Optimal Operation of Climate Control Systems of Indoor Ice Rinks

by

Rupali Jain

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2012

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Ice rinks are large commercial buildings which facilitate various activities such as hockey, figure skating, curling, recreational skating, public arenas, auditoriums and coliseums. These have a complex energy system, in which an enormous sheet of ice is maintained at a low temperature while at the same time the spectator stands are heated to ensure comfortable conditions for the spectators. Since indoor ice rinks account for a significant share of the commercial sector and are in operation for more than 8 months a year, their contribution in the total demand cannot be ignored. Thus, there is significant scope for energy savings in indoor ice rinks through optimal operation of their climate control systems.

In this work, a mathematical model of indoor ice rinks for the implementation of Energy Hub Management System (EHMS) is developed. The model incorporates weather forecast, electricity price information and end-user preferences as inputs, and the objective is to shift the operation of climate control devices to the low electricity price periods, satisfying their operational constraints while having minimum impact on spectator comfort. The inside temperature and humidity dynamics of the spectator area are modeled to reduce total electrical energy costs while capturing the effect of climate control systems including radiant heating systems, ventilation systems and dehumidification systems. Two different pricing schemes, Real Time Pricing (RTP) and Time-of-Use (TOU), are used to assess the model, applied to a realistic arena example and the resulting energy costs savings are compared. The expected energy cost savings are evaluated for a 8 month period of operation of the rink incorporating the uncertainties in electricity price, weather conditions and spectator schedules through Monte Carlo simulations. The results demonstrate that significant savings in the order of 40% can be achieved. The proposed work can be implemented as a supervisory control in existing climate controllers of indoor ice rinks, and could play a significant role in the customer energy management systems in the context of Smart Grids.

Acknowledgements

I would like to express my sincere gratitude towards my supervisors Professor Kankar Bhattacharya and Professor Claudio A. Cañizares for their excellent support and encouragement, and exceptional guidance throughout the tenure of my master's studies. I have learned many valuable lessons from them and this work wouldn't have been possible without their supervision and able suggestions.

I would like to offer my warmest thanks and appreciation to my family, my loving parents and brother, for believing in me and boosting my confidence for all these years. Special thanks to my colleague Isha Sharma and my project team members Rajib Kundu and Felipe Ramos for their timely cooperation and support.

My sincere thanks to the Department of Electrical and Computer Engineering for their great services and the University of Waterloo for giving me an opportunity to shape up my career in the best possible manner. I would also like to thank all my lab colleagues for building a friendly and fun environment at work, and my friends for their care and affection.

I would like to thank Dr. Steve Wong, CanmetENERGY, for his insightful comments and suggestions, at various stages of the work. Finally, the funding provided by the NSERC Smart Microgrid Network to support my studies and research is kindly acknowledged.

Dedication

This work is dedicated to my parents and brother.

Table of Contents

List of Tables

List of Figures

Glossary of Terms

AMI	Advanced Metering Infrastructure
AMPL	A Modeling Language for Mathematical Programming
CFD	Computational Fluid Dynamics
DR	Demand Response
DSM	Demand Side Management
EHMS	Energy Hub Management System
FIT	Feed-In-Tariff
FRP	Flat Rate Pricing
GAMS	General Algebraic Modeling System
HOEP	Hourly Ontario Energy Price
HVAC	Heating, Ventilation and Air Conditioning
LDC	Local Distribution Company
LMP	Locational Marginal Pricing
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
NYISO	New York Independent System Operator
OPA	Ontario Power Authority
PID	Proportional-Integral-Derivative
PLC	Programmable Logic Controller
RTP	Real Time Pricing
TOU	Time-Of-Use

Chapter 1

Introduction

1.1 Motivation

1.1.1 Demand Response

The electricity demand in Canada has grown at an average annual rate of 1.2 percent since 1990. In 2010, the final electricity demand, excluding line losses and consumption by electricity generators, amounted to 497.5 billion kilowatt hours [1]. Figure 1.1 presents the sector-wise electricity demand distribution in Canada from 2003 to 2010. The Canadian industrial sector accounted for the largest share of the electrical energy demand, followed by the commercial and residential sectors together accounting for 58% of the energy consumption.

The potential of Demand Side Management (DSM) in Canada is explored in the Integrated Power System Plan by Ontario Power Authority (OPA) [2]. The energy demand savings aggregated for all the three sectors are calculated in [2] by projecting the energy demand to 2025. The energy cost reduction is evaluated by comparing the reference case with no demand response and the economic potential case with demand response through energy management actions. The analysis predicts total energy demand savings of up to 14% through demand response technologies, observing that among various fuels, electricity holds the greatest potential with savings of up to 24% in 2025, as shown in Figure 1.2. The pie chart in this figure presents the percentage share of all the three sectors and savings potential through energy reduction in 2025.

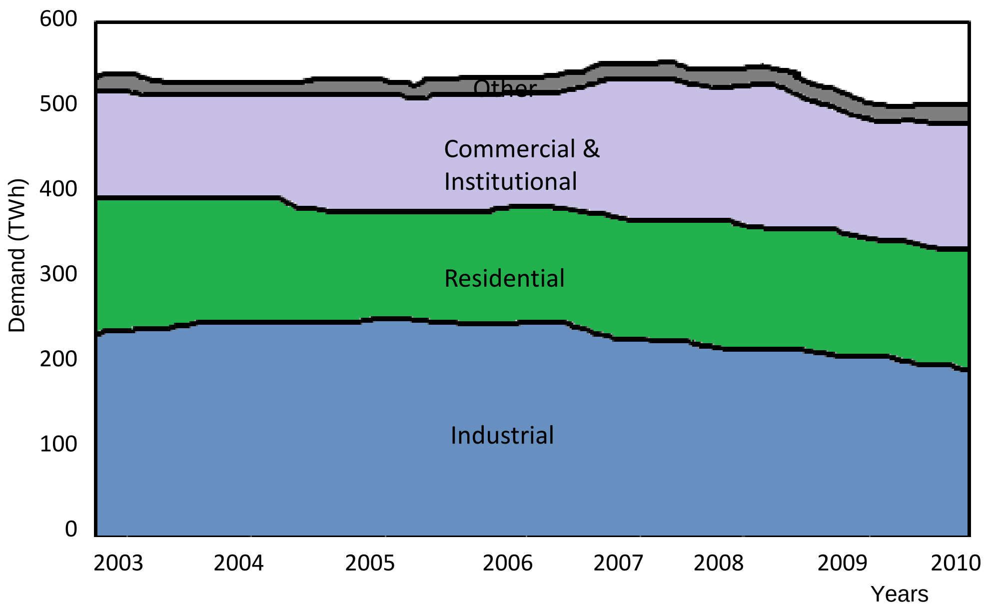

Figure 1.1: Sector-wise electricity demand in Canada [1].

Figure 1.3 presents the variation of peak demand in Ontario, Canada, over the past few years. The highest peak was recorded in 2006 which was considerably reduced in 2007 and 2008; however, since 2008 the peak demand is showing an increasing trend. Many factors contribute to the increasing electricity demand such as climatic conditions, economic growth and population growth. Utilities are looking at DSM and Demand Response (DR) programs that allow customers to make informed decisions regarding their energy consumption, which in return helps the energy providers to reduce the system peak demand [3]. DR technologies and strategies seek to induce customers to reduce electricity usage usually through incentives, hence enhancing the system operational security and adequacy, and in the long run avoiding capacity investments in peaking generation.

The New York Independent System Operator (NYISO) has identified four generic types of DR programs: Emergency Demand Response Program (EDRP), Day-Ahead Demand Response Program (DADRP), Installed Capacity (ICAP) and Demand-Side Ancillary Service Program (DSASP) [4]. EDRP involves demand reduction under emergency conditions specified by the NYISO; interval metering is adequate in this case, and when asked to curtail, the participant is paid \$500/MWh or the zonal real-time locational-based marginal price (LBMP). Under DADRP, demand reduction is measured compared to a pre-determined base line; if the participant fails to reduce demand from the baseline, he is

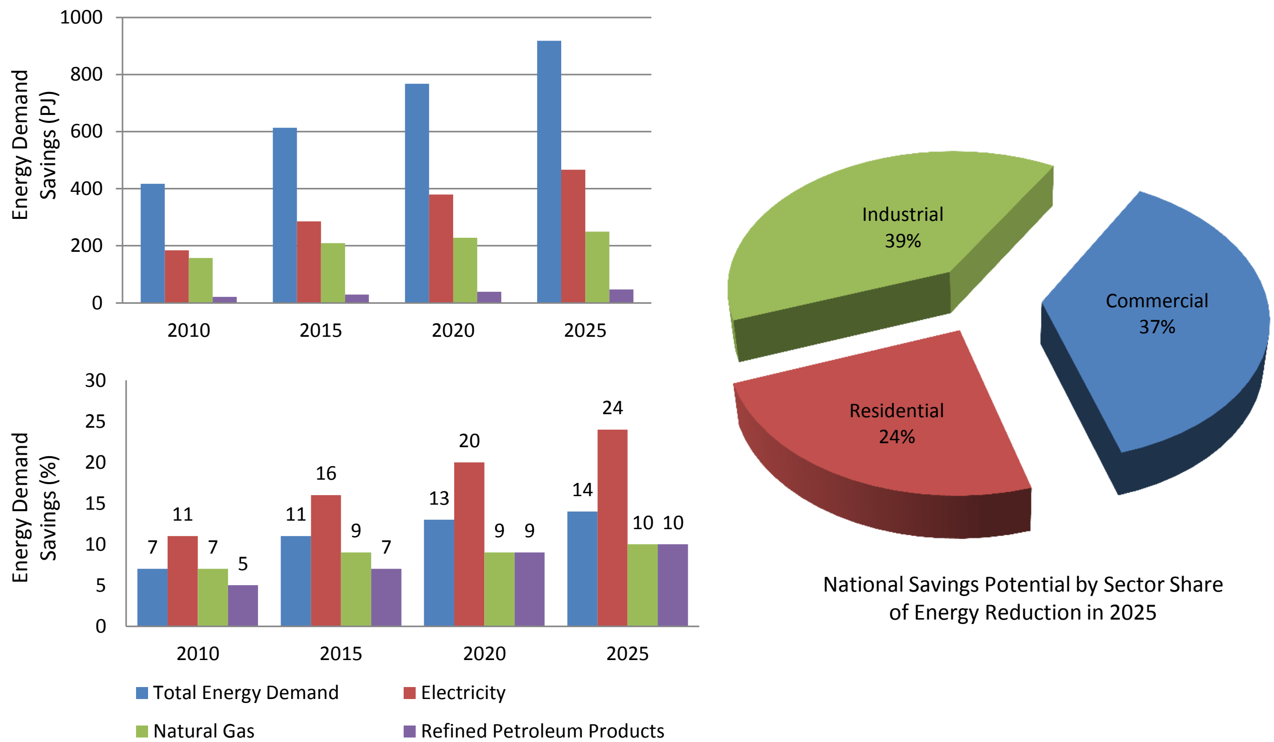

Figure 1.2: Canada's saving potential for aggregated energy demand reduction for all sectors by type of fuel and milestone year [2].

charged higher than the day ahead or real time price. Participants in the ICAP program are required to reduce power usage, and as part of their agreement are paid in advance to curtail their demand usage upon request; to register for this program, participants commit to a load reduction of a minimum of 100 kW with 100 kW increments, when provided with a 21-hour advanced notice. DSASP program provides retail customers that can meet telemetry and other qualification requirements with an opportunity to bid their load curtailment capability into the real-time market to provide operating reserves and regulation service.

In Ontario, Canada, different initiatives have been undertaken to promote DR programs [5]. The Demand Response Voluntary (DR1) program was initiated in order to provide compensation to customers voluntarily reducing their energy consumption. The Demand Response Contractual (DR3) program was then launched, in which a participant agrees to reduce its energy use during periods of peak demand; however, to be eligible for this program, the customer must be operating during a predefined schedule of about 1600

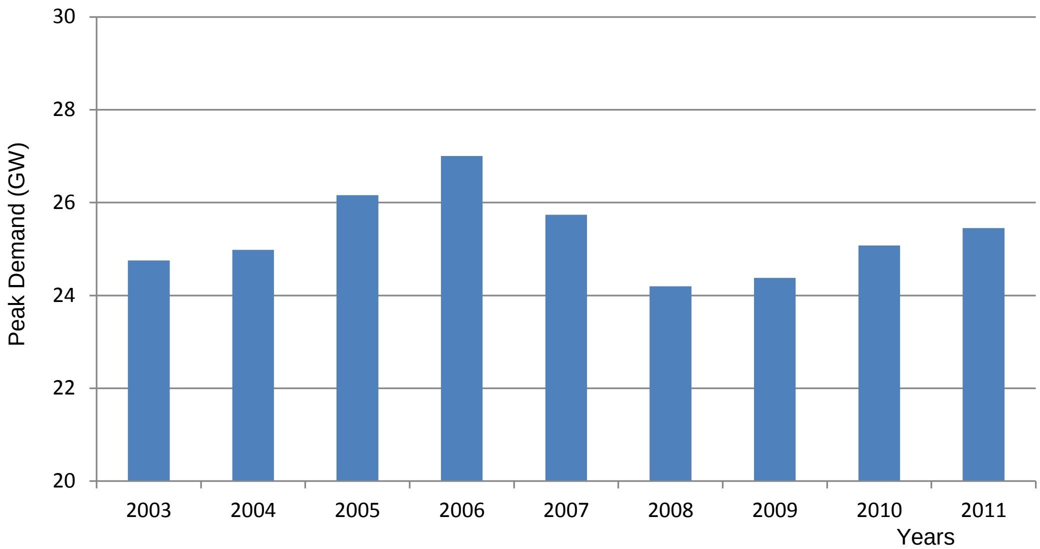

Figure 1.3: Peak demand recorded in Ontario Electricity Markets [2].

hours per year. The RetroFIT program was introduced to encourage installation of new control systems by providing substantial incentives to replace existing equipment. Another program known as Peaksaver was proposed to reduce customers' electricity demand by controlling central air conditioners or electric waters heater through installation of a direct load management device. Thus, utilities in different countries are using DSM and DR programs to encourage customer involvement in the supply of energy services.

1.1.2 Smart Grids and Energy Hub Management Systems

The power sector is in a transition phase with the introduction of smart grid technologies, which is rapidly influencing the way customers consume energy. A smart grid is an automated, widely distributed energy delivery network, characterized by a two-way flow of electricity and information, and capable of monitoring and responding to changes in everything from power plants to customer preferences to individual appliances [6].

With the advent of advanced communication and information technology systems in smart grids, Energy Hub Management Systems (EHMSs) are becoming more sophisticated and popular. The benefits of EHMS include effective management of energy usage, intelligent decision making to control major electrical loads, and real-time and automated DR to

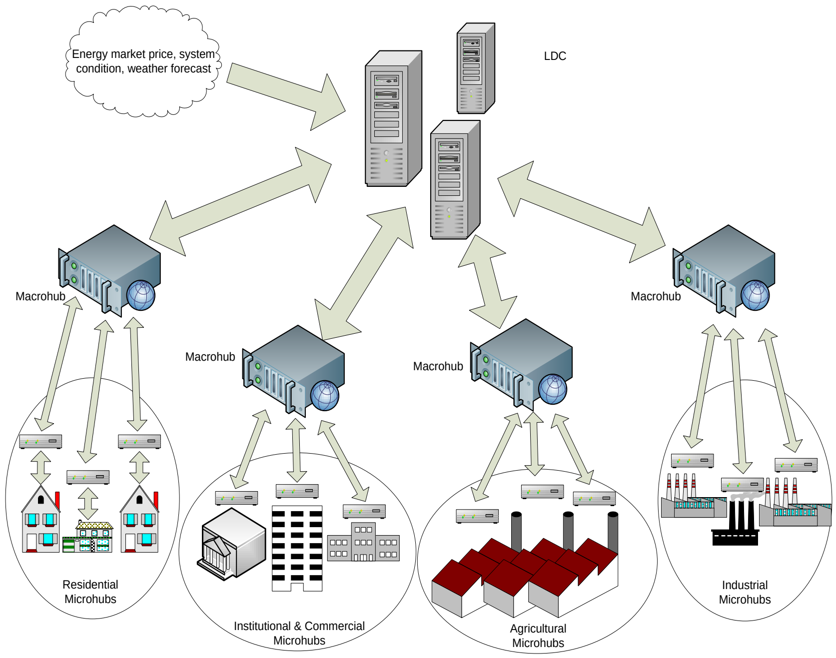

Figure 1.4: EHMS project architecture [7]. (Used with permission of the EHMS project.)

yield energy savings. Figure 1.4 shows a representation of the EHMS project architecture [7].

Advanced Metering Infrastructure (AMI) is an inevitable step towards grid automation and an integral part of EHMSs. AMI is an integration of multiple technologies such as smart metering, home area networks, integrated communications through visual interfaces, data management applications utility and asset management processes, providing a bi-directional link between the Local Distribution Companies (LDCs) and customers to efficiently manage and control their energy needs [8, 9, 10]. The new generation of meters, typically referred to as "smart meters", form an important component of AMI. Smart meters can read and securely communicate the information on the real-time energy consumption of consumers [11]. These developments are constantly improving EHMSs and are aiding in a more mature implementation of DR technologies.

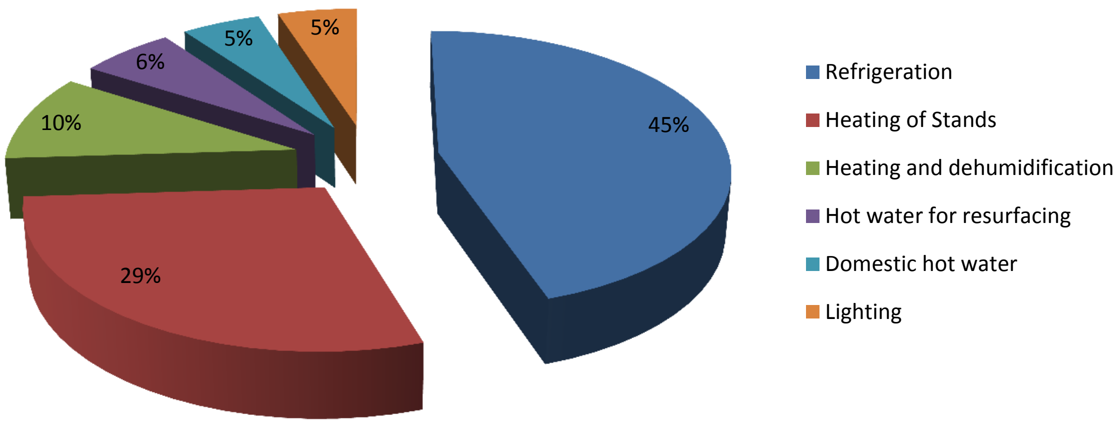

Figure 1.5: Break-up of energy consumption in indoor ice rink facilities [12].

1.1.3 Indoor Ice Rinks

Ice rinks of different sizes and dimensions are used for various activities such as hockey, figure skating, curling, recreational skating, public arenas, auditoriums and coliseums. Indoor ice rinks are large commercial buildings with a complex energy system, in which a large sheet of ice is maintained at a low temperature while, at the same time, the spectator area is heated to ensure comfortable conditions for the spectators. Also, the building is ventilated to provide good air quality. The major activities that contribute to energy consumption in indoor ice rinks are refrigeration of ice, heating of spectator area, ventilation and dehumidification, water heating for resurfacing, and lighting. Figure 1.5 shows the breakup of each of these components in the total energy consumption of indoor ice rinks.

The energy use of a standard arena is approximately 1500 MWh/year [12]. Refrigeration of ice is a complex phenomenon which is responsible for almost 45% of the total energy consumption in indoor ice rinks. However, as indicated in [13], not much savings can be accomplished by altering the condition of ice on the ice rink, and hence there is very little scope for their energy management. On the other hand, there is substantial scope for energy cost savings by optimal operational scheduling of the climate control systems to accommodate DR. These climate control systems, which consist of heating of spectator stand area, ventilation and dehumidification systems, can be optimally operated by taking into account the operational constraints of these systems [14]. Since ice rink arenas are a significant class of commercial buildings and are in operation for more than 8 months a year, their contribution to total system demand cannot be ignored, thus justifying the need to develop optimal operating strategies to minimize their energy costs and consumption.

1.1.4 Electricity Price Structures

Dynamic pricing schemes are becoming popular tools in aiding DR programs. Dynamic prices are rates that reflect time-varying electricity prices on a day-ahead, hour-ahead or real-time basis. Electricity customers could obtain information on real-time prices through advance metering devices having two-way communication capability. Consequently, they can determine the optimal decisions to operate their electrical devices so as to reduce electrical energy costs [15].

Flat-rate pricing (FRP) is a tariff rate which remains constant over a period. Dynamic pricing schemes such as Time-of-Use (TOU), Real-Time Pricing (RTP) and Locational Marginal Pricing (LMP) are available to electricity customers in different market structures. RTP signals can be on an hour-to-hour basis or even in shorter intervals (i.e., every 5 minutes), reflecting the system conditions, electric supply, and demand for electricity. For example in Ontario, Canada, the Hourly Ontario Electricity Price (HOEP) is the RTP signal that applies to large customers participating in the wholesale electricity market. Figure 1.6 presents an example of a typical RTP scheme [16].

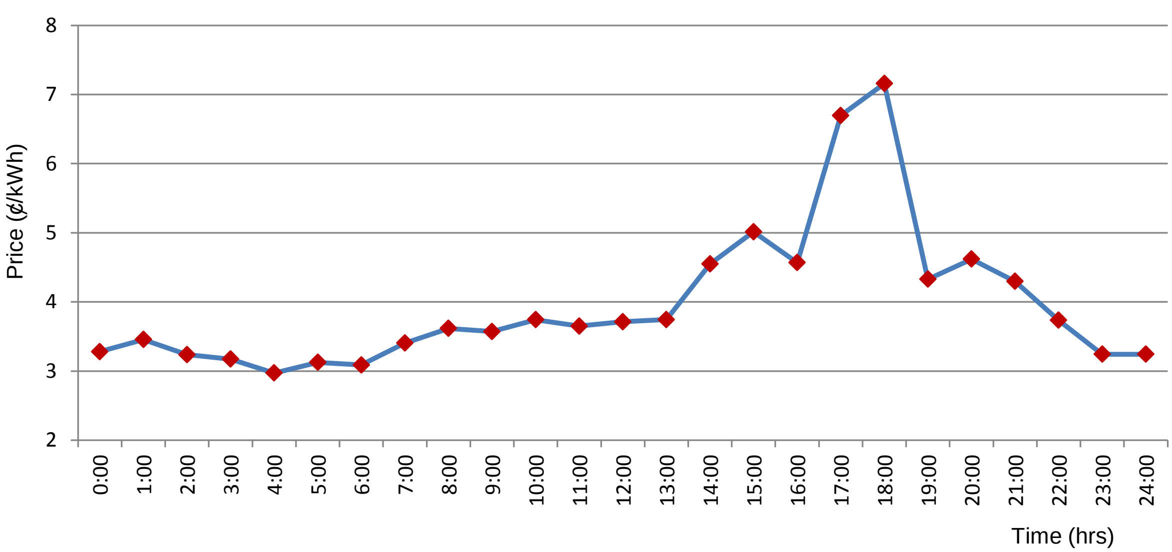

Figure 1.6: An example of RTP: The HOEP in Ontario [16].

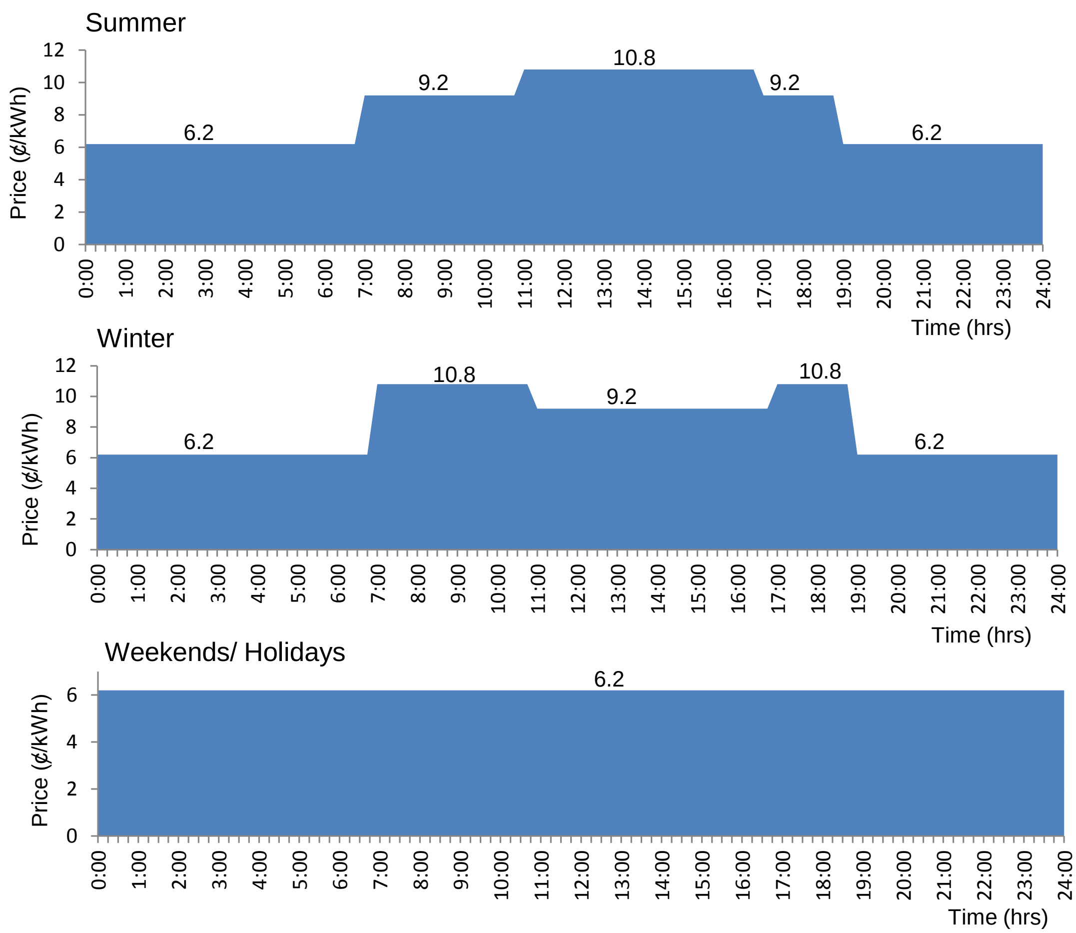

Figure 1.7: Ontario's TOU pricing scheme [17].

With TOU prices, the price of electricity varies for different times during the day. In Ontario, Canada, TOU prices are currently based on Off-peak, Mid-Peak and On-Peak hours of the day (Figure 1.7) and also varies by season (summer and winter) and day of the week (weekday or weekend).

1.2 Literature Review

1.2.1 EHMS in the Context of Smart Grids

Extensive research has been carried out pertaining to the development of mathematical models for EHMS in the context of Smart Grids for various sectors such as residential, commercial and industrial. Some of these works are briefly described next.

A comprehensive mathematical optimization model is proposed in [18] for residential energy hubs to optimally control the major residential loads including air-conditioner, heating, water heater, fridge, dishwasher, and lighting in order to minimize the total electrical energy cost over 24 hours. Three different pricing schemes, FRP, TOU and RTP are considered, and operational schedules of the above devices are compared. The electrical energy cost is minimized with RTP, and load shifting is used to reduce peak demand. In order to understand the development and implementation of mathematical optimization models for customer energy management systems, a case study using the residential mathematical model described in [18] is discussed in Section 2.2.

The mathematical modeling of climate control systems for a storage facility is presented in [19]. In a typical storage facility, the mixture of outdoor air and inside air is circulated by ventilation fans, the air flow is controlled by fans capacity and the position of hatches in the air mixer, and the humidifiers and dehumidifiers control humidity of the storage space. These systems are modeled to maintain optimum temperature and humidity levels inside the storage facility. The model incorporates electricity price information, outside climatic conditions and end-user preferences, and optimal operating decisions are obtained for the climate control devices in the form of ON-OFF decisions to minimize electrical energy cost. This automated decision making technology can be integrated into smart grids to optimize the operation of these devices. A very similar approach to model the indoor temperature and humidity dynamics, while maintaining different operational constraints, is adopted in this work.

A mathematical optimization model for optimal operation of various precesses in a greenhouse in the context of Smart Grids is proposed in [20]. The coordination of heating, ventilation, fogging and supplementary lighting sub-systems, as well as CO_2 demand, are modeled to optimally regulate the temperature and humidity of the greenhouse within predefined ranges. Energy cost savings up to 20% are achieved while maintaining all operational constraints such as maximum window opening for natural ventilation, flow rate of the fans in case of forced ventilation, rate of fogging system and temperature of hot water tubes. This work provided the basic understanding of forced ventilation to regulate the temperature and humidity inside the facility and its mathematical formulation.

A load survey system is proposed in [21] to determine the temperature sensitivity of load demand for various customer classes including residential, commercial and industrial, to investigate the potential of air conditioning load management in Taiwan. It is observed that the power consumption will increase by 1.0%, 0.6% and 0.2% for commercial, residential and industrial customers respectively when the temperature rises by 1%, and it is concluded that large commercial and office customers have the best potential for air conditioning load management. This work provided relevant details about the the variation of power consumption with temperature change, and the temperature sensitivity of large commercial customers.

The state of California in USA introduced an emergency peak reduction program in the winter of 2001 [22] for irrigation districts, after experiencing a severe imbalance in electricity supply and demand that resulted in brownouts. During the first 9 months of implementation, the irrigation districts voluntarily participated in load shifting, hence utilizing approximately $6.2 million in cost-sharing grant money. In addition, approximately 550 pumps were tested and pump repairs were made, resulting in an estimated savings of 16 million kWh. The presented study also highlights the relevance of load shifting to reduce peak demand in indoor ice rink arenas to reduce energy costs.

An optimal control strategy for a load shifting application to a South African colliery is reported in [23]. TOU electricity tariff is used to minimize the electricity cost and thus maximize load shifting through optimal control of conveyor belt system. It is reported that energy costs are reduced up to 49% during five weekdays in a high demand season. This study provided an understanding of the operation of control systems for demand response applications with a dynamic pricing scheme.

A generalized DR strategy using load shifting by a central controller in smart grids, is presented in [24]. An objective load curve is formulated by maximizing the use of renewable energy resources, maximizing the economic benefit, minimizing the power imported from the main distribution grid, or reducing the peak demand. The DR strategy seeks to bring the final load curve as close to the objective load curve as possible. The proposed DR strategy is tested on different customer groups such as residential (2600 controllable devices from 14 different types of devices), commercial (800 controllable devices from 8 different types), and industrial (100 controllable devices belonging to 6 different types) with the primary objective of reducing customers' energy costs. A Smart Energy Management System (SEMS) proposed in [25] comprises power forecasting module, energy storage system (ESS) management module and an optimization module for economic operation of a microgrid. Suitable set points are determined for all sources and energy storage devices to enable short-term energy scheduling at minimum cost. Both of these studies highlight the significance of using optimization modules for the economic operation of customers' energy levels in smart grids, which is also an aim of this work.

From the above literature review, it can be concluded that the installation of modern controllers for effective energy management in different sectors can bring about substantial savings in total electrical energy costs. Thus, the present work proposes a model for optimal energy management of a particular customer type, i.e., indoor ice rinks.

1.2.2 Indoor Ice Rink Energy Hubs

Energy analysis of indoor ice rinks is a well researched topic. However, most of the studies have focused on energy consumption in the refrigeration system [26, 27]. The heating and ventilation systems have been studied in recent years because of their role in energy savings.

The annual energy requirement of four indoor ice rinks, each in a different North American city (Edmonton, Houston, Montreal and Pittsburgh) is calculated and compared in [24]. The model evaluates monthly energy consumption of different systems of a ice rink facility such as refrigeration of ice, ventilation system, lighting system, brine pumps, underground electric heating system and radiant heating system. It is observed that the annual refrigeration load does not vary significantly (less than 7%) for the above four locations despite their very different climates. The annual energy consumption by the ventilation system is significantly influenced by the climatic conditions, and is highest for hot and humid locations. It is experimentally proved for the control of radiant heaters that using a bimetallic thermostat with a high hysteresis is more suitable from the system's point of view than an electronic thermostat with a low hysteresis; however, the energy savings with the bimetallic thermostat are achieved at the expense of the spectator's comfort. This study helped in the understanding the influence of climatic conditions on the functioning of ventilation systems of indoor ice rinks, and also their impact on energy consumption.

The impact of building thermodynamics and different operating schedules on the energy demand of indoor rinks, which is of importance to the present work, is discussed in [28]. The effect of climate, design parameters such as ceiling emissivity, insulation thickness and sub-floor heatings and operating conditions are analyzed to calculate daily energy demand of indoor ice rinks using Computational Fluid Dynamics (CFD) simulations. Case studies are carried out considering different operating schedules of weekdays and weekends and different climatic conditions ranging from quite cold to quite hot. The difference in the number of resurfacing operations between a weekday and weekend, which is more in the latter case, led to notable increase in energy consumption. Also, outside climatic conditions have significant effect on the total daily ice sheet load, increasing by 46% with a change in the climate from extreme cold to extreme hot.

The impact of ventilation control strategies on indoor air quality using CFD technique is discussed in [29] from a field survey of ten indoor ice rinks selected from United States, Canada and Europe. It is found that the operation strategy of ventilation systems, the air distribution method, the fuel type used by ice resurfacer and air exchanger have a significant impact on the indoor air quality. The paper allowed a better understanding of different ventilation control strategies and their impact on indoor air quality.

The heat and mass transfer phenomenon in a ventilated ice rink using a standard κ-ϵ turbulence model is studied in [30] to predict energy consumption as well as ice and comfort conditions. The flow pattern, the isotherms and the lines of constant absolute and relative humidity for two suggested configurations of air inlets and exhaust valves are analyzed. The heat losses through the walls and ceiling, convective heat flux and radiative heat flux are calculated to be approximately 15%, 13% and 26% respectively. Energy and exergy analyses for ice rinks is presented in [31] for one of the Mediterranean climate cities in Turkey with a net area of 648 m^2. Lowex (low exergy) analysis approach for varying state reference temperatures is used to understand the exergy flows in buildings in order to find the potential for further improvements in energy utilization. An energy study is performed to analyze pre-cooling and operation cooling load of a ice rink, and the cost of performance of compressors was obtained. The review of both of these studies helped in determining the impact of different heat fluxes and energy flows due to varying temperature and humidity conditions inside an ice rink facility.

The simulation of thermal and airflow fields using energy transfer, zonal airflow, radiation and humidity models to predict the heat fluxes, the transient airflow pattern as well as the temperature and humidity distributions in a 3D section of an indoor ice rink is discussed and modeled in [32]. The entire 3D section is divided into a small number of control volumes with homogeneous temperature and air density. All these models are coupled through an iterative onion method to generate transient heat fluxes between the zones, and temperature and humidity distributions. It is found that radiation heat flux is the most dominant followed by convective heat flux. The condensation heat flux is a nominal value which depends upon the outside humidity conditions, and the value of average heat flux due to resurfacing remains constant. It is observed that decreasing the thermostat set point reduces radiation heat flux especially in winter and spring, however during the summer the thermostat set point has no prominent effect. This study is of particular relevance for the present work, since a similar concept of using zones to represent temperature distributions inside an ice rink facility is adopted here.

Different methods to predict the ventilation performance such as analytical, experimental, zonal and CFD are compared in [33]. It is reported that a CFD modeling approach gives the most accurate analysis of indoor air quality, natural ventilation, and stratified ventilation. However, CFD studies require considerable computer memory and CPU time, making the approach less suitable for real-time applications [34]. The proposed mathematical model in this work is based on approximate, yet relatively accurate, modeling of the ice rink that can be solved in a few seconds, making it more suitable for real-time applications.

Most of the research work discussed in this section, present detailed physical models of indoor ice rinks mainly to analyze building thermodynamics including airflow, energy flux transients, heat transfer and indoor air quality. To the best of the author's knowledge, no work is reported in the literature which focuses on reducing the electrical energy costs through optimal operation of climate control systems of indoor ice rinks.

1.3 Research Objectives

In the present work, a comprehensive mathematical model of indoor ice rinks for optimal operation of climate control systems is developed based on their approximate physical models and prediction of climatic conditions. The following are the main objectives of this research:

- Develop a mathematical optimization model to represent indoor temperature and humidity dynamics of an ice rink spectator area in order to maintain them within predefined and acceptable ranges.
- Incorporate operational constraints of ventilation systems, radiant heating systems and dehumidification systems of a typical indoor ice rink facility.
- Estimate realistic values of the model parameters to appropriately represent an actual ice rink.
- Undertake realistic studies using a proper optimization platform on an existing indoor ice rink facility.
- Test the effectiveness of the model by running multiple simulations, appropriately considering the uncertainty of relevant parameters.

1.4 Thesis Organization

This thesis is divided into five chapters. Chapter 2 presents the relevant background topics such as a discussion of the EHMS model for a single unit residential system, and the schematics and climate control systems of an indoor ice rink facility. In Chapter 3, the proposed mathematical model for optimal operation of ice rink climate control systems is presented; this chapter also discusses the estimation of the required model parameters. Simulation studies and results are presented in Chapter 4 for a realistic ice rink arena, in Chapter 5 finally, the summary and conclusions of the work presented here, are highlighted, and the scope of possible future work is discussed.

Chapter 2

Background

2.1 Nomenclature

Sets	
A	Set of devices; $A = \{ht, wh, pv\}$
T	Set of indicies in scheduling horizon
Indices	
i	Index of devices
t	Index of time interval
Subscripts	
ht	Electric heating
wh	Water heater
pv	PV system
Variables	
$\theta(t)$	Indoor temperature at time t; $[^{\circ}C]$
$\theta_{wh}(t)$	Water temperature at time t; $[^{\circ}C]$
$ESL(t)$	Energy storage level at time t; $[kWh]$
$S_i(t)$	Operation state of device i at time t
Parameters	
$AL(t)$	Activity level at time t

$C_D(t)$	Electricity price; [$/kWh]
C_{FIT}	Feed-In-Tariff price; [$/kWh]
$chd_{pv}(t)$	Charged energy into PV battery system at time t
$dch_{pv}(t)$	discharged energy from PV battery system at time t
ESL_{pv}^{max}	Maximum energy storage level
ESL_{pv}^{min}	Minimum energy storage level
$HWU(t)$	Average hourly hot water usage at time t
k_i	Cooling/Warming effect of an OFF state of device i on corresponding variable; [$°C$/interval]
α_i	Cooling/Warming effect of a ON state of device i on corresponding variable; [$°C$/interval]
ρ	Effect of inside and outside temperature difference on the inside temperature
P_i	Power rating of device i; [kW]
P_D	Household power demand; [kW]
P_G	Power generated through PV; [kW]
τ	Time interval length
θ_{set}	Indoor set point temperature; [$°C$]
$\theta^{max}(t)$	Maximum temperature range; [$°C$]
$\theta^{min}(t)$	Minimum temperature range; [$°C$]
$\theta_{out}(t)$	Outdoor temperature at time t; [$°C$]
$\theta_{wh}^{max}(t)$	Maximum water temperature range; [$°C$]
$\theta_{wh}^{min}(t)$	Minimum water temperature range; [$°C$]
γ_i	Cooling/Warming effect of activity level on corresponding variable; [$°C$/interval]

2.2 Introduction

In order to understand the development and implementation of mathematical models for customer's energy management systems, this chapter discusses a case study of the optimal energy management in a single residential energy hub. The objective of this work is to study the possible energy cost savings through a demand response strategy. The chapter also discusses the schematics of a typical indoor ice rink facility, and the modeling approach and control strategies of climate control systems of indoor ice rinks, providing the required background review for the present work.

2.3 Optimal Operation of Residential Energy Hubs in Smart Grids

A case study is undertaken on a single unit residential energy hub by modeling its behavior during winter conditions, considering the electric heating system, water heater, PV array and its energy storage system to minimize total electrical energy costs. The effect of four different pricing schemes i.e. RTP, TOU, FRP and LMP, on the operational schedules of these devices is analyzed. Three different scenarios, i.e. base case, two-meter model and the net-meter model, are considered. The mathematical model for base case and two-meter model is taken from [18], and modified for the purpose of this case study. A Modeling Language for Mathematical Programming (AMPL), a high level mathematical modeling platform for optimization, is used and the Mixed Integer Linear Programming (MILP) problem is solved using Gurobi solver [35]. The mathematical model, inputs for the system and the relevant results of the case studies are presented next:

2.3.1 Mathematical Model

Objective Functions

- Case 0 (Base Case), minimization of temperature deviations from the set point: This objective seeks to closely follow the temperature set point in order to maximize customer comfort. Hence, the following minimization of the square of temperature deviation from the given set point is formulated as an objective function:

$$J_1 = \sum_{t \in T} (\theta(t) - \theta_{set})^2 \tag{2.1}$$

- Case 1 (Two-meter Model), minimization of total electrical energy costs: This objective minimizes total electrical energy cost for the customer over the entire scheduling horizon. The first term in the following equation represents cost of electricity usage, and the second term represents the revenue by selling electricity generated from solar PV to the grid:

$$J_2 = \sum_{t \in T} \sum_{i \in (ht,wh)} \tau \, C_D(t) \, P_i \, S_i(t) - \sum_{t \in T} \sum_{i \in (pv)} \tau \, C_{FIT} \, P_i \, S_i(t) \tag{2.2}$$

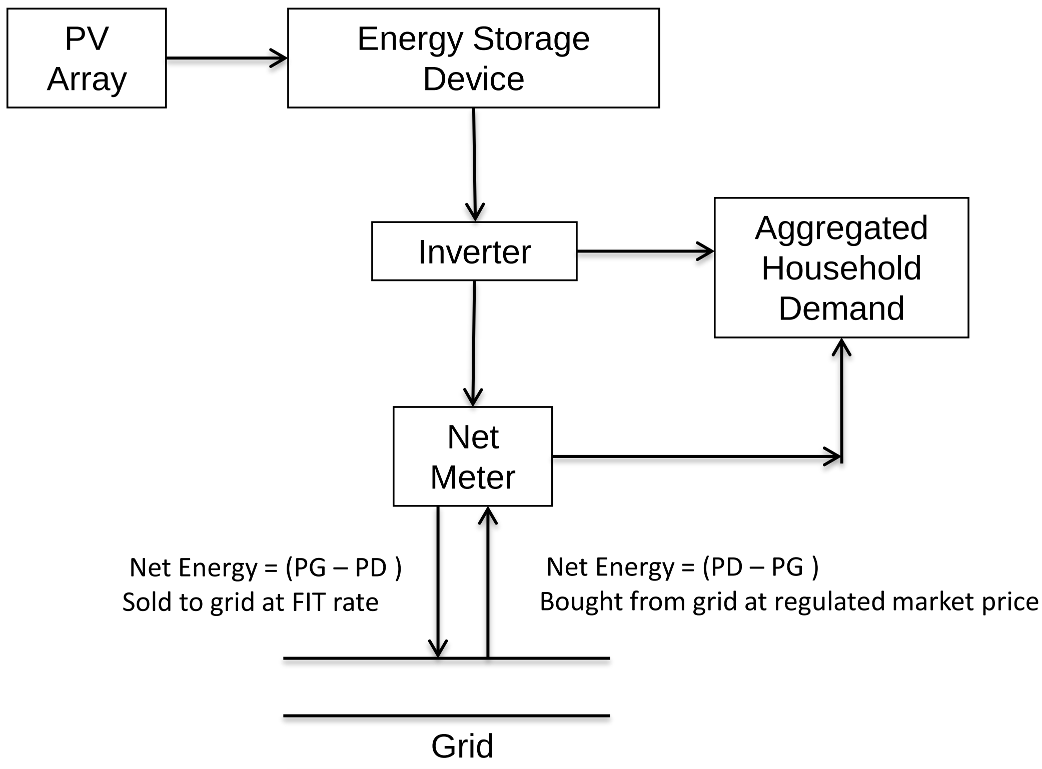

Figure 2.1: Net Metering Model

- Case 2 (Net-meter Model), minimization of total electrical energy costs through net metering: Figure 2.1 presents the schematic representation of a net-metering scheme. The customer utilizes energy produced from a PV system to operate electrical devices such as electric heating and water heater, instead of selling it entirely to the grid. If the energy produced from the PV array is greater than the household demand, then the excess is sold to the grid at Feed-In-Tariff (FIT) rate; otherwise, if the energy demand is greater than energy produced, then the net energy is bought from the grid at regulated market prices (RTP, TOU, FRP or LMP):

$$J_3 = \begin{cases} C_D(t)\,(P_D(t) - P_G(t)) & \text{if } \mathrm{P}_D(\mathrm{t}) \geq \mathrm{P}_G(\mathrm{t}) \\ C_{FIT}\,(P_G(t) - P_D(t)) & \text{if } \mathrm{P}_G(\mathrm{t}) > \mathrm{P}_D(\mathrm{t}) \end{cases} \quad \forall t \in T \tag{2.3}$$

Model Constraints

- Electric Heating: The following constraint states that the indoor temperature at time t is a function of the temperature at time $t-1$; household activity level at time t; ON/OFF state of the heating system at time t; and the outdoor and indoor temperature difference:

$$\begin{aligned}\theta(t) = \theta(t-1) + \tau\,[k_{ht}\,AL(t) + \alpha_{ht}\,S_h(t) \\ + \rho(\theta_{out}(t) - \theta(t)] \quad \forall t \in T\end{aligned} \tag{2.4a}$$

$$\theta^{min}(t) \leq \theta(t) \leq \theta^{max}(t) \tag{2.4b}$$

The indoor temperature is kept within the limits specified by the end-user through constraint (2.4b).

- Water Heater: The following equation states that the water heater temperature at time t is a function of the temperature at time $t-1$; the average hot water usage; and the ON/OFF state of the water heater at time t:

$$\begin{aligned}\theta_{wh}(t) = \theta_{wh}(t-1) + \tau\,[\alpha_{wh}\,S_{wh}(t) \\ - k_{wh}\,HWU(t) - \gamma_{wh}] \quad \forall t \in T\end{aligned} \tag{2.5a}$$

$$\theta_{wh}^{min}(t) \leq \theta_{wh}(t) \leq \theta_{wh}^{max}(t) \tag{2.5b}$$

Constraint (2.5b) ensures that the water heater temperature is within the minimum and maximum limits.

- PV Array: The following constraint represents the energy storage level at time t due to charging and discharging decisions of the battery; the second constraint ensures protection of the battery against over charging and deep discharging; and the charging and discharging operations are guaranteed not to occur simultaneously due to the last constraint:

$$\begin{aligned}ESL_{pv}(t) = ESL_{pv}(t-1) + \tau\,[S_{pv}^{chd}(t)\,chd_{pv}(t) \\ - S_{pv}^{dch}(t)\,dch_{pv}(t)] \quad \forall t \in T\end{aligned} \tag{2.6a}$$

$$ESL_{pv}^{min} \leq ESL_{pv}(t) \leq ESL_{pv}^{max} \tag{2.6b}$$

$$S_{pv}^{chd}(t) + S_{pv}^{dch}(t) \leq 1 \tag{2.6c}$$

- Operational Constraints: The operation of all the devices are binary variables defined as follows:

$$S_i(t) = \begin{cases} 1 & \text{if device is ON} \\ 0 & \text{if device is OFF} \end{cases} \quad \forall i \in \{ht, wh, pv\} \;\; \forall t \in T \tag{2.7}$$

2.3.2 Example

Inputs

The model requires the outdoor climatic conditions (Figure 2.2), solar power profile (Figure 2.3), electricity price information (Figure 2.5), activity level of the residential unit and an assumed base load (Figure 2.4) as inputs. The values of the parameters used in the above equations are extracted from [18].

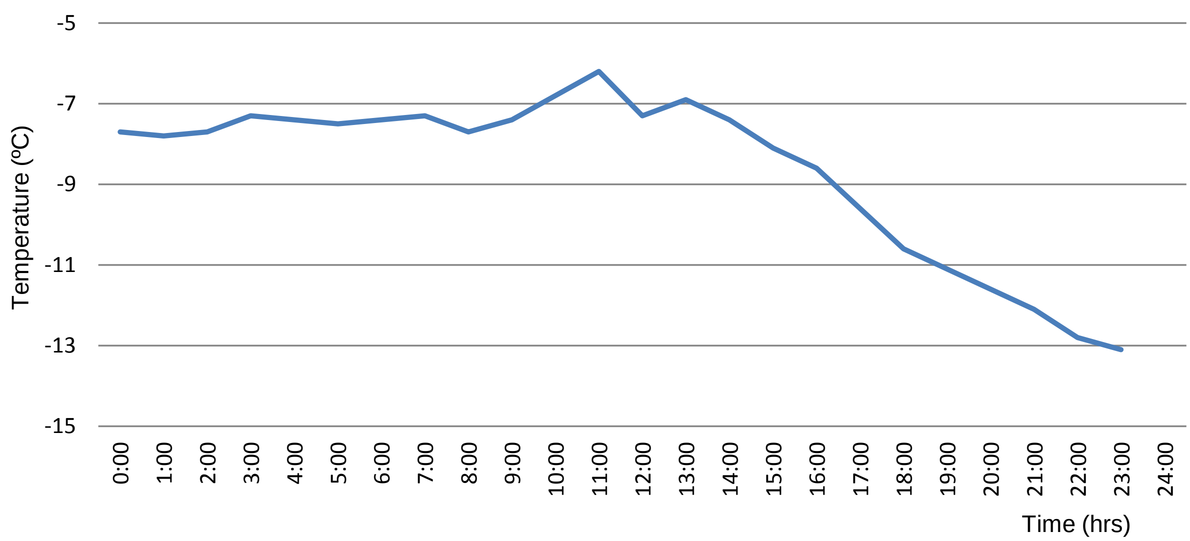

Figure 2.2: Ambient air temperature profile for a typical winter day in Toronto [36].

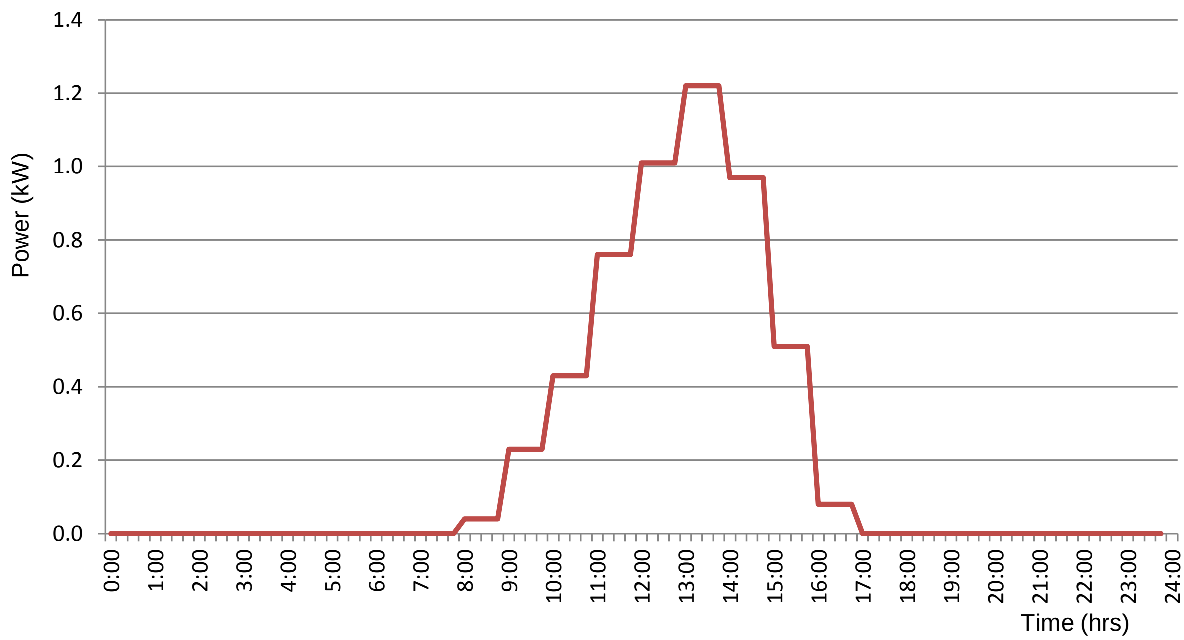

Figure 2.3: Solar power profile for a typical winter day in Toronto [36].

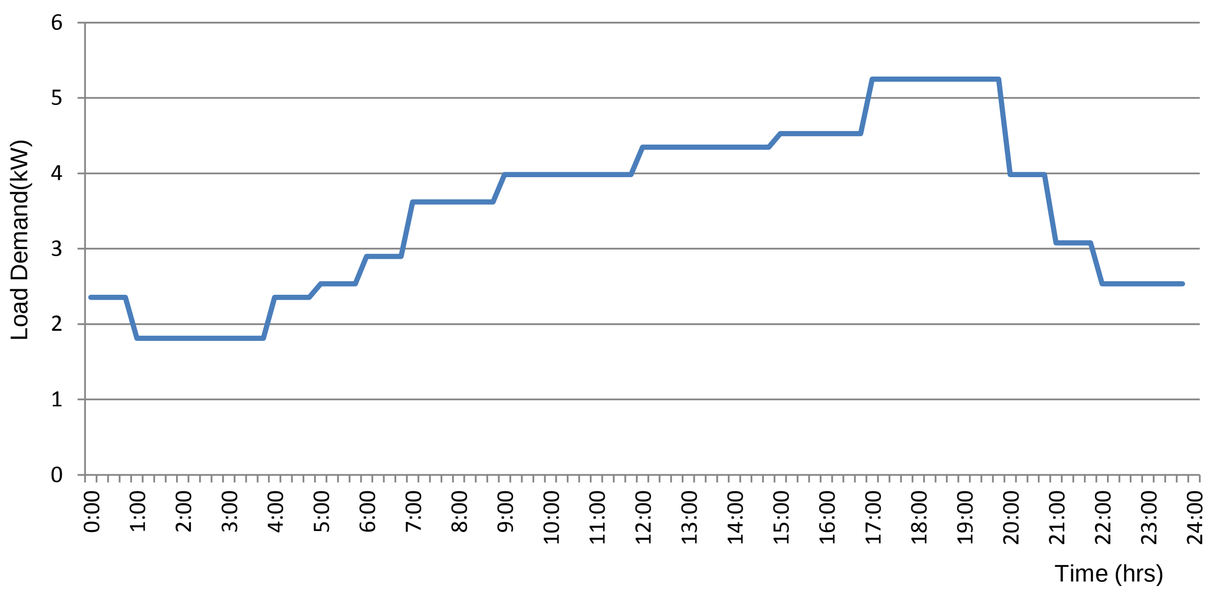

Figure 2.4: Assumed base load without heating and water heater.

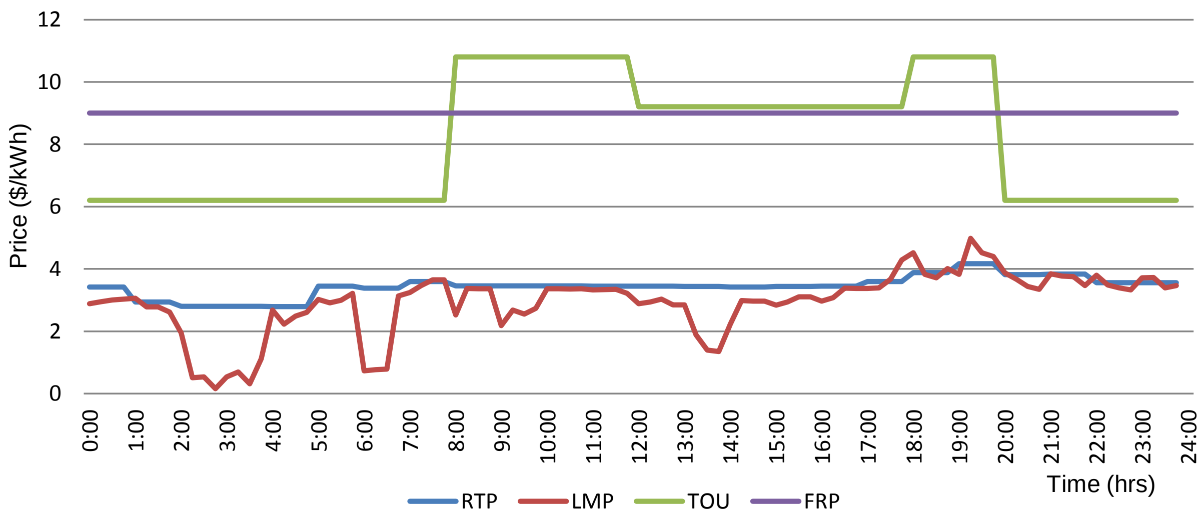

Figure 2.5: Electricity price information of a typical winter day in Toronto [16].

Results

Optimal operational schedules of the electric heating, water heater and PV array system are obtained for a typical winter day for all the pricing schemes including LMP, RTP, TOU and FRP. Figure 2.6, Figure 2.7 and Figure 2.8 present the optimal operational schedules of the devices obtained for Case 1, i.e., minimization of total electrical energy costs with a two-meter model.

The electric heating system, as shown in Figure 2.6, tries to schedule its operation during lower energy price periods in all the pricing schemes, while maintaining inside temperature within the limits. After 6:00 PM, since the outside temperature drops considerably, the schedules appear to be quite similar for all the pricing schemes. For the water heater operation shown in Figure 2.7, the ON decisions are obtained so as to maintain the water temperature within the predefined range. The energy storage level of the PV module and its charging and discharging operations are given in Figure 2.8. Since the solar power is available from 8:00 AM to 5:00 PM, the PV module charges during that period, irrespective of the electricity price. The energy is not necessarily discharged simultaneously for all the pricing schemes, because of the existence of multiple local solutions over the scheduling horizon of 24 hours.

The energy storage level of the PV module and the charging and discharging operations for Case 2, i.e. net meter model, is presented in Figure 2.9. The PV module charges for the duration solar power is available and discharges the stored energy during the periods when electricity price is high, as expected. For example, the LMPs are high at 6:00 PM and between 7:00 to 8:00 PM, and hence the discharging takes place during these intervals.

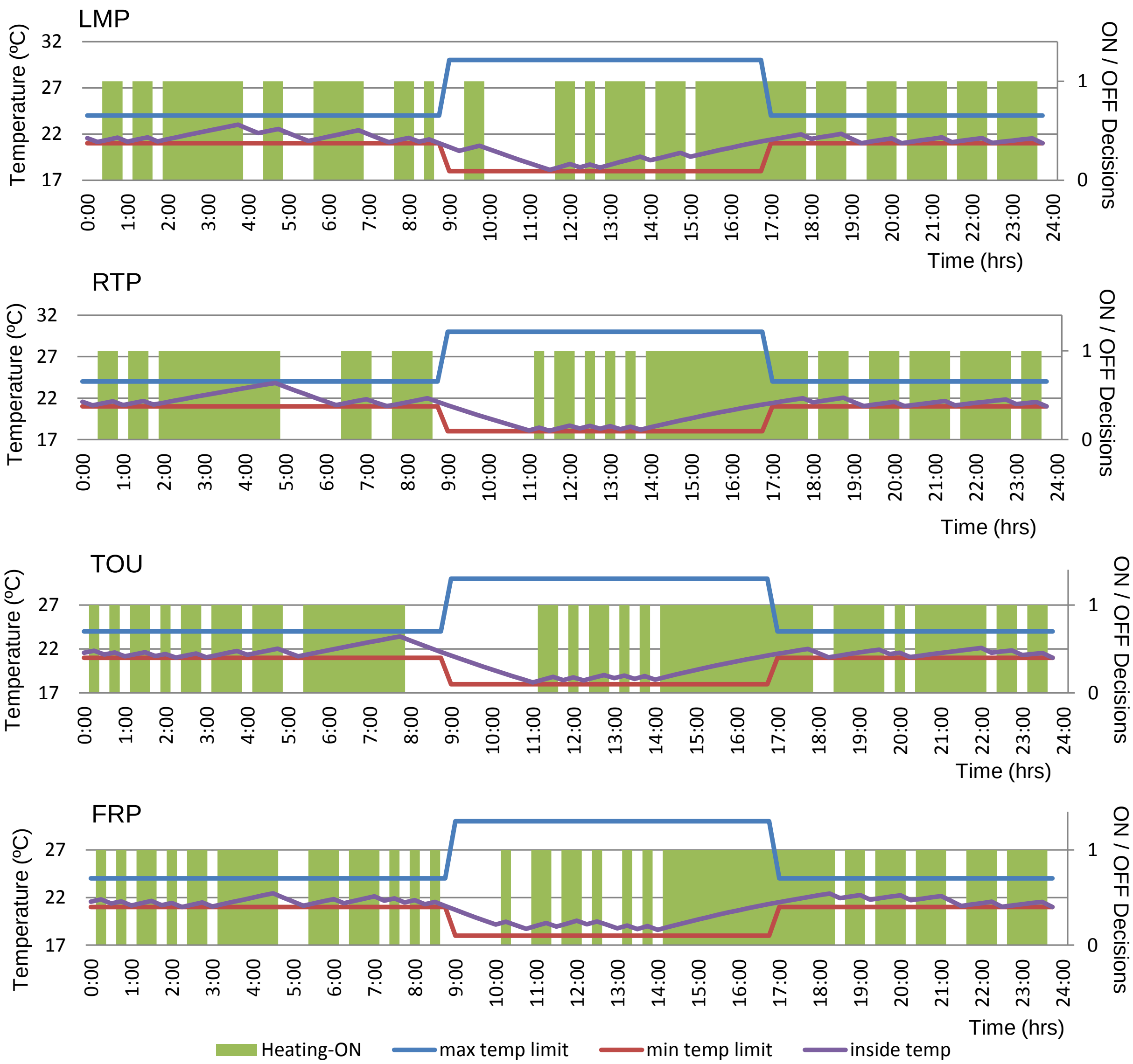

Figure 2.6: Variation of indoor temperature, maximum and minimum temperature limits and operational schedules of the electric heating system for different pricing schemes, Case 1.

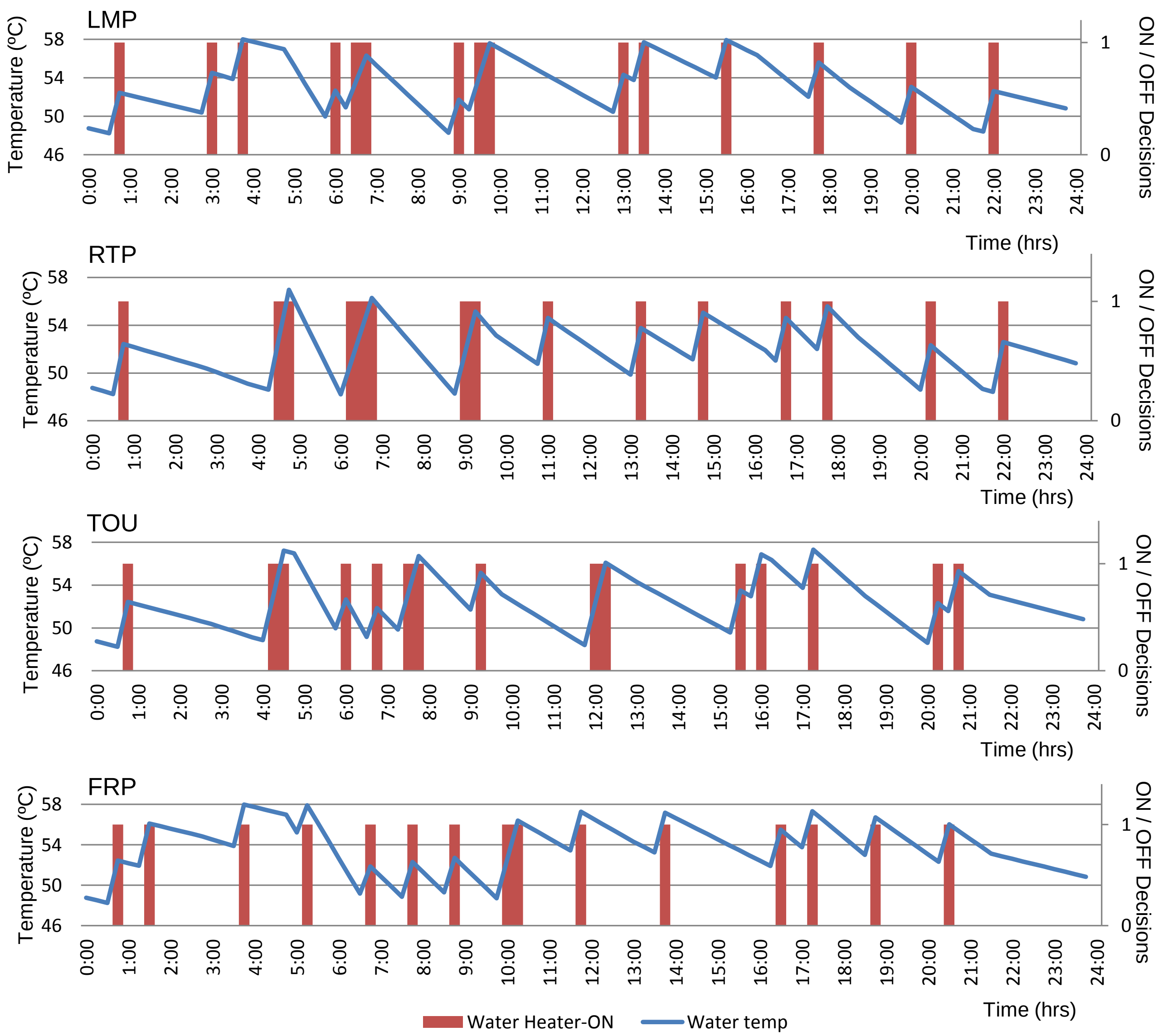

Figure 2.7: Variation of water heater temperature and operational schedules for the water heater during winter for different pricing schemes, Case 1.

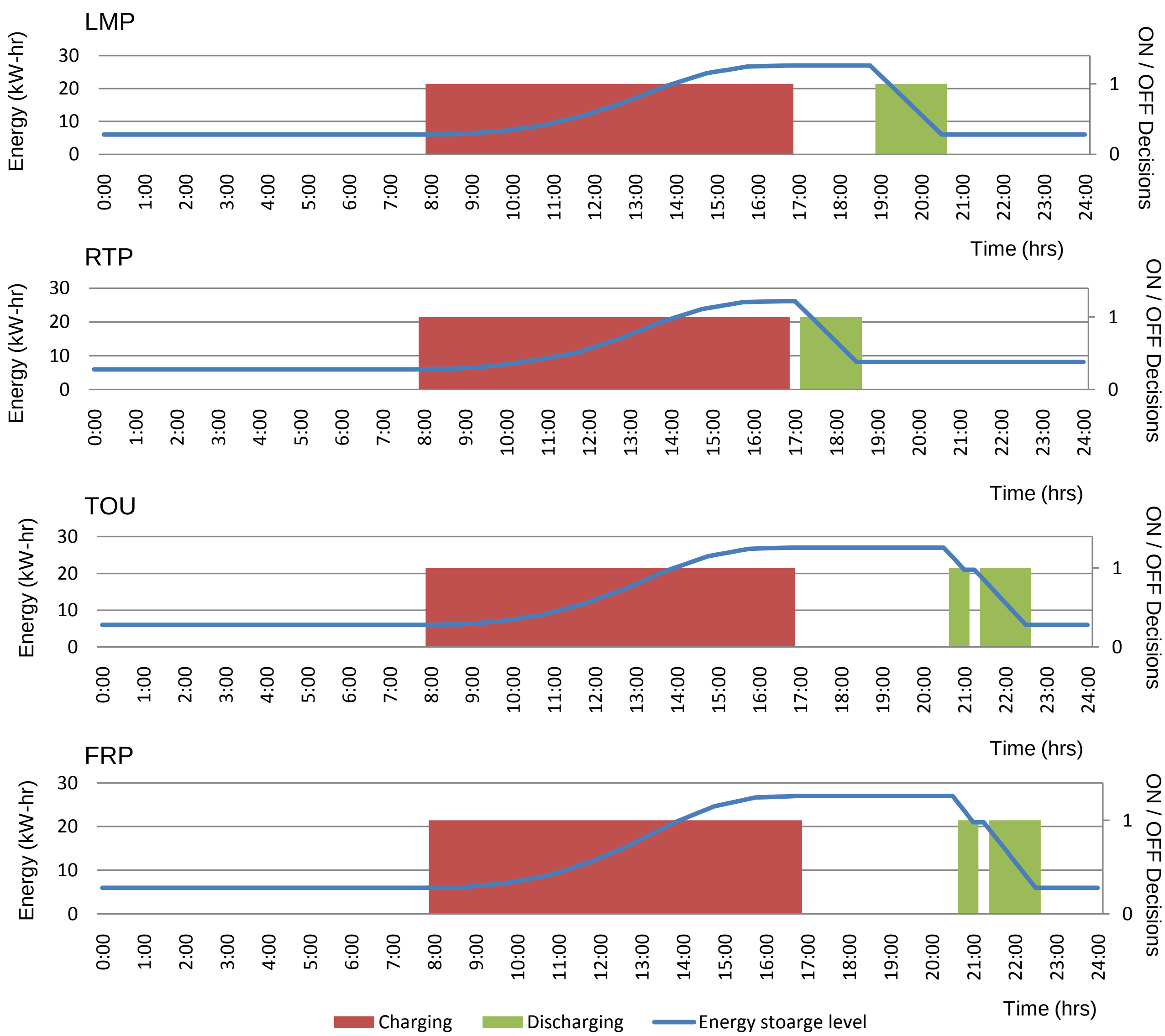

Figure 2.8: Variation of energy storage level and operational schedules of charging and discharging operations of the PV system battery for different pricing schemes, Case 1.

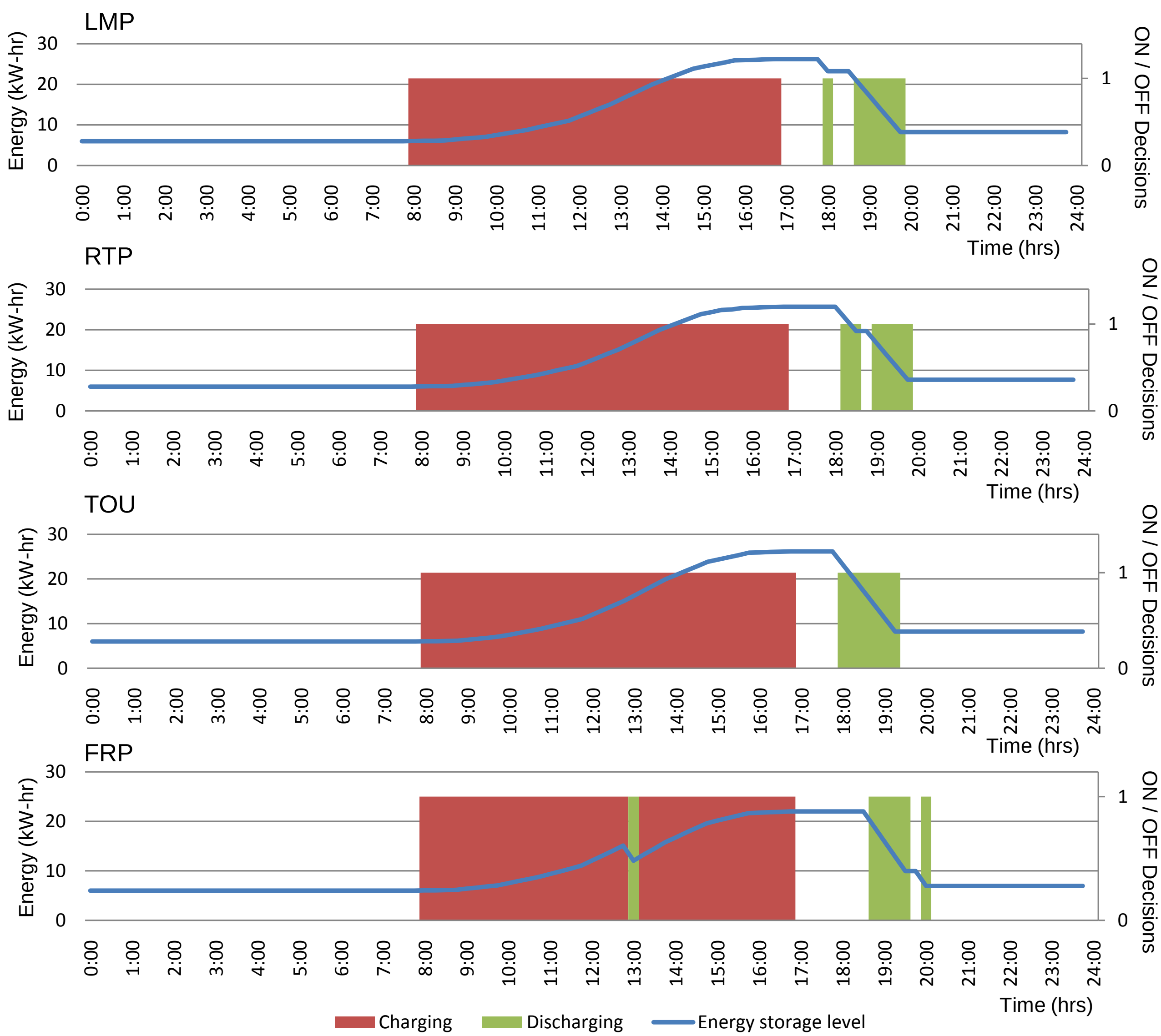

Figure 2.9: Variation of energy storage level and operational schedules of charging and discharging operations of the PV system battery for different pricing schemes, Case 2.

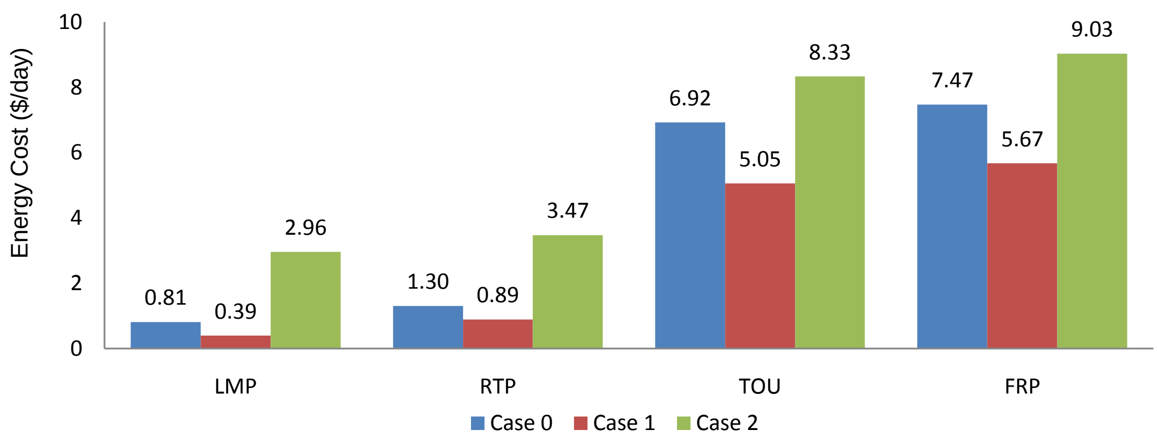

Figure 2.10: Comparison of total electrical energy costs for all cases for different pricing schemes.

Table 2.1: Comparison of electrical energy cost savings for the devices for different pricing schemes.

Device	LMP			RTP			TOU			FRP		
	Case 0 ($/day)	Case 1 ($/day)	Savings (%)	Case 0 ($/day)	Case 1 ($/day)	Savings (%)	Case 0 ($/day)	Case 1 ($/day)	Savings (%)	Case 0 ($/day)	Case 1 ($/day)	Savings (%)
Electric Heating	0.610	0.492	19.292	0.733	0.607	17.217	1.726	1.370	20.620	1.915	1.604	16.216
Water heater	0.069	0.060	13.218	0.078	0.072	8.717	0.190	0.169	11.058	0.203	0.191	5.679

Figure 2.10 presents a comparison of total electrical energy costs for different pricing schemes for the various case studies. The electrical energy cost is minimum with LMP and maximum with FRP in all the cases, due to the difference in the price profiles over the period considered. For the net-meter model, the energy generated through PV is used by the customer and any excess is sold to the grid at FIT, unlike Case 0 and Case 1, wherein

the entire energy from PV is sold to the grid. Therefore, the total electrical energy cost for the net-meter model is higher as compared to other cases.

A comparison of device specific electrical energy costs is presented in Table 2.1. As expected, the cost of operation of the heating system is much higher than the water heater. The optimal operation of heating system and water heater, for Case 1 results in approximately 20% and 10% energy savings respectively for all the pricing schemes as compared to Case 0.

Discussions

An efficient mathematical model for real-time residential demand response is applied and analyzed here for four different pricing schemes. The most significant observations resulting from the presented case studies can be briefly summarized as follows:

- In terms of aggregated energy costs, the lowest cost is obtained with LMP and the highest with FRP.
- As compared to the base case, there is a significant reduction in energy cost in Case 1 for all pricing signals; this is due to the device optimized schedules.
- In Case 1, the schedules for charging and discharging of the energy storage device change slightly for different pricing signals because of multiple local solutions, but the total number of charging and discharging events, and hence revenue from solar PV, remain the same.
- The optimal schedules of devices are not affected by the operation of solar PV in Case 1 (two-meter model), and this study confirms that using two meters instead of a net meter is beneficial from the customer's point of view, as expected.

2.4 Climate Control Systems of Indoor Ice Rinks

The objective of climate control systems in an indoor ice rink facility is to regulate the operation of climate control devices while maintaining the indoor parameters, particularly temperature and humidity, within predefined ranges. The various conditions that affect indoor parameters of the building include outdoor weather conditions, inside climatic conditions, thermodynamics of the building, and type and purpose of the facility, as discussed in some detail next.

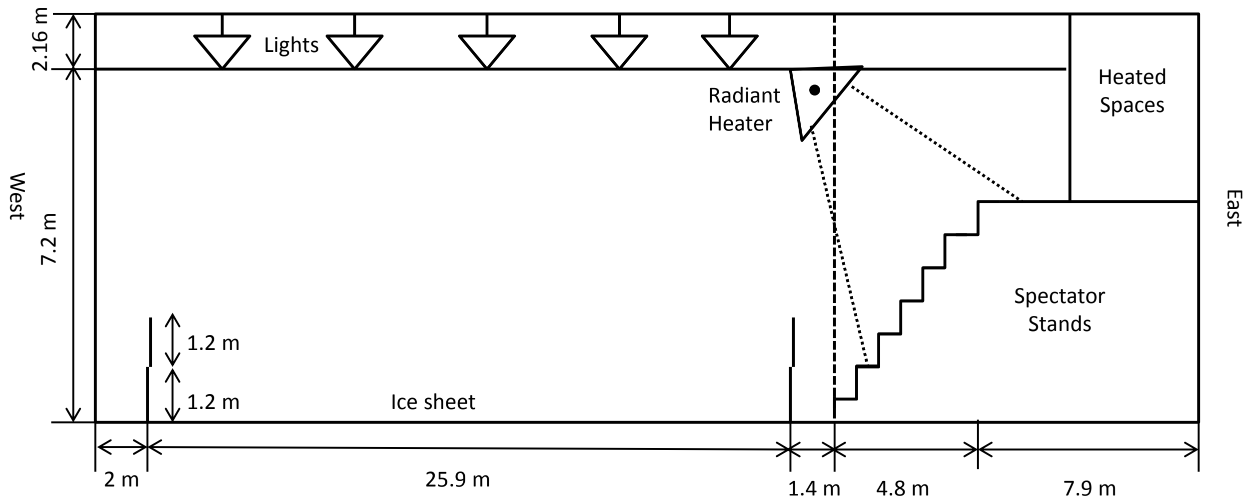

Figure 2.11: Schematic representation of an indoor ice rink facility [32].

2.4.1 Indoor Ice Rink Facility

This thesis aims at building a mathematical model of climate control systems of indoor ice rinks that seeks to maintain the temperature and humidity conditions in the spectator zone, since the savings in the maintenance of the ice rink surface are limited due to the severe constraints associated with such process. Figure 2.11 shows a layout of a typical ice rink facility [32]. It is 42 m wide, 64 m long, and 9.36 m high, with a rectangular ice sheet of 26 x 61 m. Six rows of stands run the whole length of the building on one side and a narrow corridor encircles the ice surface. Barriers delimiting the ice surface have a total height of 2.4 m, with the lower part made of wood and the upper part made of plastic having a height of 1.2 m each.

The inlet, outlet and radiant heating conditions are shown in Figure 2.12. The spectator zone is heated by eight radiant heating units and ventilation is performed by fans intercalated between the elements of radiant heating. The air is evacuated by the outlets on the east, north and south walls. Also, two dehumidifiers are diagonally located in the corners of the ice rinks to provide dehumidification in the spectator zone.

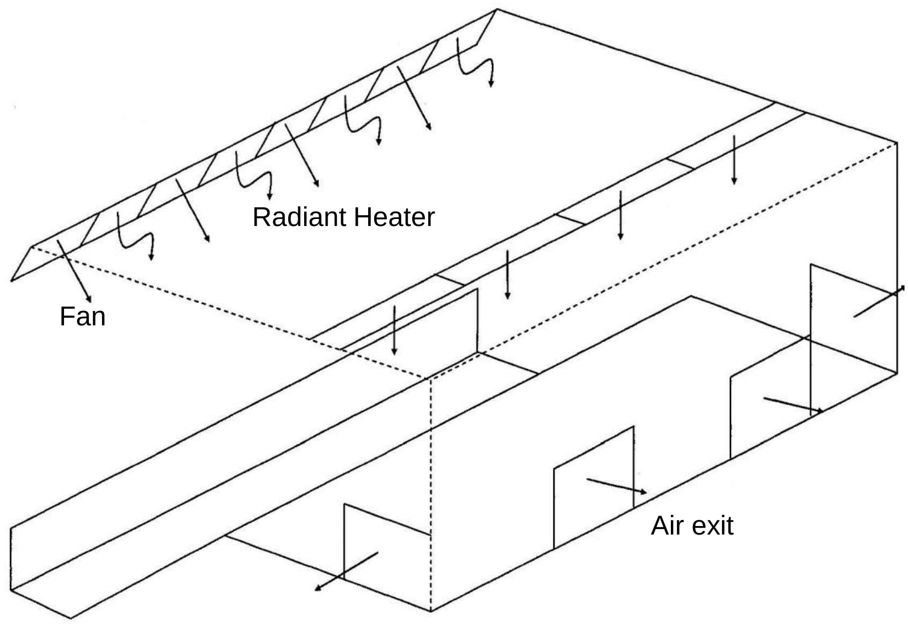

Figure 2.12: Inlet, outlet and radiant heating system configuration in the spectator zone [37].

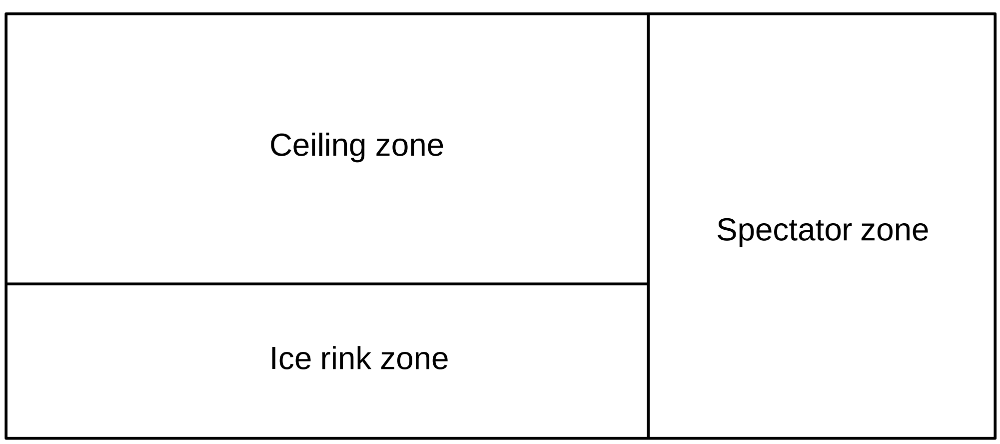

Figure 2.13: Division of the ice rink facility (side view) into three zones.

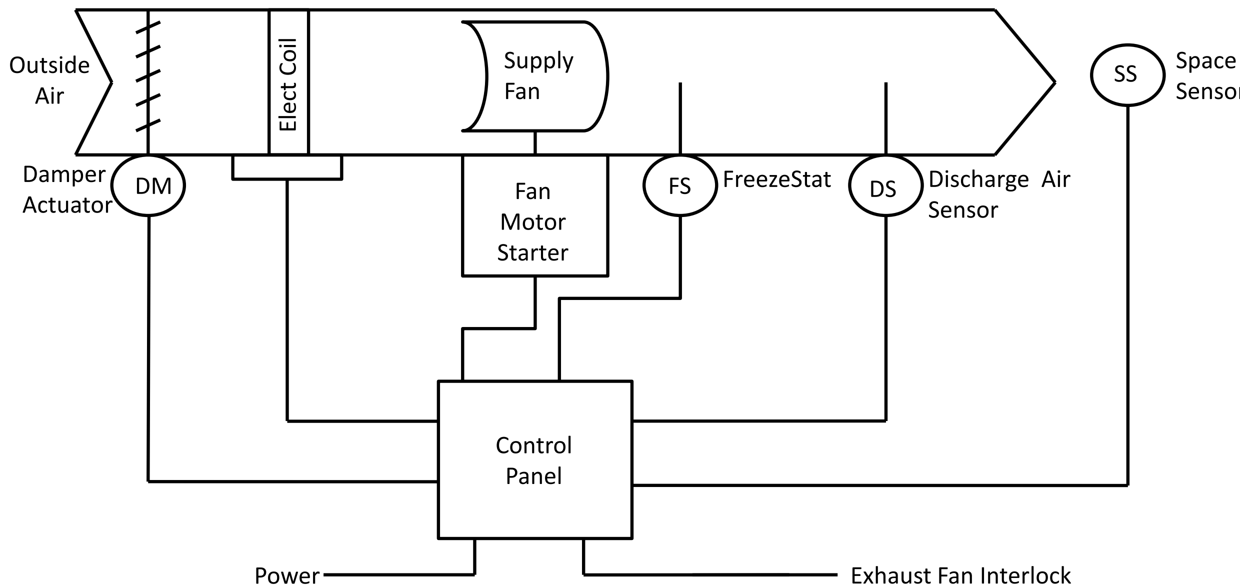

Figure 2.14: Typical arrangement of "built up make-up" air unit with electric heating [38].

2.4.2 Control System

The indoor ice rink facility is divided into three zones, i.e. ice rink zone, ceiling zone and spectator zone, as shown in Figure 2.13, and uniform thermal properties are assumed for all these zones. Since the proposed study is focused on the operation of climate control systems for the spectator zone, this division will help in determining the effect of ice sheet and above areas on the temperature and humidity conditions of the spectator zone. The refrigeration conditions at the surface of the ice rink zone, i.e. temperature and humidity of ice, as well as in the ceiling zone are considered as inputs to the model.

The ventilation system considered is a "built up make-up air unit" with electric heating and no re-circulation of air (100 percent outside air systems) [38]. Figure 2.14 shows a typical arrangement of built up make-up air unit, which comprises a motorized outside air intake damper, electric heating section, and supply fan. The electric heating section of the ventilation unit is controlled by a discharge air temperature control system. In order to maintain the discharge air temperature set-point, the stages of electric duct heater should be controlled via a multistage controller or sequencer. The number of stages of electric heating depend upon the parameter referred to as "deltaT", which is an amount of increase in temperature that an electric heater gives to the outside air passing through it. Hence, the total electrical power of the ventilation system is the sum of the power of ventilation fans and the power required by the electric heaters.

Radiant heaters are designed to provide spot heating through the application of radiant heat transfer. The heated infrared rays from the radiant heating equipment are radiated until they are absorbed by the objects, floors, furniture or people without warming up the air. Due to increase in temperature of the heated objects, only the immediate air surrounding these objects gets warmed up. Radiant heaters are advantageous in ice rink applications where heating of the spectator stands only is required, without heating the ice rink itself. The important benefits of employing infrared radiant heaters are fast response, control accuracy and clean air [39].

2.5 Summary

This chapter discussed relevant background topics pertaining to the operation and implementation of energy management systems. A case study was carried out on a single unit residential energy hub, and optimal schedules of devices were obtained in order to reduce the total electrical energy costs for four different electricity pricing schemes and two energy metering strategies. Finally, the chapter discussed the structure and climate control systems of indoor ice rinks.

Chapter 3

Mathematical Modeling

3.1 Nomenclature

Sets

A	Set of devices; $A = \{dh,\ fv,\ ht\}$
T	Set of indicies in scheduling horizon

Indices

i	Index of devices
t	Index of time interval
x	Index of ice rink zone
y	Index of ceiling zone
z	Index of spectator zone

Subscripts

dh	Dehumidifier
fv	Forced ventilation
ht	Radiant heating

Variables

$\phi_z(t)$	Relative humidity of zone z at time t; [%]
$\theta_z(t)$	Temperature of zone z at time t; [$^\circ C$]
$S_{i,z}(t)$	Operation state of device i of zone z at time t
$S_t(t), S_h(t)$	Binary variables for linearization purpose

$\omega_z(t)$	Water content of air of zone z at time t; $[kg_{H_2O}/kg_{air}]$

Parameters

A	Area of the zone; $[m^2]$
α_z	Thermal leakage of zone z; $[kJh^{-1}K^{-1}]$
β_z	Effect of operation of ventilation system on temperature of zone z; $[kJh^{-1}K^{-1}]$
C_D	Electricity price; [$/kWh]
C_z	Total heat capacity of zone z; $[kJ/K]$
k_{ht}	Heat rate of the radiant heating system; $[kJh^{-1}]$
$N_s(t)$	Spectator schedule
p_1	Constant; 100 [no dimension]
p_2	Constant; 1.7001 $[Pa]$
p_3	Constant; 7.7835 $[Pa]$
p_4	Constant; 1/17.0789 $[Pa]$
p_5	Constant; 0.6228 $[kg_{H_2O}/kg_{air}]$
P_{atm}	Atmospheric air pressure; $[Pa]$
P_{par}	Partial vapor pressure; $[Pa]$
P_{sat}	Saturated vapor pressure; $[Pa]$
Q_z^{leak}	Air leakage from zone z; $[m^3/hr]$
Q_z^{max}	Maximum volumetric air flow through fans in zone z; $[m^3/hr]$
$q_{fv,z}(t)$	Effect of operation of ventilation system on temperature of zone z; $[kJh^{-1}]$
$q_{re,z}(t)$	Respiration heat of the spectators; $[kJh^{-1}]$
$q_{rad,z}(t)$	Effect of radiation heat transfer on temperature of zone z; $[kJh^{-1}]$
ρ_a	Density of air; 1.27 $[kg/m^3]$
ϕ_z^{max}	Maximum relative humidity set point of zone z; [%]
ϕ_z^{min}	Minimum relative humidity set point of zone z; [%]
$\theta_{out}(t)$	Ambient air temperature; $[^\circ C]$
θ_z^{set}	Inside temperature set point
θ_z^{fv}	Discharge air temperature of ventilation system; $[^\circ C]$
θ_x	Temperature of ice rink zone; $[^\circ C]$
θ_y	Temperature of ceiling zone; $[^\circ C]$
θ_z^l	Inside temperature lower limit; $[^\circ C]$
θ_z^u	Inside temperature upper limit $[^\circ C]$
τ	Time interval length
U	Thermal transmittance for heat transfer between ambient and inside air; $[W/(m^2K)]$

V_z	Volume of zone z; $[m^3]$
V_a	Volume of air per volume zone z; [no dimension]
σ	Stephan Boltzmann constant; 5.67 X 10^{-8} $[Wm^{-2}K^{-4}]$
ϵ	Surface emissivity;
ν_z	Effect of operation of dehumidifier on water content of air in zone z; $[kg_{H_2O}/kg_{air}]$
ζ_z	Effect of air leakage on water content of air in zone z; $[kg_{H_2O}/kg_{air}]$
ξ_z	Effect of volumetric air flow on water content of air in zone z; $[kg_{H_2O}/kg_{air}]$
ω_z^{set}	Inside humidity set point
$\omega_{out}(t)$	Water content of outside air; $[kg_{H_2O}/kg_{air}]$
$\omega_{rs,z}(t)$	Effect of resurfacing on water content of air in zone z; $[kg_{H_2O}/kg_{air}]$
$\omega_{fv,z}(t)$	Effect of operation of ventilation system on water content of air in zone z; $[kg_{H_2O}/kg_{air}]$
$\omega_{s,z}(t)$	Moisture due to spectators; $[kg_{H_2O}/kg_{air}]$
ω_{dh}^{max}	Maximum rate of dehumidifier; $[kg_{H_2O}/h]$
$\theta_{max}, \omega_{max}$	Constants for linearization purpose

3.2 Introduction

This chapter will first discusses the supervisory control strategy using the optimization model proposed for the existing climate control systems of indoor ice rinks. The detailed discussion of the development of the proposed mathematical model including objective functions, and different constraints associated with the indoor humidity and temperature dynamics, is then discussed. Finally, the chapter will present various parameters used in the model, their calculations, and also the linearization techniques to make the model linear to suit real-time applications.

3.3 Supervisory Control Strategy of Climate Control Systems

Some of the earlier indoor ice rinks adopted electro-mechanical relays, switches and motor starters for the control of refrigeration of ice and Heating, Ventilation, and Air-Conditioning (HVAC) systems. However, in recent years, the electro-mechanical systems are being replaced by Programmable Logic Controllers (PLCs) to monitor and control temperature and humidity conditions. Proportional-Integral-Derivative (PID) controllers have superseded conventional relay logic to improve the overall control of temperature, pressure and flow rates. Also, integration of an operator console with PLCs and development of a customized operator interface makes the entire system convenient to use and also saves time [40]. For these types of control systems, it is possible to develop optimal supervisory control strategies, as discussed next.

3.3.1 Proposed Operational Strategy

The control scheme in the present work is designed to provide optimal energy management considering weather conditions, electricity price information and end-user preferences representing the ON-OFF decisions of the smart climate control devices. With the development of weather prediction tools, it is now possible to obtain accurate weather forecast updates at short intervals. It is also possible to forecast electricity markets prices such as LMPs and RTPs; for example, in Ontario, Canada, the HOEP is predicted a day ahead and updated every hour. For an indoor ice rink facility, the operation of climate control systems also largely depends on the spectator schedules which could be easily approximated through close observation of previous trends. All this information can be used to improve the performance of the climate control systems for indoor ice rinks.

The architecture of the optimal operational control strategy of the climate control system of an indoor ice rink facility is shown in Figure 3.1. The supervisory optimization engine incorporates forecasts of weather, energy price and number of expected spectators, and the actual end-user preferences to generate optimal operational set points for the current control system in order to reduce total electrical energy costs. The existing feedback climate controller continuously monitors the actual conditions and target parameters of the ice rink facility and turns the devices ON/OFF accordingly. The supervisory controller also monitors the system, and in case of larger discrepancies with the actual conditions, reruns the optimization algorithm and generates new operational set points for the climate controllers.

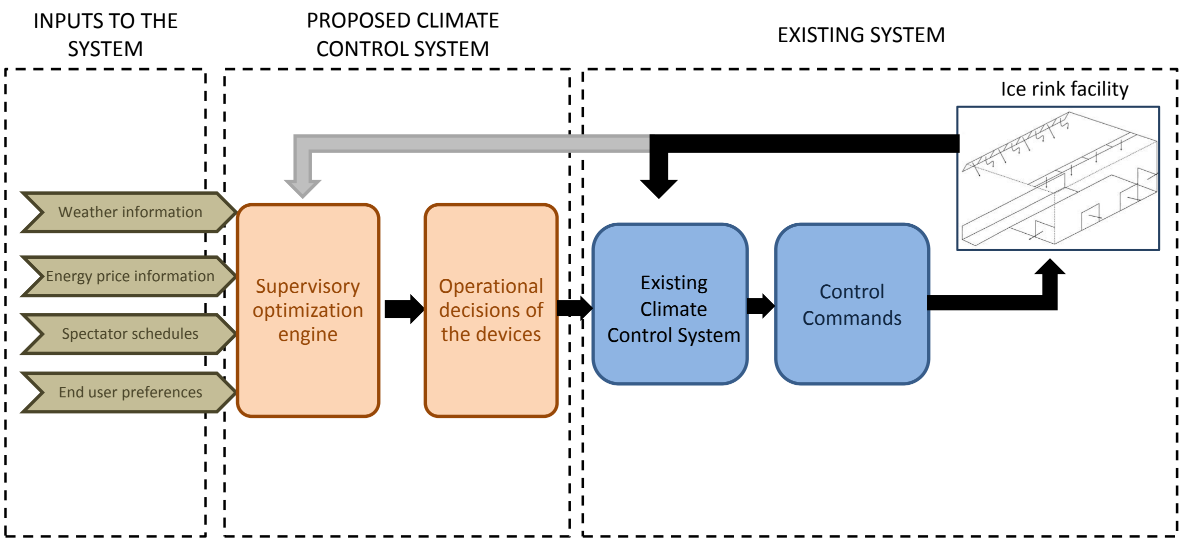

Figure 3.1: Overall architecture of proposed supervisory control system and existing climate control system.

3.3.2 Scheduling Horizon

The proposed optimization model can be simulated for various scheduling horizons (e.g. daily or weekly), depending upon the accuracy of electricity price data and weather forecasts. Considering climate control systems in a typical indoor ice rink facility, a daily scheduling horizon with time intervals of five minutes is considered in the present study.

In a typical indoor ice rink facility, the climate control system comprises a ventilation system, radiant heating system and dehumidifiers. Each of these sub-systems work in co-ordination to maintain the temperature and humidity in the spectator area within predefined ranges and have their own functional behavior, operational constraints and settings in order to operate appropriately. The mathematical model proposed in the present study, which considers these components and their operational constraints is described next. All indices, parameters and variables are defined in the Nomenclature section.

3.4 Objective Function

3.4.1 Minimization of Temperature and Humidity Deviations

This objective seeks to minimize the variations in inside temperature and humidity by closely following their respective set points at every time interval, which effectively maximizes spectator comfort level. This objective is used to simulate the current operation of an existing climate control system for comparison purposes. Thus, the minimization of the sum of the squares of temperature and humidity variations from their respective set points is considered as the objective function as follows:

$$J_1 = \sum_{t \in T} ((\theta_z(t) - \theta_z^{set})^2 + (\omega_z(t) - \omega_z^{set})^2) \tag{3.1}$$

However, the above objective renders the problem non-linear. This is linearized in this work by defining a set of auxiliary variables and constraints as follows:

$$J_1 = \sum_{t \in T} (\theta_1(t) + \theta_2(t) + \omega_1(t) + \omega_2(t)) \tag{3.2}$$

$$\theta_1(t),\, \theta_2(t),\, \omega_1(t),\, \omega_2(t) \geq 0\,; \tag{3.3a}$$
$$\theta_z(t) - \theta_z^{set} = \theta_1(t) - \theta_2(t)\,; \tag{3.3b}$$
$$\omega_z(t) - \omega_z^{set} = \omega_1(t) - \omega_2(t)\,; \tag{3.3c}$$
$$\theta_1(t) \leq S_t(t)\,\theta_{max}\,; \tag{3.3d}$$
$$\theta_2(t) \leq (1 - S_t(t))\,\theta_{max}\,; \tag{3.3e}$$
$$\omega_1(t) \leq S_h(t)\,\omega_{max}\,; \tag{3.3f}$$
$$\omega_2(t) \leq (1 - S_h(t))\,\omega_{max}\,; \tag{3.3g}$$

3.4.2 Minimization of Electrical Energy Costs

This objective seeks to minimize the total electrical energy cost of operation of the climate control system over the entire scheduling horizon. It incorporates power consumption of the devices with their ON-OFF decisions to calculate the electrical energy cost. This objective function is defined as follows:

$$J_2 = \sum_{t \in T} \sum_{i \in A} \tau \, C_D(t) \, P_i \, S_i(t) \tag{3.4}$$

The effect of operation of climate control devices, heat loss through leakage, outdoor atmospheric conditions, heat transfer between the zones and miscellaneous heat loads including lighting, resurfacing of ice and number of spectators affect the variation of indoor temperature and humidity of an indoor ice rink facility. Thus, the developed model should be able to control these variations within predefined ranges, while taking into consideration the technical aspects of the operation of climate control devices. The model constraints representing these requirements are described next.

3.5 Inside Humidity Dynamics

Moisture content of inside air in an indoor ice rink facility is affected by several factors such as ventilation, infiltration, number of spectators, and resurfacing. Due to its basic nature, moisture condenses on colder surfaces which is quite significant in the case of ice rinks, because of the large area of ice surface and indoor ventilation. Resurfacing using hot water and air infiltration causes more moisture to be released into the air. Also moisture introduced by spectators depends on the event schedules and may vary over a day. The inside relative humidity should be kept such as to maintain comfortable conditions for spectators as well as quality of the ice sheet.

Relative humidity inside an ice rink facility can be defined as [17]:

$$\phi = \frac{P_{par}}{P_{sat}} 100\% \tag{3.5}$$

where the partial vapor pressure and saturated vapor pressure can be approximated by:

$$P_{par} = \frac{\omega P_{atm}}{p_5} \tag{3.6}$$

$$P_{sat} = p_1 \, (-p_2 \, + \, p_3 \, e^{p_4 \theta} \,) \tag{3.7}$$

The saturated vapor pressure can be linearized using Taylor's series expansion and ignoring higher order terms as follows:

$$P_{sat} = p_1 \left(-p_2 + p_3 \, e^{p_4(\frac{\theta^l + \theta^u}{2})} \, (1 + p_4(\theta - (\frac{\theta^l + \theta^u}{2}))) \right) \tag{3.8}$$

3.5.1 Operational Constraints

In order to model relative humidity, water content of air inside the ice rink facility is modeled using the following constraint:

$$\begin{aligned} \omega_z(t) = \omega_z(t-1) + \tau \, [\omega_{fv}(t) + \zeta_z(\omega_{out}(t) - \omega_z(t)) \\ + \omega_{rs}(t) + \omega_s N_s(t) - \nu_z \, S_{dh,z}(t)] \quad \forall t \in T \end{aligned} \tag{3.9}$$

This represents the water content of inside air at time t as a function of the water content at time $t-1$; effect of operation of ventilation fans and dehumidifiers; moisture loss through leakage; moisture produced due to resurfacing; and number of spectators in the facility.

To guarantee that relative humidity of inside air is kept within the minimum and maximum relative humidity limits, the following constraints are used:

$$\omega_z(t) \leq \phi_z^{max} \frac{p_1 p_5}{P_{atm}} (-p_2 + p_3 \, e^{p_4 \theta}) \tag{3.10a}$$

$$\omega_z(t) \geq \phi_z^{min} \frac{p_1 p_5}{P_{atm}} (-p_2 + p_3 \, e^{p_4 \theta}) \tag{3.10b}$$

The operation states of ventilation system and dehumidifier are binary variables as follows:

$$S_{fv,z}(t) = \begin{cases} 1 & \text{if device is ON} \\ 0 & \text{if device is OFF} \end{cases} \quad \forall t \in T \tag{3.11}$$

$$S_{dh,z}(t) = \begin{cases} 1 & \text{if device is ON} \\ 0 & \text{if device is OFF} \end{cases} \quad \forall t \in T \tag{3.12}$$

3.5.2 Parameters

It is assumed that the air circulated by the ventilation unit has the same humidity as the outside air; hence, the equation for water content in air, due to ventilation, can be written as follows:

$$\omega_{fv}(t) = \xi_z S_{fv,z}(t)(\omega_{out}(t) - \omega_z(t)) \tag{3.13}$$

Here, ξ_z takes into account the effect of operation of ventilation fans inside the facility; hence, its value will depend upon the maximum volumetric air flow rate of fans in the spectator zone. This can be calculated from the measurements or estimations from simple performance tests using the following formula:

$$\xi_z = Q_z^{max}/(V_a V_z) \tag{3.14}$$

Similarly, ζ_z takes into account the effect of air leakage and infiltration due to outside air and can be calculated using:

$$\zeta_z = Q_z^{leak}/(V_a V_z) \tag{3.15}$$

The value of parameters ω_{rs} and ω_s will depend upon resurfacing and spectator schedules respectively. Thus, ω_{rs} is a constant, representing moisture content in air, given in $\mathrm{kg_{H_2O}}/\ \mathrm{kg_{air}}$, for each resurfacing operation. The total moisture due to spectator volume is calculated by using spectator schedules over the scheduling horizon.

The effect of the operation of the dehumidifier is taken into account by introducing the parameter ν_z. Its value depends on the maximum moisture removal capacity of dehumidifier and can be calculated using:

$$\nu_z = \omega_{dh}^{max}/(\rho_a V_a V_z) \tag{3.16}$$

3.6 Inside Temperature Dynamics

The temperature distribution inside an ice rink facility is a complex phenomenon. In order to appropriately model the variation of temperature of the spectator zone, many factors are taken into account, such as operation of ventilation and radiant heating system, heat transfer between the surfaces, heat loss though the walls and air leakage, and the effect of operation of miscellaneous heat loads such as lighting, resurfacing and spectator heat. Also, the temperature has to be maintained within the specified ranges ensuring spectator comfort conditions.

3.6.1 Operational Constraints

The following constraint represents the temperature of the spectator zone at time t as a function of its temperature at time $t-1$; operational status of ventilation fans and radiant heating system; heat loss through walls and air leakage; miscellaneous heat loads due to resurfacing, lighting and number of spectators; and radiation heat transfer between the zones:

$$\begin{aligned}\theta_z(t) = \theta_z(t-1) + \frac{\tau}{C}_z [k_{ht,z} S_{ht,z}(t) + \alpha_z(\theta_{out}(t) - \theta_z(t)) \\ + q_{fv,z}(t) + q_{misc,z}(t) + q_{re,z}(t) N_s(t) \\ + q_{rad,z}(t)] \quad \forall t \in T\end{aligned} \tag{3.17}$$

In order to maintain the indoor temperature of the ice rink facility within a specified range, the following constraint is used:

$$\theta_z^l \leq \theta_z(t) \leq \theta_z^u \tag{3.18}$$

The operational state of the radiant heating system is considered a binary variable as follows:

$$S_{ht,z}(t) = \begin{cases} 1 & \text{if device is ON} \\ 0 & \text{if device is OFF} \end{cases} \quad \forall t \in T \tag{3.19}$$

3.6.2 Parameters

The radiant heating system is the major source of heat within the ice rink facility and the temperature of the spectator area will depend on its maximum radiant heat capacity. However, not all energy radiated is transferred to the zone and depends on the system efficiency, the range covered and the distance between spectators and radiant heaters. The parameter k_{ht} takes into account these factors, and can be calculated using:

$$k_{ht,z} = P_{ht}^{max} \eta_{ht} \times 3.6; [(kJh^{-1}] \tag{3.20}$$

The effect of leakage can be simulated considering the thermal transmittance, U value, and air leakage from the spectator zone as follows:

$$\alpha_z = UA_z + \rho_a c_a Q_z^{leak}; [kJh^{-1}K^{-1}] \tag{3.21}$$

The ventilation system is a "built up make-up" air unit (100% outside air) with electric heating and no re-circulation. During cold climatic conditions, the outside air is first passed through an electric heating system to raise its temperature to the discharge air set-point. The thermal effect of forced air ventilation, as a function of the operation of fans, their volumetric air flow rate, and temperature difference between discharge air from the ventilation unit and indoor air can be expressed as:

$$q_{fv,z}(t) = \beta_z S_{fv,z}(t)\,(\theta_z^{fv} - \theta_z(t)) \tag{3.22}$$

Here, the parameter β_z can be calculated from measurements or estimations from simple performance tests using the following formula:

$$\beta_z = \rho_a c_a Q_z^{max}; [kJh^{-1}K^{-1}] \tag{3.23}$$

Equation (3.23) renders the model non-linear because of the presence of bi-linear terms. However, the technique used in [16] can be adopted to linearize the equation; thus, the term $S_{fv,z}(t)\,\theta_z(t)$ is converted to a linear form as follows: Assuming $\theta_z(t)$ is bounded by $\theta_z^l \leq \theta_z(t) \leq \theta_z^u$, a new variable μ is introduced such that $\mu = S_{fv,z}(t)\,\theta_z(t)$; the following constraints are then used to model the linearized equivalents:

$$\mu \geq \theta_z(t) - (1 - S_{fv,z}(t))\,\theta_z^u \tag{3.24a}$$

$$\mu \leq \theta_z(t) \tag{3.24b}$$

$$S_{fv,z}(t)\,\theta_z^l \leq \mu \tag{3.24c}$$

$$\mu \leq S_{fv,z}(t)\,\theta_z^u \tag{3.24d}$$

The heat transfer phenomenon between the zones play an important role in governing their respective temperatures. In order to take into account the radiation heat transfer between zones, the indoor ice rink facility is divided into three zones: spectator zone, ice rink zone and ceiling zone. This study is focused on determining the temperature variation in the spectator zone; hence, the effect of radiation heat transfer from the other two zones is calculated as follows:

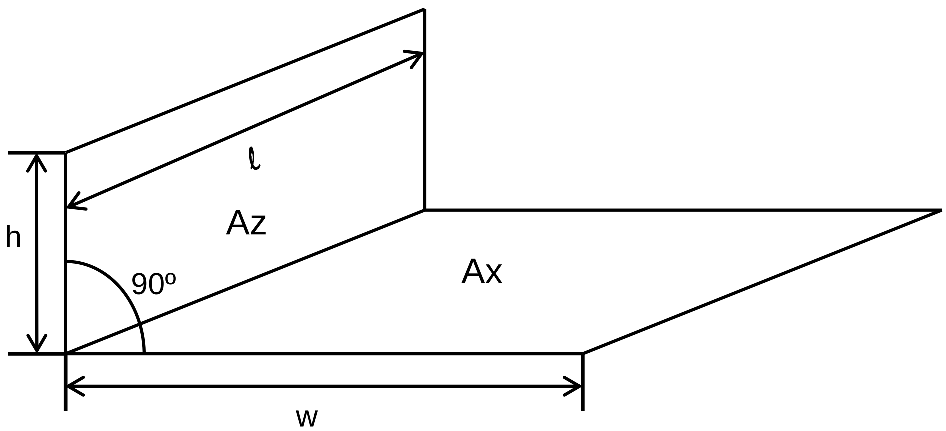

Figure 3.2: Calculation of the geometric configuration factor for the spectator zone and ice rink zone [42].

$$
\begin{aligned}
q_{rad,z}(t) &= \sigma A\epsilon F_{x,z}(\theta_x^4(t) - \theta_z^4(t)) \\
&+ \sigma A\epsilon F_{y,z}(\theta_y^4(t) - \theta_z^4(t))
\end{aligned} \tag{3.25}
$$

The above Stephan-Boltzmann equation makes the model non-linear; however, since the scheduling interval is assumed to be five minutes, i.e. variation in inside temperature is calculated for every five minutes, the equation can be closely approximated as follows [41]:

$$
\begin{aligned}
q_{rad,z}(t) &= 4\sigma A\epsilon F_{x,z}\theta_x(t)(\theta_x(t) - \theta_z(t)) \\
&+ 4\sigma A\epsilon F_{y,z}\theta_y(t)(\theta_y(t) - \theta_z(t))
\end{aligned} \tag{3.26}
$$

$F_{(x/y),z}$ is the geometric configuration factor that considers relative orientation and distance between the zones in order to account for the value of actual radiative heat transfer. This can be calculated as follows [42]: For $H = h/l$ and $W = w/l$, as shown in Figure 3.2, the geometric configuration factor is given by:

$$F_{x,z} = \frac{1}{W\pi}(Wtan^{-1}\frac{1}{W\pi} + Htan^{-1}\frac{1}{H\pi} - \sqrt{H^2+W^2}\,tan^{-1}\sqrt{\frac{1}{H^2+W^2}}$$
$$+ \frac{1}{4}\left(\frac{(1+W^2)(1+H^2)}{1+H^2+W^2}\left[\frac{W^2(1+H^2+W^2)}{(1+W^2)(W^2+H^2)}\right]^{W^2}\left[\frac{H^2(1+H^2+W^2)}{(1+H^2)(W^2+H^2)}\right]^{H^2}\right)) \tag{3.27}$$

Similarly, the geometric configuration factor can be calculated between the spectator and ceiling zones as well.

3.7 Summary

A comprehensive mathematical model for the operation of climate control devices including radiant heating and ventilation systems, and dehumidifiers was developed in this chapter. The mathematical details of the indoor humidity and temperature dynamics were presented, and methods to linearize the model were also discussed. The chapter also presented approaches to estimate the various parameters of the thermal system of the indoor ice rink facility using empirical relationships.

Chapter 4

Case Studies

4.1 Introduction

Several case studies are conducted to test the performance of the mathematical model proposed in Chapter-3 for a typical indoor ice rink facility. Realistic input data is used for outside temperature and humidity, electricity prices, and number of spectators. The total electrical energy cost savings are calculated for two different pricing schemes, i.e. TOU and RTP (referred to as HOEP) for the province of Ontario, Canada. Finally, the effectiveness of the model is tested by running multiple simulations incorporating uncertainties in electricity price, weather forecasts, and number of spectators using a Monte Carlo Simulation approach. A detailed discussion of the case studies and analysis of the results is also presented in this chapter.

4.2 Indoor Ice Rink Data

The case studies are performed considering an actual indoor ice rink facility, and the parameters and device ratings are suitably chosen to suit a real-time application of the model. Data and information of an actual indoor ice rink facility are taken from [32]. The considered indoor ice rink facility is 42 m wide, 64 m long and 9.36 m high, with an ice sheet of 26 x 61 m as shown in Fig. 4.1. Six rows of stands run the whole length of the building and there are a total of 200 seats for spectators. Eight radiant heating units, of 176 kW total capacity, provide local heating to spectators and ventilation is performed by air inlets intercalated between the radiant heating units with a total capacity of 4000 L/s.

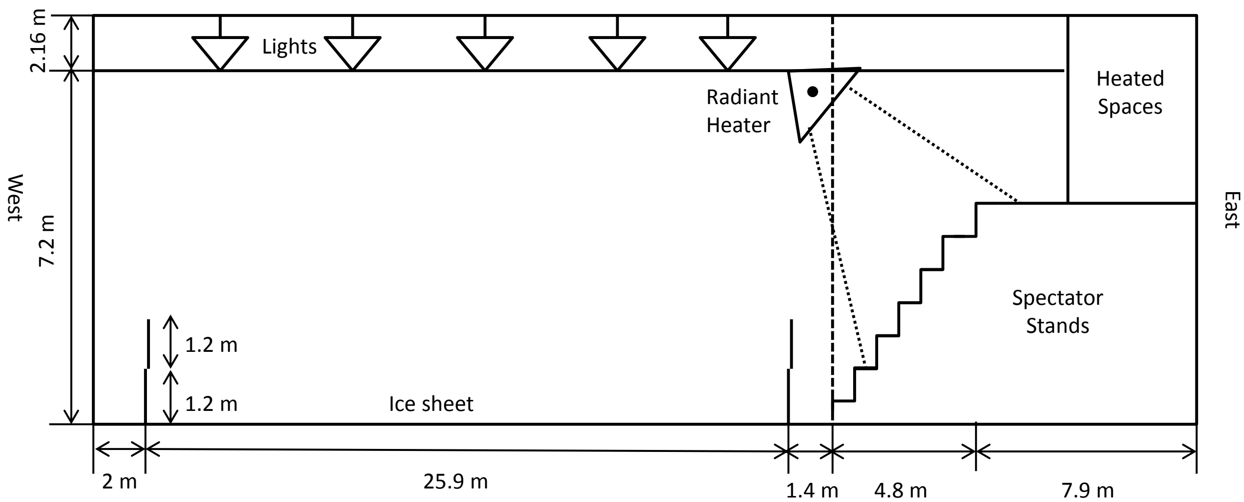

Figure 4.1: Indoor ice rink facility [32].

The ventilation system is a "built up make-up" air unit (100% outside air) with electric heating. Two dehumidifiers of 30 kW total capacity are diagonally located at the corners of the ice rink to provide dehumidification. The spectator, resurfacing and lighting schedules are taken from [43].

4.3 Simulation Scenarios

The performance of the mathematical model presented in Chapter-3 for a typical indoor ice rink facility is examined by means of the following two scenarios:

- Minimization of indoor temperature and humidity deviations from their respective set-points (Case 0): The model tries to closely follow the pre-specified set points for indoor temperature and humidity to maximize spectator comfort, while maintaining all the indoor temperature, indoor humidity and operational constraints over the entire scheduling horizon. This basically represents the way these climate controllers are operated at present.
- Minimization of total electrical energy costs (Case 1): The objective is to minimize total electrical energy cost of the ice rink facility considering two different pricing schemes.

Based on the different objectives, optimal operational schedules of climate control systems including radiant heating system, ventilation system, and dehumidification system are obtained.

4.4 Results and Discussions

4.4.1 Daily Energy Cost Savings

The proposed mathematical model incorporates outside climatic conditions i.e. ambient air temperature and humidity, and electricity price information as the inputs. Figures 4.2 and 4.3 present the input data for a particular winter day in Toronto, Canada, on January 23, 2012 [36, 37].

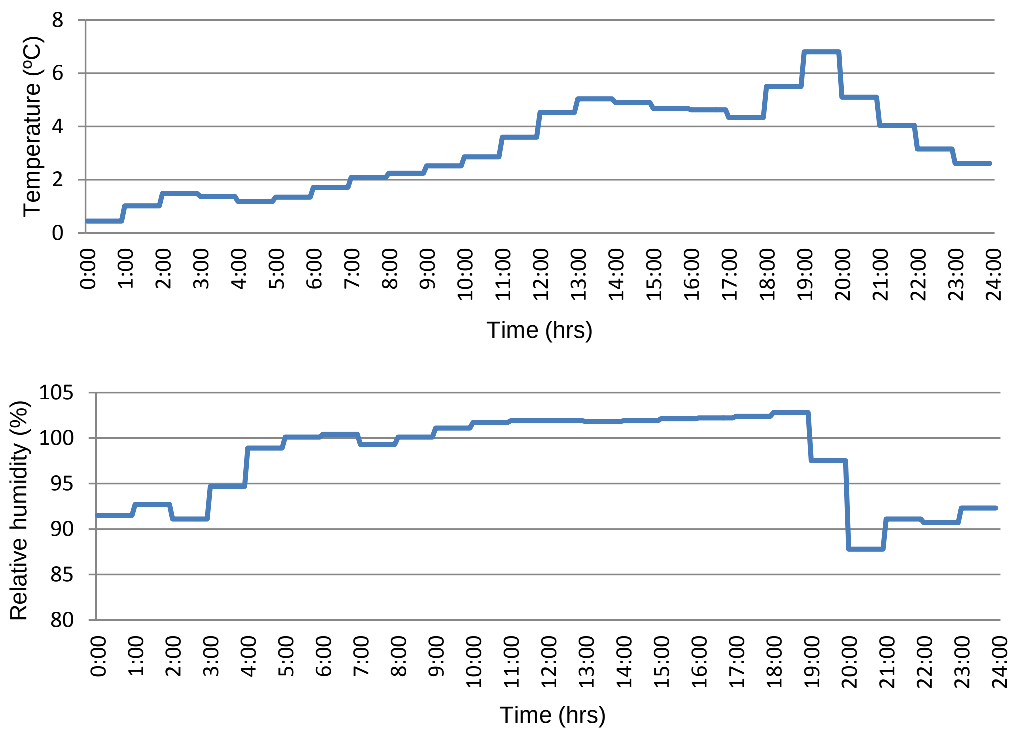

Figure 4.2: Temperature and humidity profiles of a typical winter day in Toronto [36].

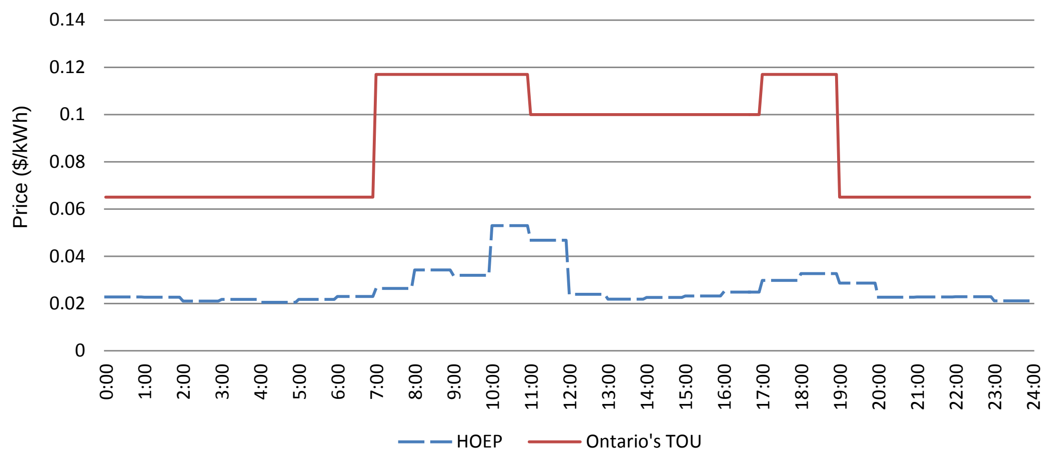

Figure 4.3: Electricity price information of a typical winter day in Ontario, Canada [16].

Figures 4.4 and 4.5 present the optimal operational schedules of the radiant heating system with two different pricing schemes, HOEP and TOU, obtained for Case 0 and Case 1. It can be observed that in Case 0, with comfort maximization as the objective, the radiant heating system is turned ON more frequently in order to minimize the deviations of temperature from the set point. However, in Case 1, with the objective to minimize the total electrical energy costs, the radiant heating system is turned ON during the intervals when the electricity price is low, as expected.

The optimal operational schedules of the ventilation system with HOEP and TOU pricing schemes, obtained for both cases, are shown in Figures 4.6 and 4.7, respectively. Since fresh air has to be continuously circulated inside the facility to maintain air quality, there is not much difference between the number of operations of the ventilation system for Case 0 and Case 1. However, Case 1 seeks to obtain ON decisions considering the lower electricity price periods. Figures 4.8 and 4.9 depict the optimal operational schedules for the dehumidification system; the model tries to maintain the humidity set point for different objectives governing Case 0 and Case 1.

Figures 4.10 and 4.11 illustrate the variation of indoor temperature and humidity for Case 0 and Case 1 obtained for TOU pricing. In Case 0, the model minimizes the deviations in temperature and humidity by closely following the set points, for the climate control system, including radiant heating system, ventilation system and dehumidification. For Case 1, the indoor temperature and humidity varies within predefined ranges to minimize the total electrical energy costs of the operation of climate control systems while maintaining all the operational constraints.

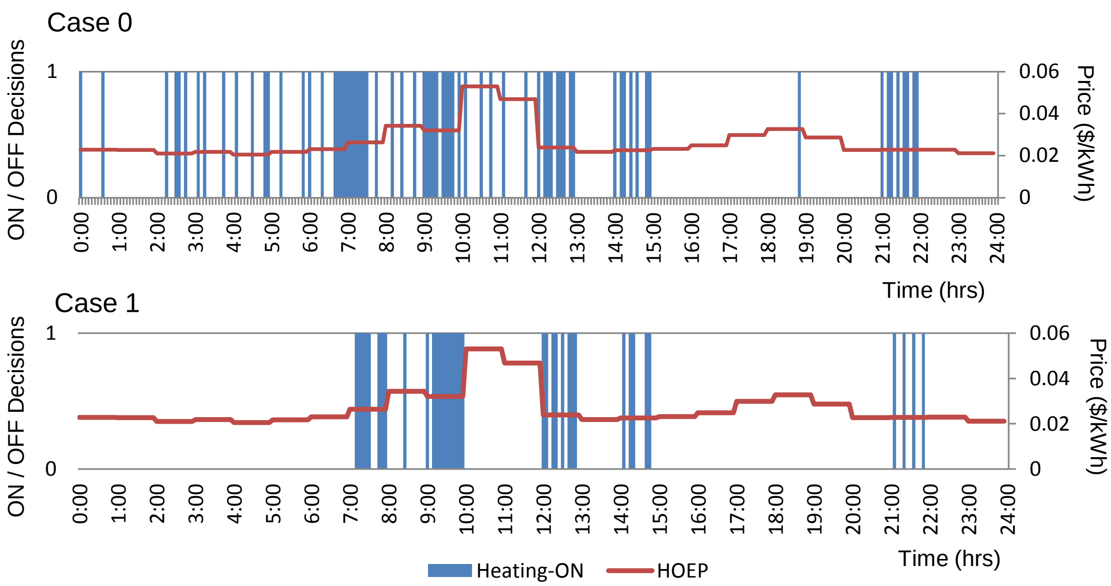

Figure 4.4: Optimal operational schedules of radiant heating system with HOEP.

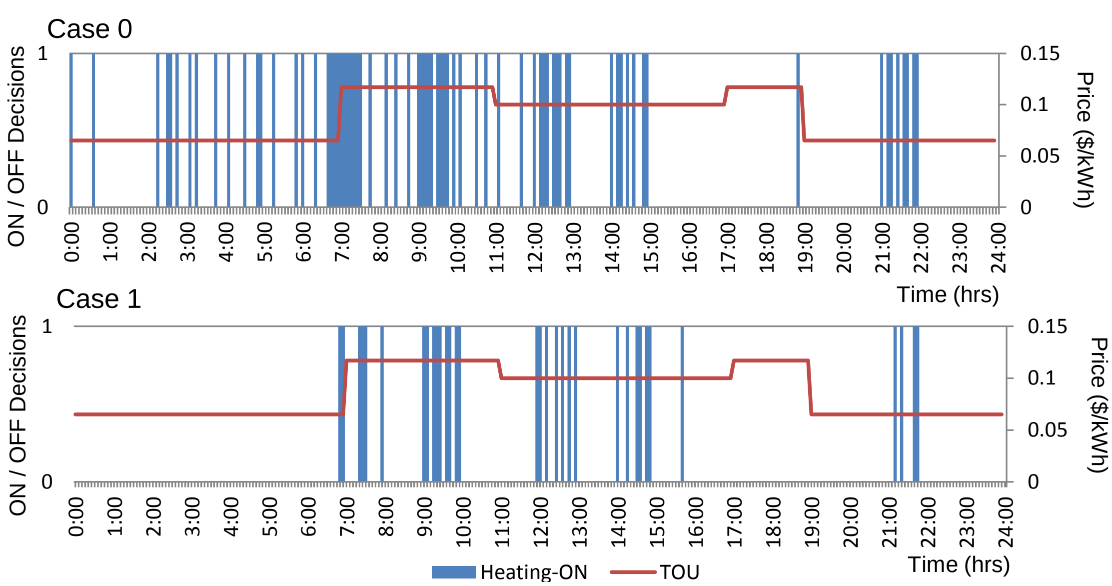

Figure 4.5: Optimal operational schedules of radiant heating system with TOU.

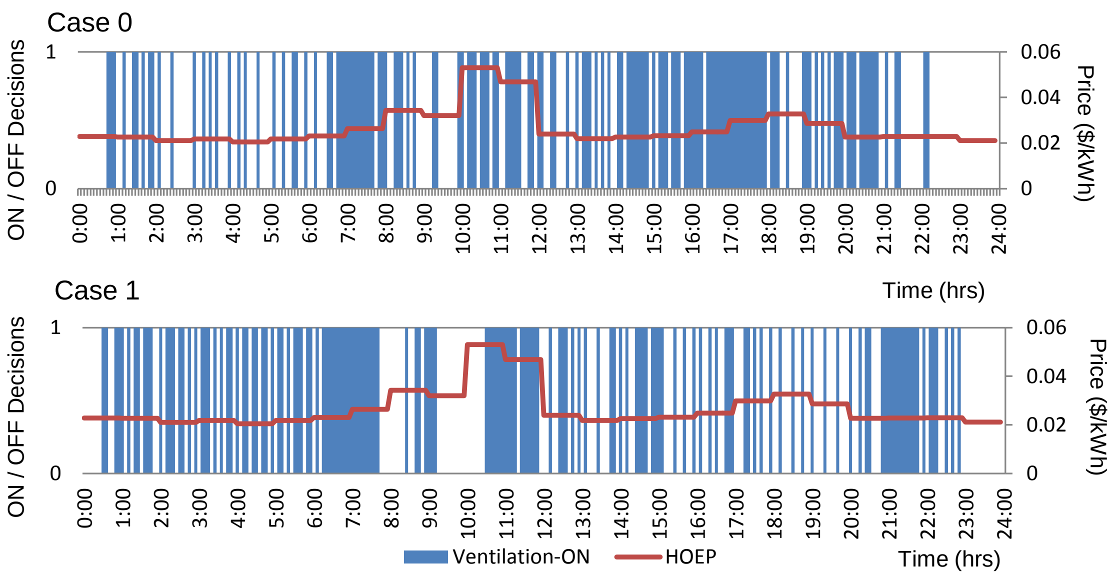

Figure 4.6: Optimal operational schedules of ventilation system with HOEP.

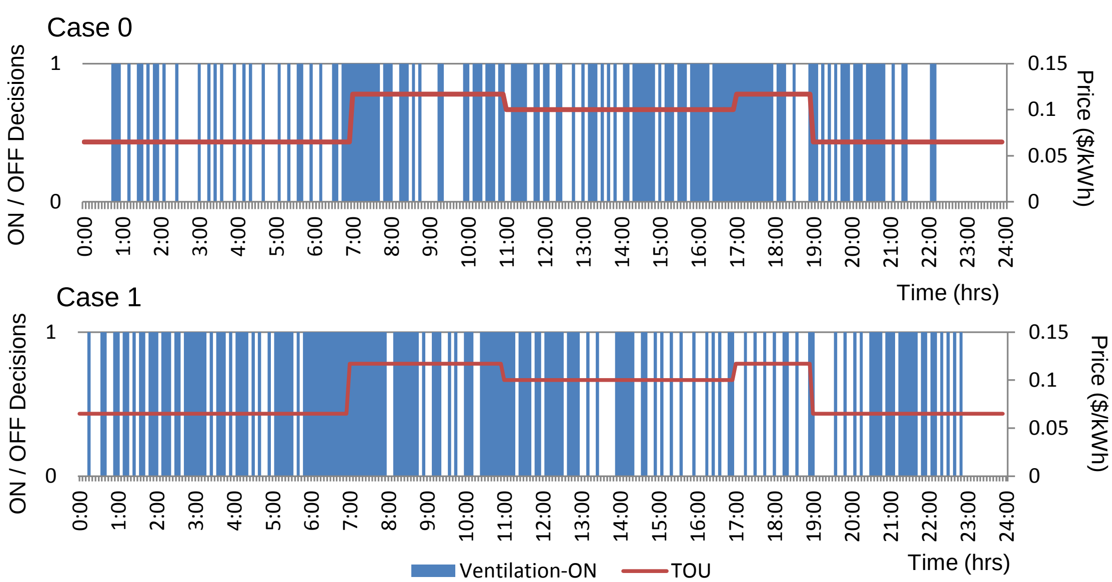

Figure 4.7: Optimal operational schedules of ventilation system with TOU.

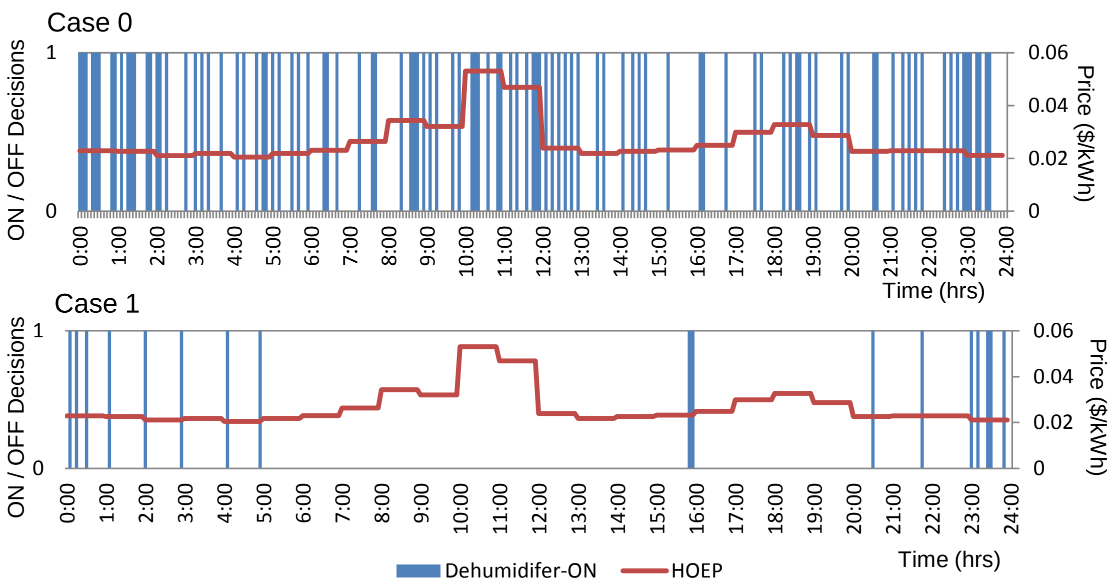

Figure 4.8: Optimal operational schedules of dehumidification system with HOEP.

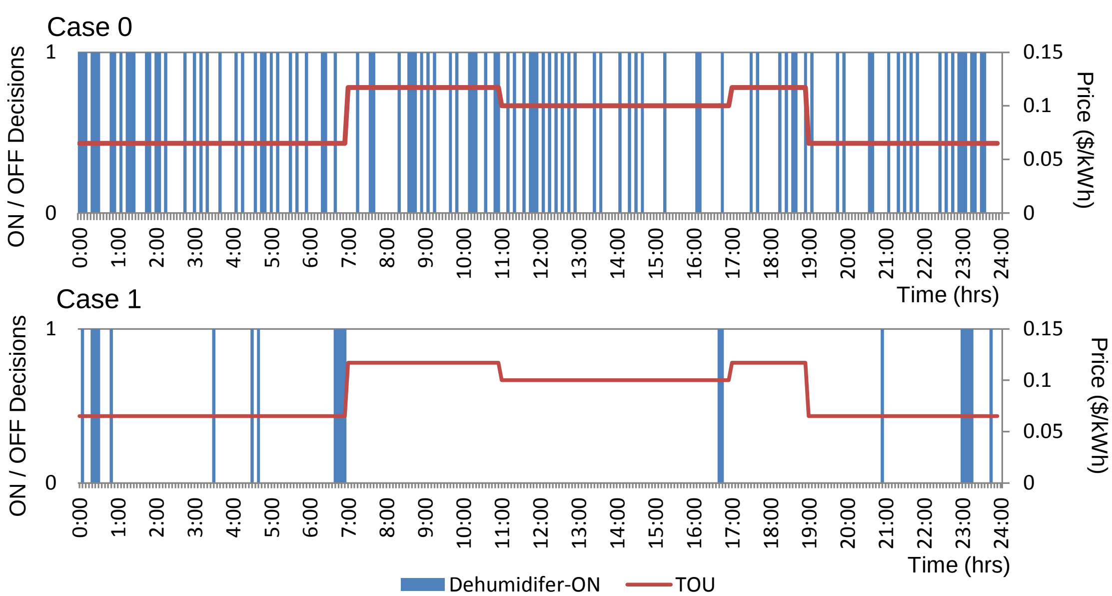

Figure 4.9: Optimal operational schedules of dehumidification system with TOU.

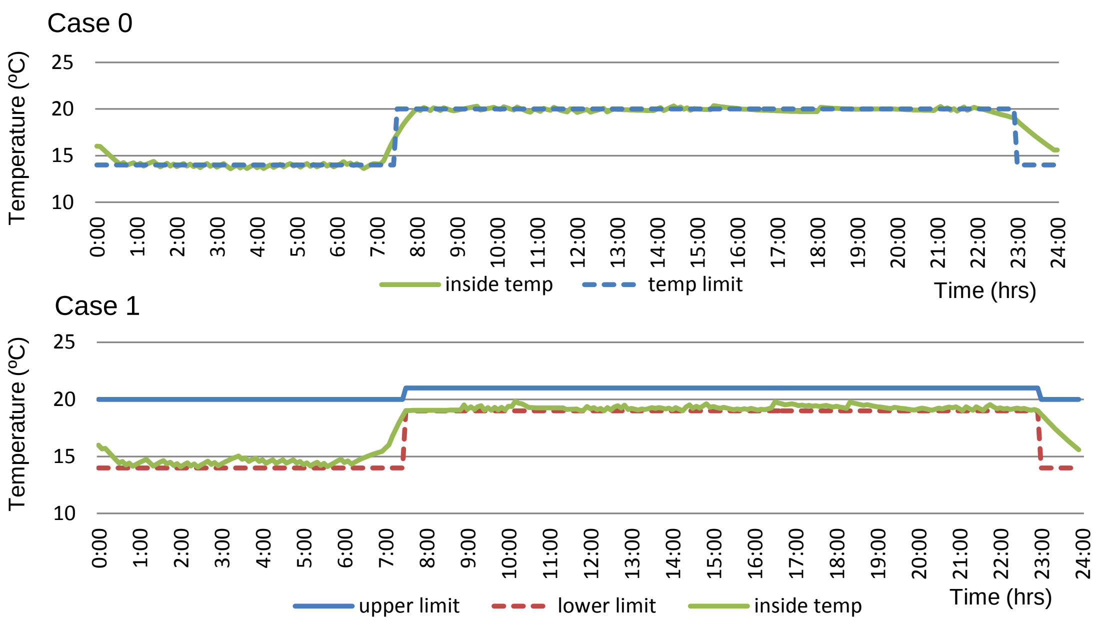

Figure 4.10: Variation of the temperature of the spectator zone over the scheduling horizon.

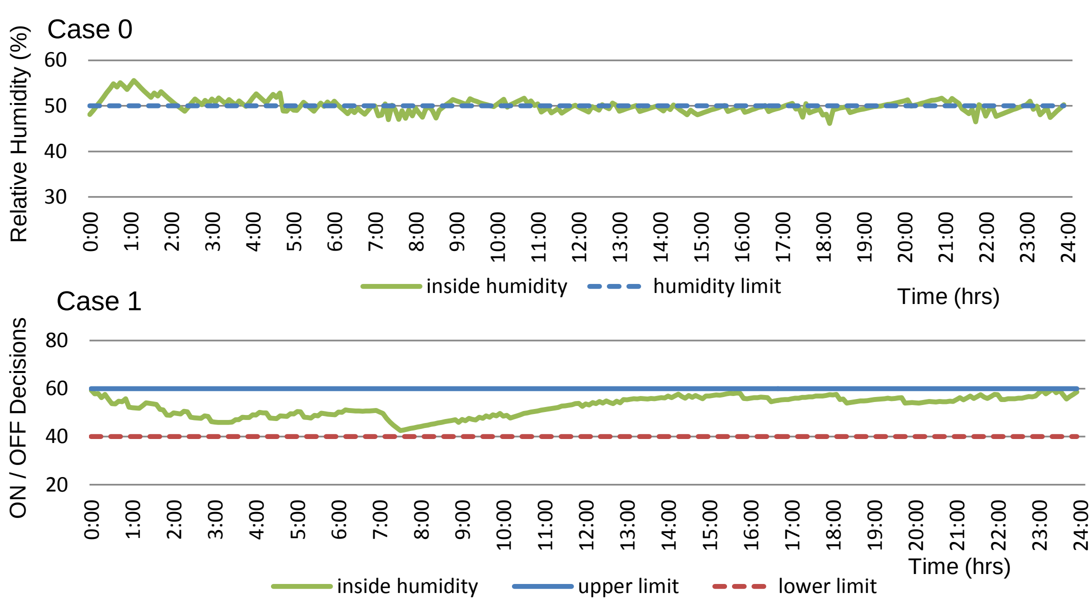

Figure 4.11: Variation of the humidity of the spectator zone over the scheduling horizon.

Table 4.1: Comparison of daily electrical energy cost for different pricing schemes for a typical winter day

Devices	RTP (HOEP)			TOU		
	Case 0 ($/day)	Case 1 ($/day)	Savings (%)	Case 0 ($/day)	Case 1 ($/day)	Savings (%)
Radiant Heating	30.144	11.727	61.096	108.623	49.073	54.823
Ventilation System	19.968	20.199	-1.160	58.247	62.906	-7.998
Dehumidifier	3.168	1.123	64.558	12.010	2.925	75.731
Total	53.280	33.049	37.970	178.880	114.903	35.765

Table 4.1 presents a comparison of electrical energy costs for the operation of the radiant heating system, ventilation system and dehumidifiers of the indoor ice rink facility on a typical winter day, for both, RTP (HOEP) and TOU. As compared to Case 0, there is more than a 35% reduction in total energy costs in Case 1 for both pricing schemes. Although the cost of operation of radiant heating system is the highest, its optimal operational schedule in Case 1 results in more than 50% energy savings for both RTP and TOU pricing. The ventilation system does not yield any savings, since it optimally operates to replace inside air with outside fresh air to maintain indoor air quality. The dehumidifiers show more than 60% reduction in energy costs through shifting their operation to lower energy price intervals. The electrical energy costs obtained with HOEP are quite low as compared to TOU, because of their difference in electricity price per kWh, depicted in Figure 4.3.

4.4.2 Annual Energy Cost Savings

In order to determine the annual energy cost savings of the ice rink facility from the application of optimization model, it is necessary to assess the model for different input conditions, considering the uncertainty in electricity price, weather forecasts and spectator schedules. These are modeled using Monte Carlo simulations, and the expected energy savings are calculated over the period of 8 months from September 15, 2011 to May 14, 2012, which is typically the duration of the operation of an indoor ice rink facility in Canada. Since the electricity price per hour and the spectator schedules vary considerably between weekdays and weekends, the entire study is carried out separately, for weekdays and weekends. Multiple simulations are performed by using actual data of HOEP, outside temperature and humidity during the 8 months, for weekdays and weekends. Figures 4.12 and 4.13 present the average temperature and humidity monthly profiles for weekdays and weekends, respectively, obtained from [36]. Figure 4.14 depicts the average profile of HOEP for the 8 months over the 24 hour horizon, both for the weekdays and weekends, obtained from [16].

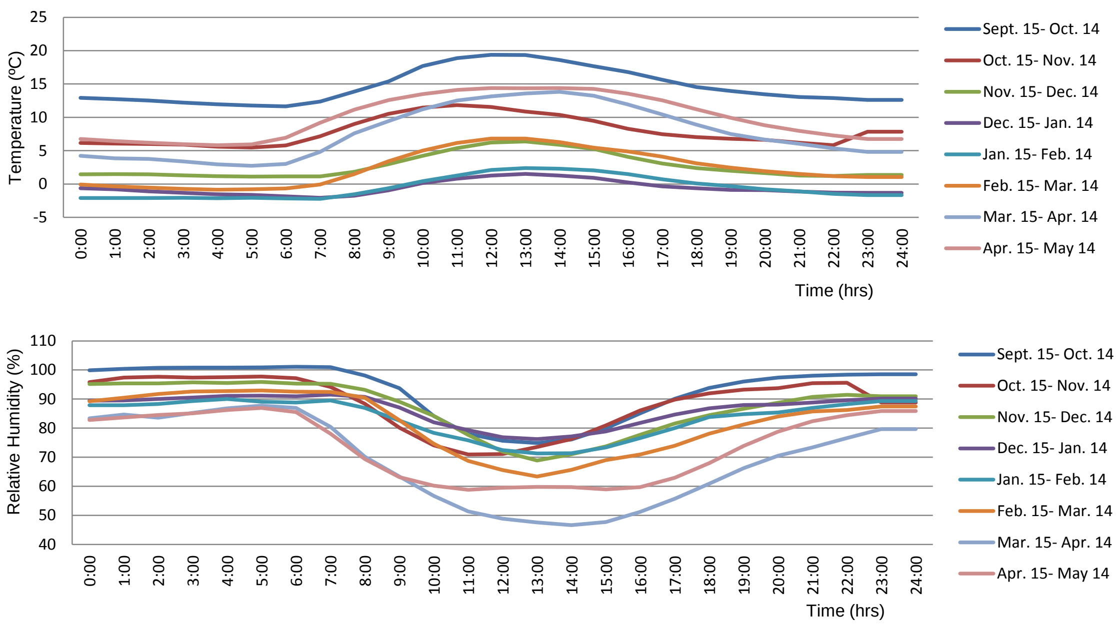

Figure 4.12: Average monthly temperature and humidity profiles for weekdays [36].

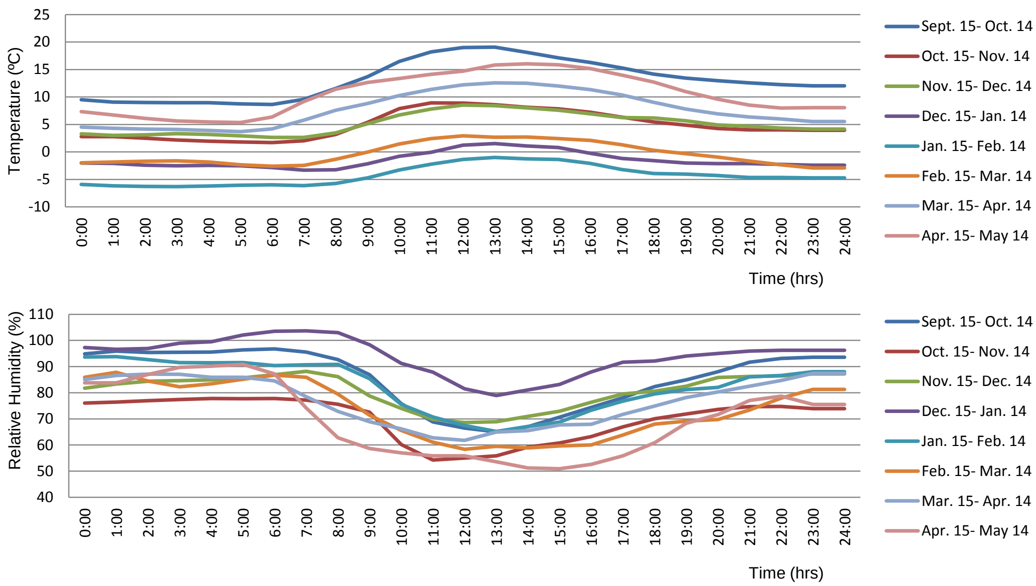

Figure 4.13: Average monthly temperature and humidity profiles for weekends [36].

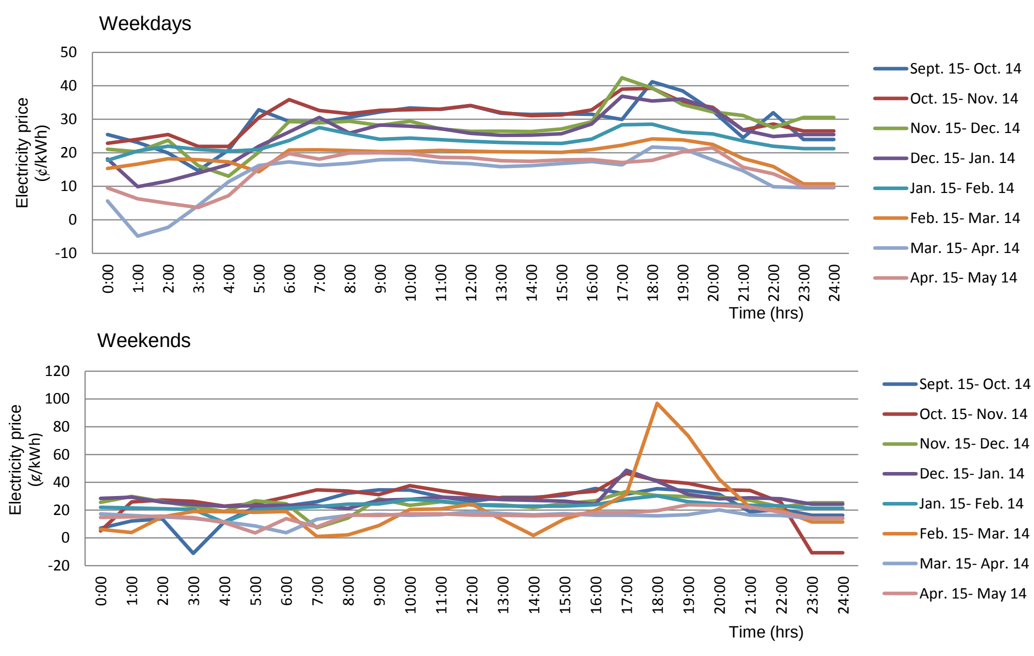

Figure 4.14: Average monthly HOEP profiles for weekdays and weekends [16].

The variability in the HOEP, is obtained by generating random values of the price within specified maximum and minimum limits using a uniform distribution obtained from the available data. Random values of outside temperature and humidity are generated using a normal distribution. The mean and standard deviations for these data and for each time interval were determined using actual weather data for the past 8 months. The uncertainty in spectator schedules is accounted by randomly using minimum and maximum limits on the number of spectators per hour, assuming a uniform distribution.

Figures 4.15 and 4.16 illustrate the maximum, minimum and mean values of outside temperature and humidity used as inputs for the Monte Carlo simulations, for weekdays and weekends, respectively. These values were calculated for each month. Similarly, the maximum, minimum and mean values for the electricity price and number of spectators are shown in Figures 4.17 and 4.18.

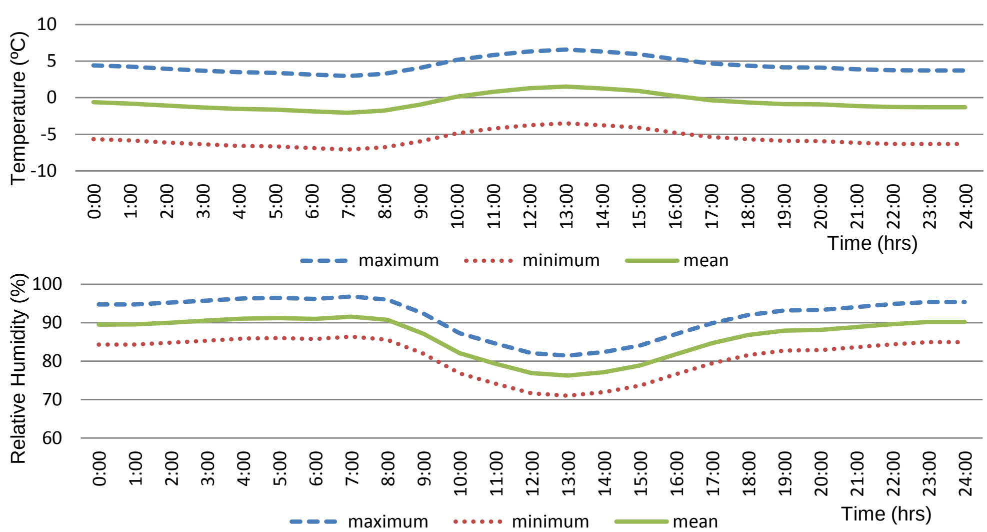

Figure 4.15: Maximum, minimum and mean values of outside temperature and humidity during weekdays for December 15, 2011, to January 14, 2012, for Toronto, Canada.

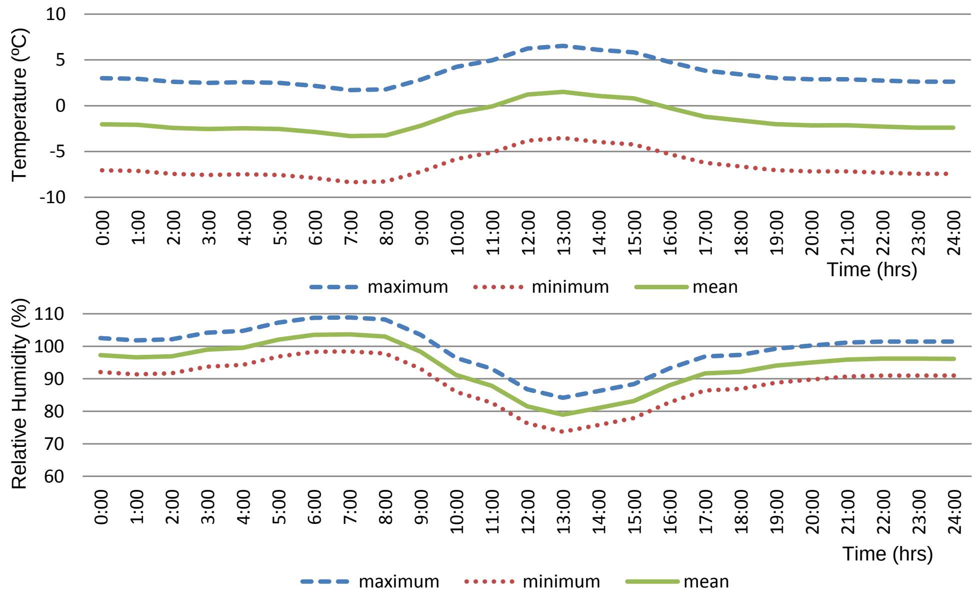

Figure 4.16: Maximum, minimum and mean values of outside temperature and humidity during weekends for December 15, 2011, to January 14, 2012, for Toronto, Canada.

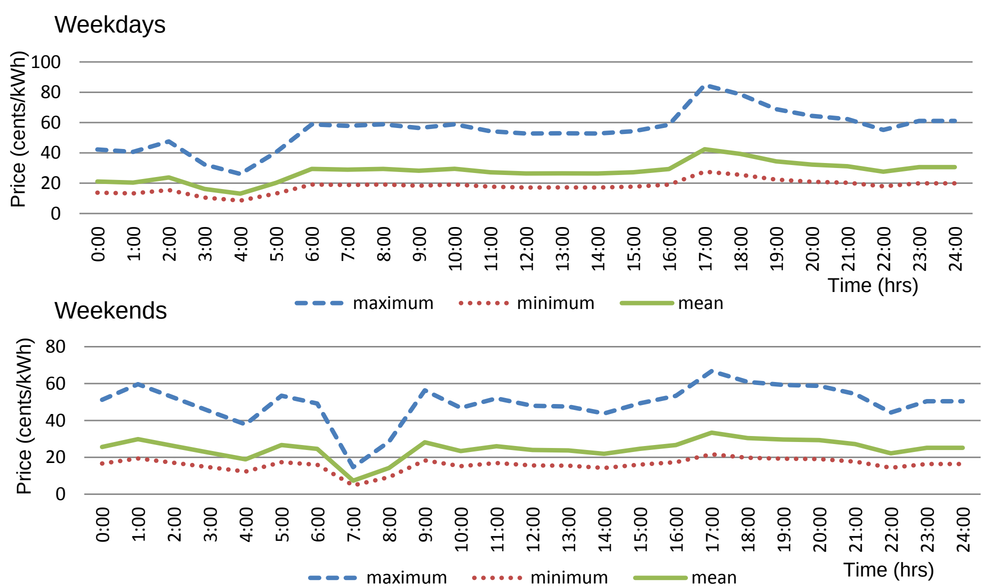

Figure 4.17: Maximum, minimum and mean values of electricity price (HOEP) during weekdays and weekends for November 15, 2011, to December 14, 2011.

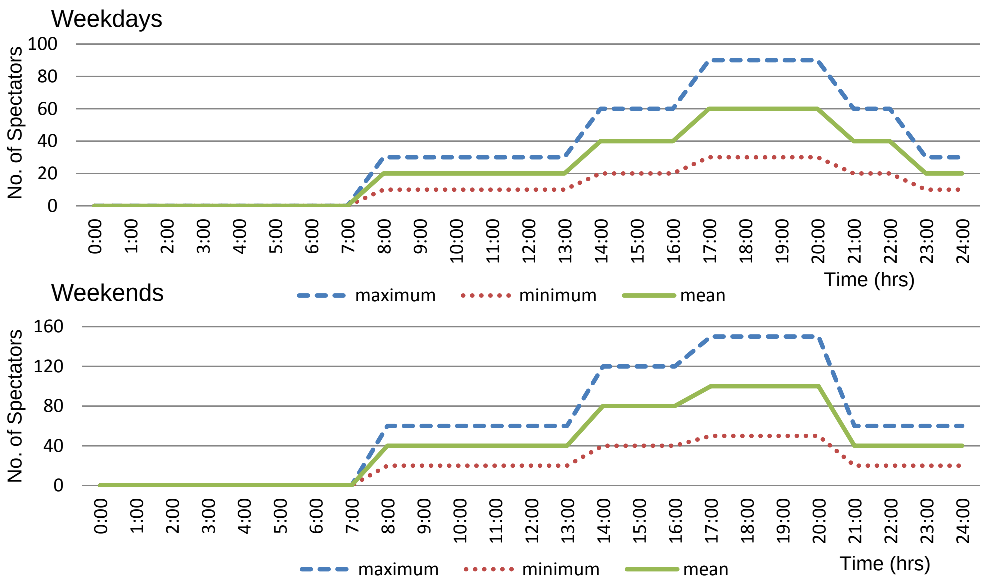

Figure 4.18: Assumed maximum, minimum and mean values of the number of spectators.

Figure 4.19 depicts a comparison of the results obtained from Monte Carlo simulations for Case 0 and Case 1 during the weekdays of the month from January 15, 2012, to February 15, 2012. The simulations are performed for 100 iterations observing that the mean electrical energy cost converge in about 60 iterations. Observe that the cost is significantly reduced in Case 1 as compared to Case 0. These simulations were performed for the weekdays and the weekends of every month over the considered 8-month period.

Figures 4.20 and 4.21 show the average electrical energy cost and percentage energy savings respectively, for each month and weekdays. The cost of operation of the climate control systems is maximum for December 15, 2011 to January 14, 2012, because of the minimum average temperatures during this period, since the number of operations of the radiant heating system increase considerably, thus increasing the overall electrical energy cost of the whole system; therefore, the savings are the least over this period. The savings are maximum during the months when temperature is neither too high nor too low, which reduces the number of operations of the climate control systems as compared to Case 0, thus yielding higher energy savings. The average electrical energy cost and energy savings for each month during weekends is shown in Figures 4.22 and 4.23. The electrical energy cost is comparatively lower during weekends than during weekdays, because of the lower electricity price profile.

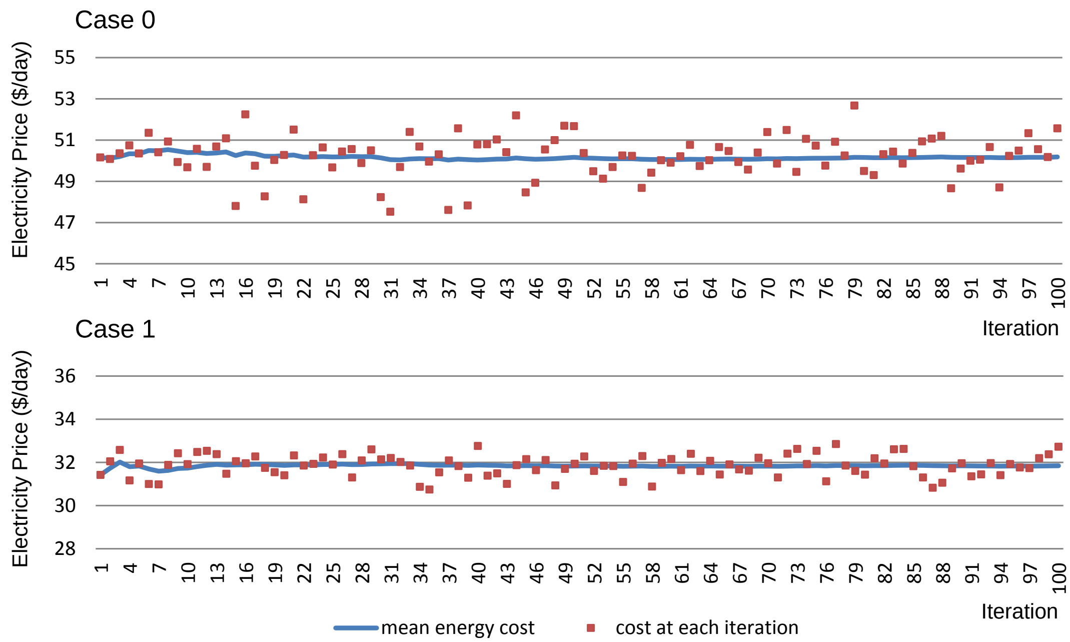

Figure 4.19: Mean electrical energy cost and cost at each iteration for the Monte Carlo simulations for weekdays on January 15 to February 15, 2012.

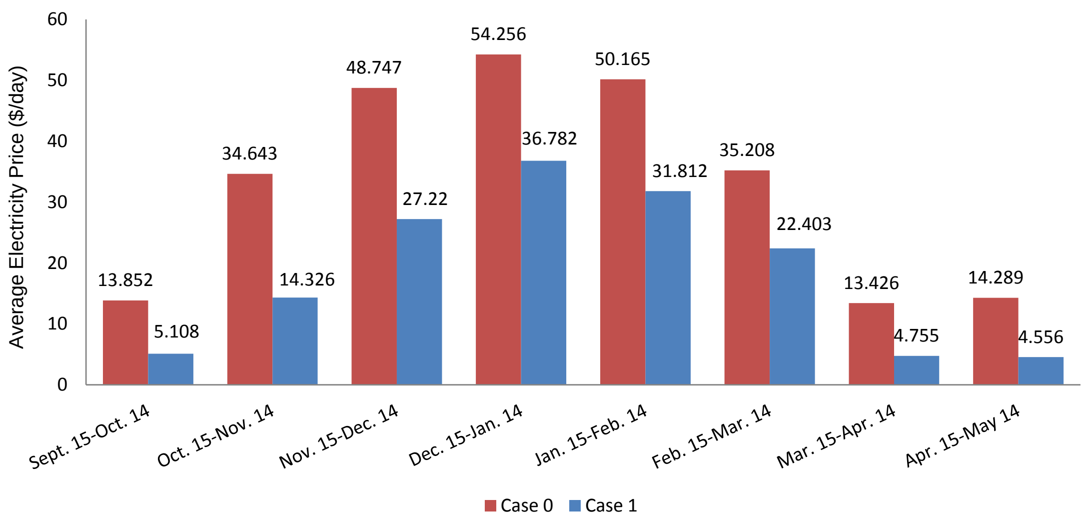

Figure 4.20: Average monthly electrical energy costs for weekdays.

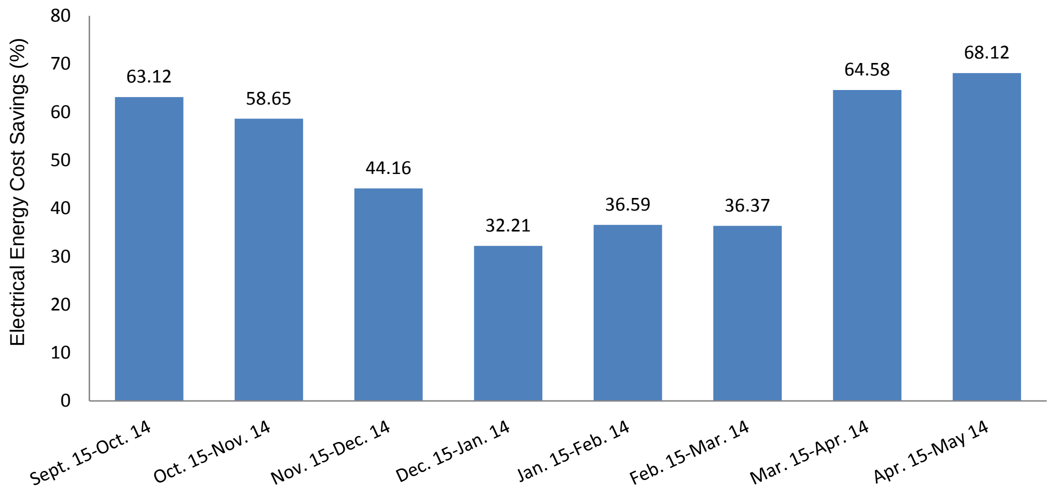

Figure 4.21: Monthly electrical energy cost savings for weekdays.

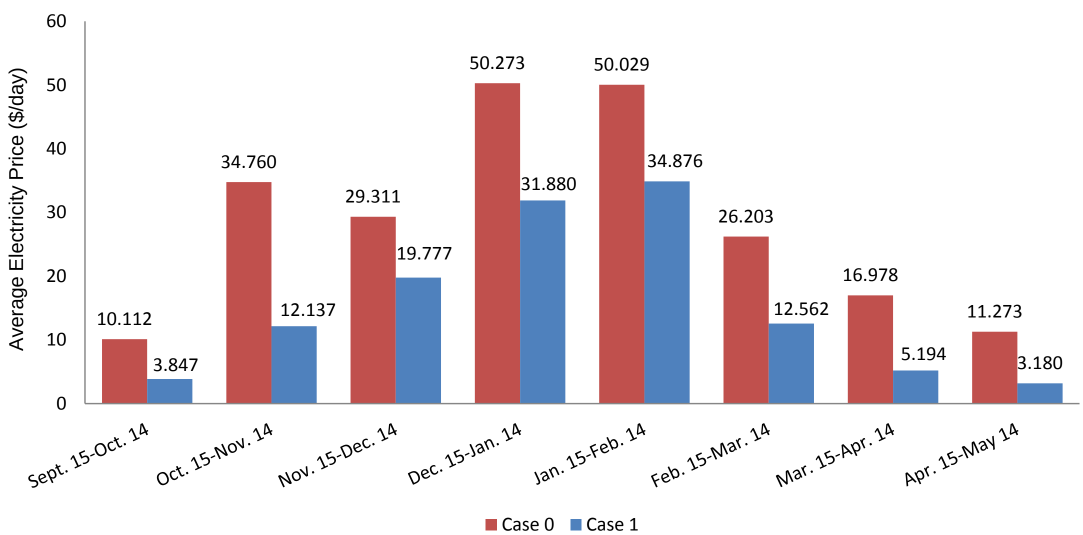

Figure 4.22: Average monthly electrical energy costs for weekends.

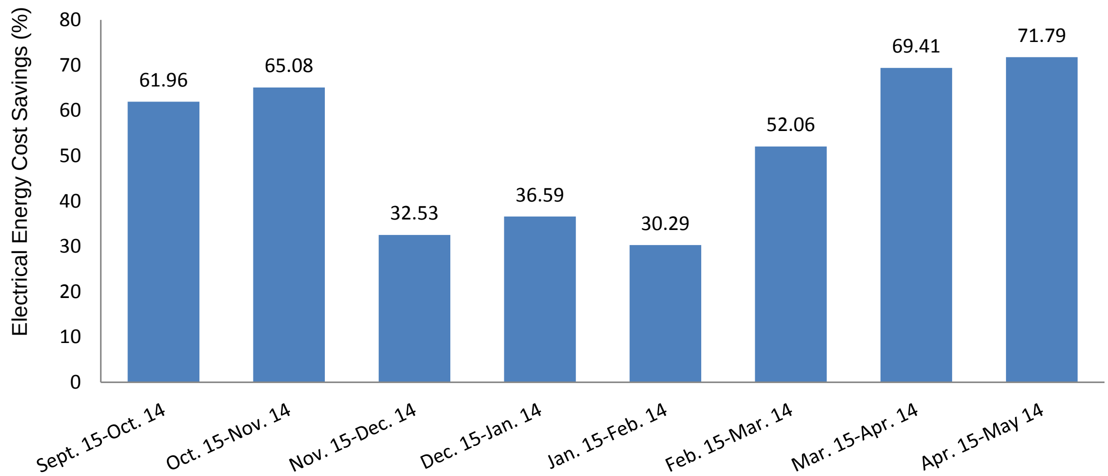

Figure 4.23: Monthly electrical energy cost savings for weekends.

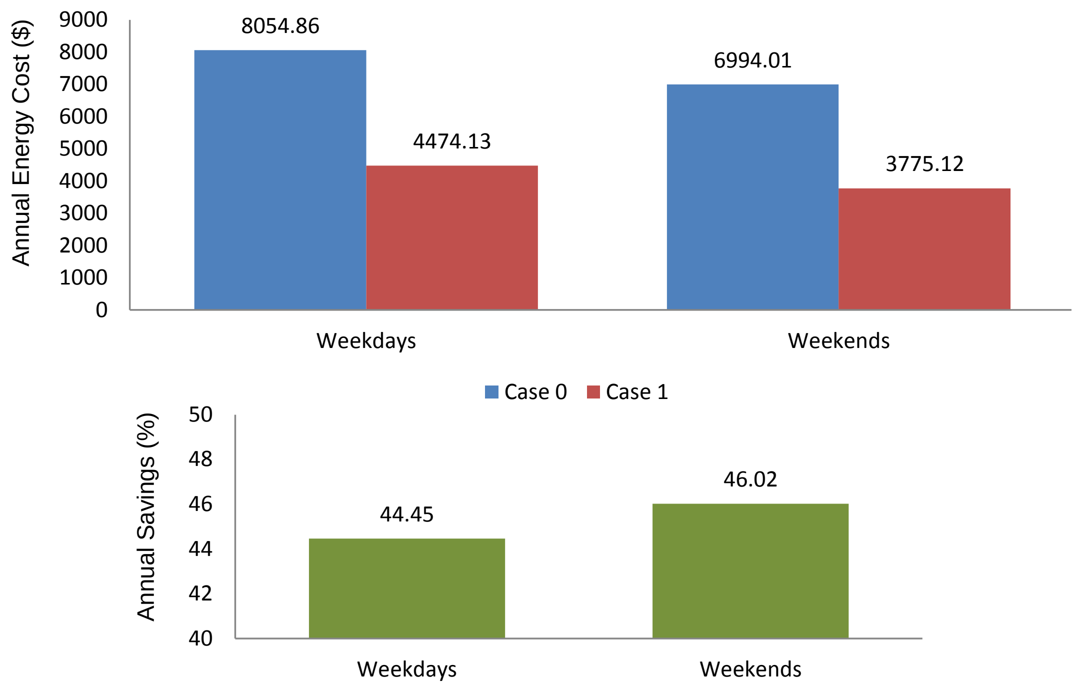

Figure 4.24: Annual electrical energy costs and energy cost savings for weekdays and weekends from September 15, 2011, to May 14, 2012.

The annual electrical energy cost and savings through the optimal operation of radiant heating system, ventilation system and dehumidifiers is shown in Figure 4.24. We observe more than 40% reduction in electrical energy cost obtained with the implementation of proposed model.

4.5 Computational Performance

The mathematical model is developed in GAMS [44], a high level modeling language based optimization platform and solved using CPLEX [45], a popular solver for Linear Programming (LP) and MILP problems. The model statistics are as follows:

- Number of Equations: 6047
- Number of Variables: 4033
- Number of Discrete variables: 1440
- Execution time: 4.7 seconds

Note that the model built with its large number of equations and variables can be solved in a few seconds, thus making it suitable for real-time applications.

4.6 Summary

This chapter discussed various case studies for the developed mathematical model. The presented results report the daily as well as annual energy cost savings, and the optimal operational schedules of the devices. Uncertainties in the inputs were analyzed by means of Monte Carlo simulations, to estimate possible annual energy savings over the period of 8 months, obtaining cost savings in the order of 40%.

Chapter 5

Conclusions and Future Work

5.1 Summary and Conclusions

This thesis explores the application of energy management systems to indoor ice rink energy hubs. A comprehensive mathematical model has been proposed in an optimization platform for real-time applications. The developed model incorporates electricity price information, weather forecast, spectator schedules and end-user preferences as inputs to generate optimal operational schedules of climate control devices, i.e. radiant heating, ventilation and dehumidification systems, satisfying their operational constraints while having minimum impact on spectator comfort. The inside temperature and humidity dynamics of the spectator area were modeled considering the complex thermodynamic configuration of the ice rink building, to minimize the total electrical energy cost of the climate control systems. The developed model was applied to a realistic indoor ice rink example and resulting energy cost savings were compared for two dynamic pricing schemes, HOEP and TOU.

The control scheme for optimal energy management is designed so that it can be implemented as a supervisory control in existing climate controllers of indoor ice rinks. The proposed optimization engine could be employed to generate optimal operational set points for the current control system, to reduce total electrical energy costs. The implementation of this model in an actual indoor ice rink facility will require accurate estimates of the proposed model parameters, either through measurements or calculations. The developed MINLP model was converted to MILP using different linearization techniques so that solutions could be obtained within a few seconds, that addresses the practical application of the proposed model.

The effect of uncertainties in weather and electricity price forecasts, and number of spectators was analyzed through Monte Carlo simulations to estimate expected annual energy cost savings, considering weekdays and weekends for a 8 month period of operation of the ice rink. It was observed that the proposed strategy may yield up to 40% savings in electrical energy costs during this period.

5.2 Contributions

This work has made several contributions that can be summarized as follows:

- Formulate a comprehensive mathematical model of an indoor ice rink facility that includes indoor temperature and indoor humidity dynamics of the spectator zone, to generate optimal set points for major climate control systems, considering radiant heating, ventilation and dehumidification systems.
- Modify the proposed model for use in real-time applications.
- Test and demonstrate the realistic application of the proposed model for different pricing schemes, considering uncertainties in various inputs and evaluating expected annual energy cost savings.

5.3 Future Work

Probable future work pertaining to the climate control systems of an indoor ice rink facility could be:

- This work considers a particular type of ventilation system, i.e. the "built up make-up" air unit, without recirculation and using 100% outside air. However, more comprehensive and detailed model of ventilation systems can be developed considering heat recovery from the refrigeration system.
- Instead of using 100% outside air, the ventilation system could be linked with the mixer operation for recirculation purposes.
- The proposed optimization supervisory strategy needs to be tested and validated by experimental analysis on an actual indoor ice rink facility.

Bibliography

[1] Natural Resources Canada, Energy Sector, About Electricity, 2010. [Online]. Available: http://www.nrcan.gc.ca/energy/sources/electricity/1387.

[2] M. Resource Consultants Ltd., M. Jaccard, and I. Associates, "Demand side management potential in Canada: Energy Efficiency Study," Integrated Power System Plan, Ontario Power Authority, Tech. Rep., 2006.

[3] B. Hamilton and M. Summy, "Benefits of the smart grid [in my view]," *IEEE Power and Energy Magazine*, vol. 9, no. 1, pp. 104 –102, Jan.-Feb., 2011.

[4] F. Rahimi and A. Ipakchi, "Demand response as a market resource under the smart grid paradigm," *IEEE Trans. on Smart Grid*, vol. 1, no. 1, pp. 82 –88, June, 2010.

[5] saveonenergy, Consumer Programs. [Online]. Available: https://saveonenergy.ca/.

[6] R. DeBlasio and C. Tom, "Standards for the smart grid," in *IEEE Energy 2030 Conference*, 2008, pp. 1–7.

[7] University of Waterloo, Energy Hub Management System (EHMS) project. [Online]. Available: http://energyhub.uwaterloo.ca.

[8] "The National Energy Technology Laboratory modern grid strategy powering our 21st-century economy: Advanced Metering Infrastructure," U.S. Department of Energy, National Energy Technology Laboratory, Tech. Rep., Feb. 2008.

[9] G. Koutitas, "Control of flexible smart devices in the smart grid," *IEEE Trans. on Smart Grid*, vol. 3, no. 3, pp. 1333 –1343, Sept., 2012.

[10] B. Xiao-min, M. Jun-xia, and Z. Ning-hui, "Functional analysis of advanced metering infrastructure in smart grid," in *International Conference on Power System Technology, 2010*, Oct., 2010, pp. 1 –4.

[11] S. Depuru, L. Wang, V. Devabhaktuni, and N. Gudi, "Smart meters for power grid; Challenges, Issues, Advantages and Status," in *IEEE/PES Power Systems Conference and Exposition, 2011*, March, 2011, pp. 1 –7.

[12] L. Nichols, "Improving efficiency in ice hockey arenas," *ASHRAE Transactions*, vol. 51, no. 16, pp. 17–20, 2009.

[13] L. Seghouani, A. Daoud, and N. Galanis, "Prediction of yearly energy requirements of indoor ice rinks," *Energy and Buildings*, vol. 41, no. 5, pp. 500 – 511, 2009.

[14] J.-T. Lin and Y. K. Chuah, "Prediction of infiltration rate and the effect on energy use for ice rinks in hot and humid climates," *Building and Environment*, vol. 45, no. 1, pp. 189 – 196, 2010.

[15] A. Ferreira and C. Dortolina, "Implementation of fast and effective dynamic pricing schemes in smart grids," in *Integration of Renewables into the Distribution Grid, CIRED 2012 Workshop*, 2012, pp. 1–4.

[16] IESO Public Reports, Market data, Jan. 2012. [Online]. Available: http://ieso.ca.htm.

[17] Horizon Utilities, Electricity Price Structures. [Online]. Available: http://horizonutilities.com/ElectricityRates.

[18] M. Bozchalui, S. Hashmi, H. Hassen, C. Cañizares, and K. Bhattacharya, "Optimal operation of residential energy hubs in smart grids," *IEEE Trans. on Smart Grid, accepted*, July, 2011.

[19] M. Chehreghani, C. Cañizares, and K. Bhattacharya, "Optimal operation of climate control systems of produce storage facilities in smart grids," *IEEE Trans. on Smart Grid, submitted*, June, 2012.

[20] ——, "Optimal operation of greenhouses in smart grids," *IEEE Trans. on Smart Grid, to be submitted*.

[21] J. Hwang, "Assessment of air condition load management by load survey in Taipower," *IEEE Trans. on Power Systems*, vol. 16, no. 4, pp. 910–915, 2001.

[22] C. Burt, R. Amón, and D. Cordova, "Electric load shifting in irrigation districts- California's program," in *USCID Conference on Benchmarking Irrigation System Performance Using Water Measurement and Water Balances*, 2002.

[23] A. Middelberg, J. Zhang, and X. Xia, "An optimal control model for load shifting–with application in the energy management of a colliery," *Applied Energy*, vol. 86, no. 7, pp. 1266–1273, 2009.

[24] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. on Smart Grid*, vol. 3, no. 3, pp. 1244 –1252, Sept., 2012.

[25] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, "Smart energy management system for optimal microgrid economic operation," *IET Renewable Power Generation*, vol. 5, no. 3, pp. 258–267, 2011.

[26] J. Mun and M. Krarti, "An ice rink floor thermal model suitable for whole-building energy simulation analysis," *Building and Environment*, vol. 46, no. 5, pp. 1087 – 1093, 2011.

[27] O. Piché and N. Galanis, "Thermal and economic evaluation of heat recovery measures for indoor ice rinks," *App. Thermal Engg.*, vol. 30, no. 14, pp. 2103–2108, 2010.

[28] M. Omri and N. Galanis, "Prediction of 3d airflow and temperature field in an indoor ice rink with radiant heat sources," *Building Simulation*, vol. 3, no. 2, pp. 153–163, 2010.

[29] C. Yang, P. Demokritou, Q. Chen, J. Spengler, and A. Parsons, "Ventilation and air quality in indoor ice skating arenas," *ASHRAE Transactions*, vol. 106, pp. 338–346, 2000.

[30] O. Bellache, M. Ouzzane, and N. Galanis, "Numerical prediction of ventilation patterns and thermal processes in ice rinks," *Building and Environment*, vol. 40, no. 3, pp. 417 – 426, 2005.

[31] H. Caliskan and A. Hepbasli, "Energy and exergy analyses of ice rink buildings at varying reference temperatures," *Energy and Buildings*, vol. 42, no. 9, pp. 1418 – 1425, 2010.

[32] A. Daoud, N. Galanis, and O. Bellache, "Calculation of refrigeration loads by convection, radiation and condensation in ice rinks using a transient 3d zonal model," *Applied Thermal Engineering*, vol. 28, no. 1415, pp. 1782 – 1790, 2008.

[33] Q. Chen, "Ventilation performance prediction for buildings: A method overview and recent applications," *Building and Environment*, vol. 44, no. 4, pp. 848 – 858, 2009.

[34] Z. Zhai, “Application of computational fluid dynamics in building design: Aspects and Trends,” *Indoor Built Env.*, vol. 15, no. 4, pp. 305–313, 2006.

[35] Gurobi Optimization, AMPL Gurobi Guide. [Online]. Available: http://www.gurobi.com/documentation/5.0/ampl-gurobi-guide/.

[36] Dept. of Geography, University of Toronto, Weather Archives. [Online]. Available: http://utm.utoronto.ca/geography/resources.htm.

[37] A. Daoud, *Analysis of heat transfer and mass transients in arenas using zonal method*, ser. PhD Thesis, Department of Mechanical Engineering, University of Sherbrook, 2008.

[38] S. Calabrese, *Practical Controls: A Guide to Mech. Systems.* Fairmont Press, 2003.

[39] F. Tiller and H. Garber, “Infrared radiant heating,” *Industrial & Engineering Chemistry*, vol. 34, no. 7, pp. 773–781, 1942.

[40] REAL Controls, Inc., Automation Integrator and Software Developer. [Online]. Available: http://realcontrols.com.htm.

[41] E. Marín, “Linear relationships in heat transfer,” *Latin-American Journal of Physics Education*, vol. 3, no. 2, p. 9, 2009.

[42] University of Texas, A Catalog for Radiation Heat Transfer Configuration Factors. [Online]. Available: http://engr.uky.edu.

[43] O. Bellache, N. Galanis, M. Ouzzane, R. Sunyé, and D. Giguère, “Two-dimensional transient model of airflow and heat transfer in ice rinks,” *ASHRAE Transactions*, pp. 706–716, 2006.

[44] GAMS: The General Algebraic Modeling System. [Online]. Available: http://www.gams.com/.

[45] R. Rosenthal and A. Brooke, *CPLEX 12- GAMS: A User's Guide.* GAMS Development Corporation, 2007.