Response within Buildings*. in *Proceedings of the ACM Workshop on Embedded Sensing Systems For Energy-Efficiency*. October 2011. Seattle.
158. *Location, location, location Domestic small-scale wind field trial report*. 2009, Energy Saving Trust.
159. Gagliano, A., Francesco, N., Francesco P. and Alfonso C., *Assessment of micro-wind turbines performance in the urban environments: an aided methodology through geographical information systems.* International Journal of Energy and Environmental Engineering. **4**(43).
160. Pandey, A.K., et al., *Recent advances in solar photovoltaic systems for emerging trends and advanced applications.* Renewable and Sustainable Energy Reviews, 2016. **53**: p. 859-884.
161. Singh, S.C., *Solar Photovoltaics : Fundamentals, Technologies and Applications*. Second ed. 2011.
162. Kalogirou, S.A., *Solar Energy Engineering (Second Edition)*. 2014. p. 481-540.
163. *SunShot Vision Study*. 2012, SunShot U.S. Department of Energy.
164. Kintner-Meyer, M., et al., *The Role of Energy Storage in Commercial Building* September 2010, Pacific Northwest National Laboratory.
165. Sehar, F., S. Rahman, and M. Pipattanasomporn, *Impacts of ice storage on electrical energy consumptions in office buildings.* Energy and Buildings, May 2012. **51**: p. 255-262.
166. Dincer, I. and M.A. Rosen, *Thermal Energy Storage Systems and Applications*. 2011, John Wiley & Sons, Ltd
167. *Source Energy and Environmental Impacts of Thermal Energy Storage*. 1996, Calfornia Energy Commission.
168. Arteconi, A., N.J. Hewitt, and F. Polonara, *State of the art of thermal storage for demand-side management.* Applied Energy, 2012. **93**: p. 371-389.
169. Hasnain, S.M. and N.M. Alabbadi, *Need for thermal-storage air-conditioning in Saudi Arabia.* Applied Energy, 2000. **65**(1–4): p. 153-164.
170. Limmeechokchai, B. and S. Chungpaibulpatana, *Application of cool storage air-conditioning in the commercial sector: an integrated resource planning approach for power capacity expansion planning and emission reduction.* Applied Energy, 2001. **68**(3): p. 289-300.
171. Zhanbo, X., et al., *Performance Analysis and Comparison on Energy Storage Devices for Smart Building Energy Management.* Smart Grid, IEEE Transactions on, 2012. **3**(4): p. 2136-2147.
172. Jubran, S.S., *Modeling and Optimization of a Hybrid Solar PV-Powered Air Conditioning System with Ice Storage*. 2011, Arizona State University.
173. Feitau Kung, M.D., and E. Bonnema, *Evaluation Framework and Analyses for Thermal Energy Storage Integrated with Packaged Air Conditioning* 2013, National Renewable Energy Laboratory.
174. Nolan, S. and M. O'Malley, *Challenges and barriers to demand response deployment and evaluation.* Applied Energy, 2015. **152**: p. 1-10.

175. Wang, X., A. Palazoglu, and N.H. El-Farra, *Operational optimization and demand response of hybrid renewable energy systems.* Applied Energy, 2015. **143**: p. 324-335.
176. Moura, P.S. and A.T. de Almeida, *Multi-objective optimization of a mixed renewable system with demand-side management.* Renewable and Sustainable Energy Reviews, 2010. **14**(5): p. 1461-1468.
177. Puchegger, M., *Electric load behavior and DSM potential of office buildings.* Energy and Buildings, 2015. **100**: p. 43-49.
178. Wang, G., et al., *Study on the promotion impact of demand response on distributed PV penetration by using non-cooperative game theoretical analysis.* Applied Energy.
179. Denholm, P., M. Kuss, and R.M. Margolis, *Co-benefits of large scale plug-in hybrid electric vehicle and solar PV deployment.* Journal of Power Sources, 2013. **236**: p. 350-356.
180. Bhatti, A.R., et al., *Electric vehicles charging using photovoltaic: Status and technological review.* Renewable and Sustainable Energy Reviews, 2016. **54**: p. 34-47.
181. Karan, E., S. Asadi, and L. Ntaimo, *A stochastic optimization approach to reduce greenhouse gas emissions from buildings and transportation.* Energy, 2016. **106**: p. 367-377.
182. Birnie, D.P., *Solar-to-vehicle (S2V) systems for powering commuters of the future.* Journal of Power Sources, 2009. **186**(2): p. 539-542.
183. Gharbaoui, M., et al. *Effective management of a public charging infrastructure through a smart management system for electric vehicles*. in *Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International*. 2012.
184. Arghandeh, R., A. Onen, and R.P. Broadwater, *Distributed Energy Storage System Control for Optimal Adoption of Electric Vehicles*, in *IEEE Power and Energy Society General Meeting*. July 2012: San Diego, CA.
185. Jung, J., et al., *Evaluation of DER Adoption in the Presence of New Load Growth and Energy Storage Technologies*, in *IEEE Power and Energy Society General Meeting*. July 2011: San Diego, CA.
186. Junga, J., et al., *Monte Carlo analysis of Plug-in Hybrid Vehicles and Distributed Energy Resource growth with residential energy storage in Michigan.* Applied Energy, August 2013. **108**: p. 218-235.
187. Li, X., L.A.C. Lopes, and S.S. Williamson, *On the Suitability of Plug-In Hybrid Electric Vehicle (PHEV) Charging Infrastructures Based on Wind and Solar Energy*, in *IEEE Power & Energy Society General Meeting*. July 2009: Calgary, AB. p. 1-8.
188. VirginiaTech. *Introducing BEMOSS™ An open source platform for building energy management*. 2016; Available from: http://www.bemoss.org/.
189. Sehar, F., M. Pipattanasomporn, and S. Rahman, *A peak-load reduction computing tool sensitive to commercial building environmental preferences.* Applied Energy, 2016. **161**: p. 279-289.
190. Toftum,J., R.V. Anderson, and K.L. Jensen, *Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions.* Building and Environment, 2009. **44**(10): p. 2009-2016.
191. Yang, K. H. and C.H. Su, *An Approach to Building Energy Savings Using the PMV Index* Building and Environment, 1997. **32**(1): p. 25-30.
192. Kumar, A., I.P. Singh, S.K. Sud, *An Approach Towards Development of PMV Based Thermal Comfort Smart Sensor.* International Journal on Smart Sensing and Intelligent Systems, December 2010. **3**(4).
193. Lee, J. and R.K. Strand, *An analysis of the effect of the building envelope on thermal comfort using the EnergyPlus program*. in *Proceedings of the ACSA technology conference*. July 2001. Austin, Texas.
194. Carlucci, S., et al., *A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design.* Renewable and Sustainable Energy Reviews, 2015. **47**: p. 1016-1033.
195. DiLaura, D.L., et al., *The Lighting Handbook Tenth edition Reference and Application*. 2011.

196. Crawleya, D.B., et al., *EnergyPlus: creating a new-generation building energy simulation program.* Energy and Buildings. **33**(4): p. 443-457.
197. Deru, M.F., et al., *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. February 2011, National Renewable Energy Laboratory (NREL).
198. *Illuminating Engineering Society of North America, IESNA Lighting Handbook*. (9th edition) ed. 2000, New York.
199. Ramos, G. and E. Ghisi, *Analysis of daylight calculated using the EnergyPlus programme.* Renewable and Sustainable Energy Reviews, 2010. **14**(7): p. 1948-1958.
200. Perez, R., et al., *Modeling daylight availability and irradiance components from direct and global irradiance.* Solar Energy, 1990. **44**(5): p. 271-289.
201. LightSearch. *Light Guide: Useful Formulas*. 2014; Available from: http://www.lightsearch.com/resources/lightguides/formulas.html.
202. RapidTables. *How to convert watts to lux*. 2015 [cited 2015; Available from: http://www.rapidtables.com/calc/light/how-watt-to-lux.htm.
203. DiLaura, D.L., et al., *Light Sources: Application Considerations*, in *IESNA The Lighting Handbook: Reference and Application*. 2011, Illuminating Engineering Society of North America.
204. Lobato, C., et al., *Selecting a Control Strategy for Plug and Process Loads* 2012, National Renewable Energy Laboratory (NREL).
205. *Retail Lighting Guide*. Holophane.
206. Crawley, D.B., et al., *EnergyPlus: New Capabilities in a Whole-Building Energy Simulation Program*, in *Seventh International IBPSA Conference*. August 2001: Rio de Janeiro, Brazil.
207. Rallapalli, H.S., *A Comparison of EnergyPlus and eQUEST Whole Building Energy Simulation Results for a Medium Sized Office Building*. December 2010, Arizona State University.
208. Melki, S. and M. Hayek, *Building simulation tools and their role in improving existing building designs*, in *International Conference on Advances in Computational Tools for Engineering Applications, ACTEA* July 2009. p. 503-507.
209. *Application Guide for EMS Energy Management System User Guide*. November 2013, U.S. Department of Energy.
210. Ellis, P.G., P.A. Torcellini, and D.B. Crawley, *Simulation of Energy Management Systems in EnergyPlus*, in *Building Simulation*. September 2007: Beijing, China.
211. Dilek, M., et al., *A Robust Multiphase Power Flow for General Distribution Networks.* IEEE Transactions on Power Systems, 2010. **25**(2): p. 760-768.
212. Stewart, E.M., S. Kiliccote, and C. McParland, *Software-based challenges of developing the future distribution grid*. 2014, Lawrence Berkeley National laboratory (LBNL).
213. Thornton, B., et al., *Technical Support Document: 50% Energy Savings Design Technology Packages for Medium Office Buildings*. 2009, Pacific Northwest National Laboratory (PNNL).
214. *Advanced Energy Design Guides*. [cited 2016; Available from: http://energy.gov/eere/buildings/advanced-energy-design-guides.
215. Thornton, B.A., et al., *Achieving the 30% Goal:Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010*. 2011, Pacific Northwest National Laboratory (PNNL).
216. *Getting Started with EnergyPlus Basic Concepts Manual - Essential Information You Need about Running EnergyPlus*. October 2013.
217. Wilkins, C. and M.H. Hosni, *Heat Gain From Office Equipment.* ASHRAE 2000: p. 33-43.
218. Hosni, M.H., B.W. Jones, and H. Xu, *Measurement of Heat Gain and Radiant/Convective Split from Equipment in Buildings*. 1999, ASHRAE.
219. ASHRAE, *Nonresidential Cooling and Heating Load Calculations*, in *ASHRAE Handbook Fundamentals*. 2013.
220. Ritter, J. and J. Hugghins, *Vending Machine Energy Consumption and VendingMiser Evaluation*. 2000, Energy Systems Laboratory Texas A&M University System.

221. Roth, K.W., F. Goldstein, and J. Kleinman, *Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings Volume I: Energy Consumption Baseline*. 2002, Arthur D. Little, Inc.
222. Hosni, M.H., B.W. Jones, H. Xu, *Measurement of heat gain and radiant/convective split from equipment in buildings Final Report for ASHRAE Research Project 1055-RP*. 1999, Institute for Environmental Research, Kansas State University.
223. Kawamoto, K., et al., *Electricity Used by Office Equipment and Network Equipment in the U.S. Detailed Report and Appendices*. 2001, Lawrence Berkeley National Laboratory (LBNL): Berkeley, CA.
224. Metzger, I., D. Cutler, and M. Sheppy, *Plug-Load Control and Behavioral Change Research in GSA Office Buildings*. 2012, National Renewable Energy Laboratory (NREL).
225. Kwong, Q.J., et al., *A Study on Energy Efficiency Improvement Opportunities for Plug Loads in Buildings in the Equatorial Region.* Energy Procedia, 2014. **56**(0): p. 621-633.
226. Webber, C.A., J.A.Roberson, M.C. McWhinney, R.E. Brown, M.J. Pinckard, and J.F. Busch, *After-hours power status of office equipment in the USA.* Energy, 2006. **31**(14): p. 2823–2838.
227. Marla S., et al., *Space Heaters, Computers, Cell Phone Chargers: How Plugged In Are Commercial Buildings?* . 2007, Lawrence Berkeley National Laboratory (LBNL).
228. Mungwititkul, W., and B.Mohanty, *Energy efficiency of office equipment in commercial buildings: The case of Thailand.* Energy, 1997. **22**(7): p. 673-680.
229. Schaltegger, M., *Bestimmung des Energieverbrauchs von Unterhaltungselektronikgeraeten, Buerogeraeten und Automaten in der Schweitz*. 1999, Research Programme, Communication and Information Systems, Swiss Federal Office of Energy, Berne, Switzerland.
230. *Energy Efficient Office Technologies: the 1 Watt / 1 Volt-Ampere Challenge*. 1998, MACEBUR work group.
231. *EnergyPlus Web-Based Documentation*. 2015 [cited 2015; Available from: http://bigladdersoftware.com/epx/docs/8-0/engineering-reference/index.html.
232. Denholm, P. and R. Margolis, *Supply curves for rooftop solar PV-generated electricity for the United States*. 2008, National renewable Energy Laboratory (NREL).
233. Paidipati, J., et al., *Rooftop photovoltaics market penetration scenarios*. 2008, National Renewable Energy Laboratory (NREL).
234. Melius J., R.Margolis, and S. Ong, *Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques*. 2013, National Renewable Energy Laboratory (NREL).
235. Chaudhari, M., L. Frantzis, and T.E. Hoff, *PV grid connected market potential under a cost breakthrough scenario*. 2004, Navigant Consulting.
236. Olis, D. and G. Mosey, *Integration of rooftop photovoltaic systems in St. Paul Ford site's redevelopment plans*. 2015, National Renewable Energy Laboratory (NREL).
237. *Solar Calculator*. 2016; Available from: http://www.rbisolar.com/solar-calculator/.
238. Camps, X., et al., *Contribution to the PV-to-inverter sizing ratio determination using a custom flexible experimental setup.* Applied Energy, 2015. **149**: p. 35-45.
239. *DC Loading of PV Powered Inverters*. 2012, Advanced Energy Industries Inc.
240. *Go Solar California*. 2016 [cited 2016; Available from: http://www.gosolarcalifornia.org/equipment/.
241. *PVI 60KW, PVI 77KW, PVI 90KW Installlation and Operation Manual Commercial, Grid-Tied Photovoltaic Inverters*. 2006, Solectria Renewables LLC.
242. Sehar, F., M. Pipattanasomporn, and S. Rahman, *An energy management model to study energy and peak power savings from PV and storage in demand responsive buildings.* Applied Energy, 2016. **173**: p. 406-417.
243. Sehar, F., M. Pipattanasomporn, and S. Rahman, *Demand management to mitigate impacts of plug-in electric vehicle fast charge in buildings with renewables.* Energy.
244. *Thermal Storage*, in *2012 ASHRAE Handbook - HVAC Systems and Equipment*. 2012.

245. Sehar, F., *Impact of Ice Storage on Electrical Energy Consumption in Large and Medium-sized Office Buildings in Different Climate Zones* in *ECE*. 2011, Virginia Tech.
246. *Electric Vehicle Charging Stations Technical Installation Guide*. 2015, Hydro Quebec.
247. Pokrzywa, J., *SAE International standards work, including communication protocols and connectors, fast charge, batteries*. 2011, SAE International.
248. Robinson, A.P., et al., *Analysis of electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips.* Energy Policy, 2013. **61**: p. 337-348.